Materials and Processing Technology Area
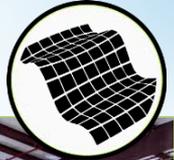
Cliff Eberle

Director,
Materials and Processing TA

January 13, 2016

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Institute for ADVANCED
Composites Manufacturing
INNOVATION

Materials and Process Technology Area Snapshot

Carbon Fiber Technology Facility

- Carbon fibers
- Lab-scale intermediates and composites prototyping
- Recycling
- Nondestructive evaluation (NDE)
- Materials characterization

Nonwovens Research Lab

Polymer AM Cell

Robotic preformer

Wide area flaw detection

ORNL: US leading neutron characterization and computing power

CO
-Thermo-plastic-glass-carbon recycling
-Factory floor NDE
-Full-scale molding with LCCF
-Pultruded spar caps

IN
-Product lifecycle modeling
-Process modeling for lab-scale validation

KY
-Largest open access solution spinning lab in US

MI
-Closed loop recycling
-Factory floor NDE
-Full-scale preforming
-Molding processes with LCCF

OH
-Factory floor NDE
-Full-scale preforming and winding processes with LCCF

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Integration is Critical

Srdjan Simunovic

Cliff Eberle

Claus Daniel

Bob Norris

Matt Weisenberger

Doug Adams

Soydan Ozcan

Dayakar Penumadu

- M&P liaisons assigned to lead integration with other Technology Areas
- M&P leaders responsible for seamless integration within M&P Technology Area
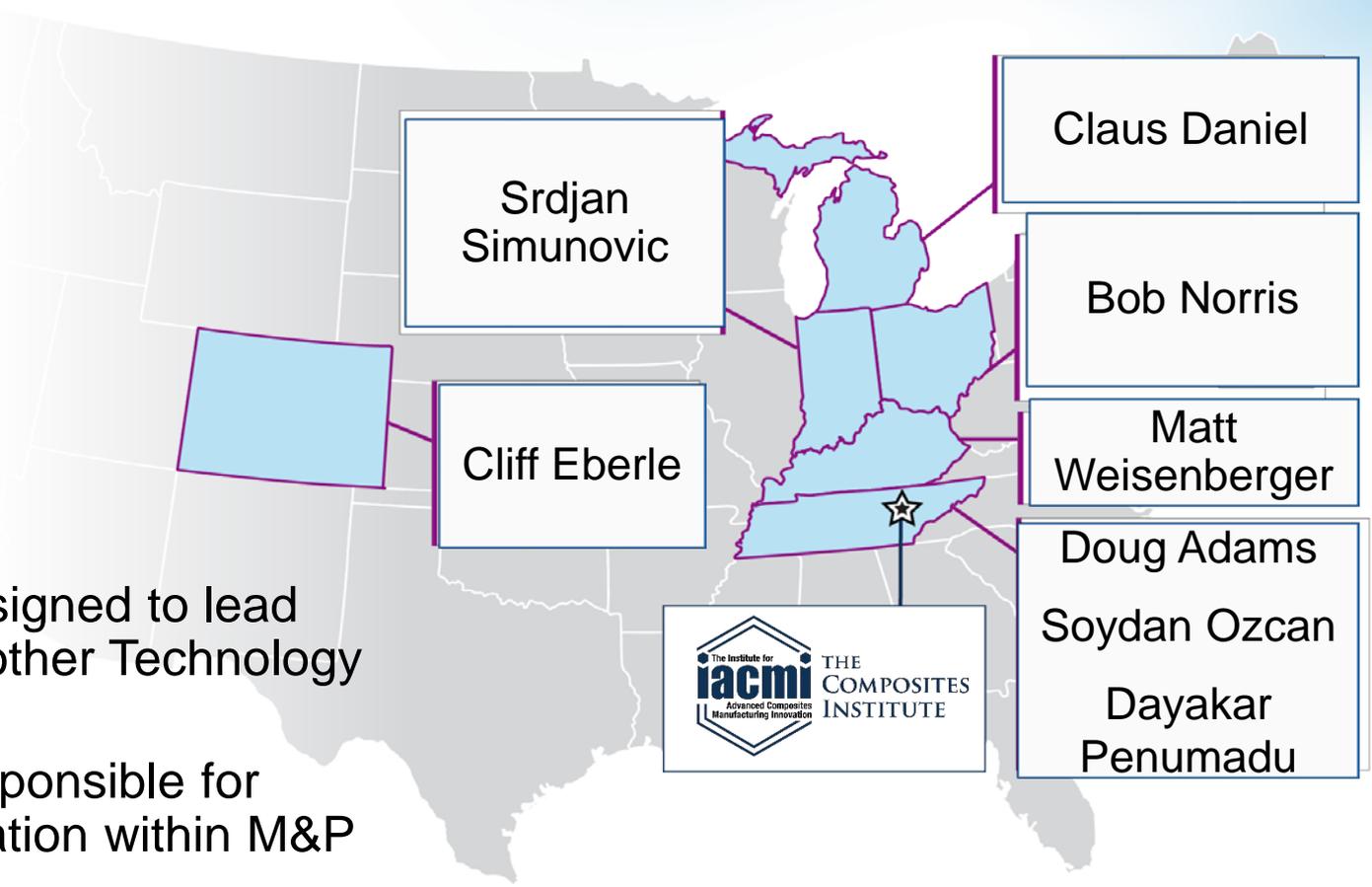
M&P Technology Area mission is to enable technology deployment through Application Technology Areas

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Innovations in NDE for Composites Manufacturing

Doug Adams
Tech Fellow in NDE,
Daniel F. Flowers Professor,
Vanderbilt University

January 13, 2016

What is NDE?
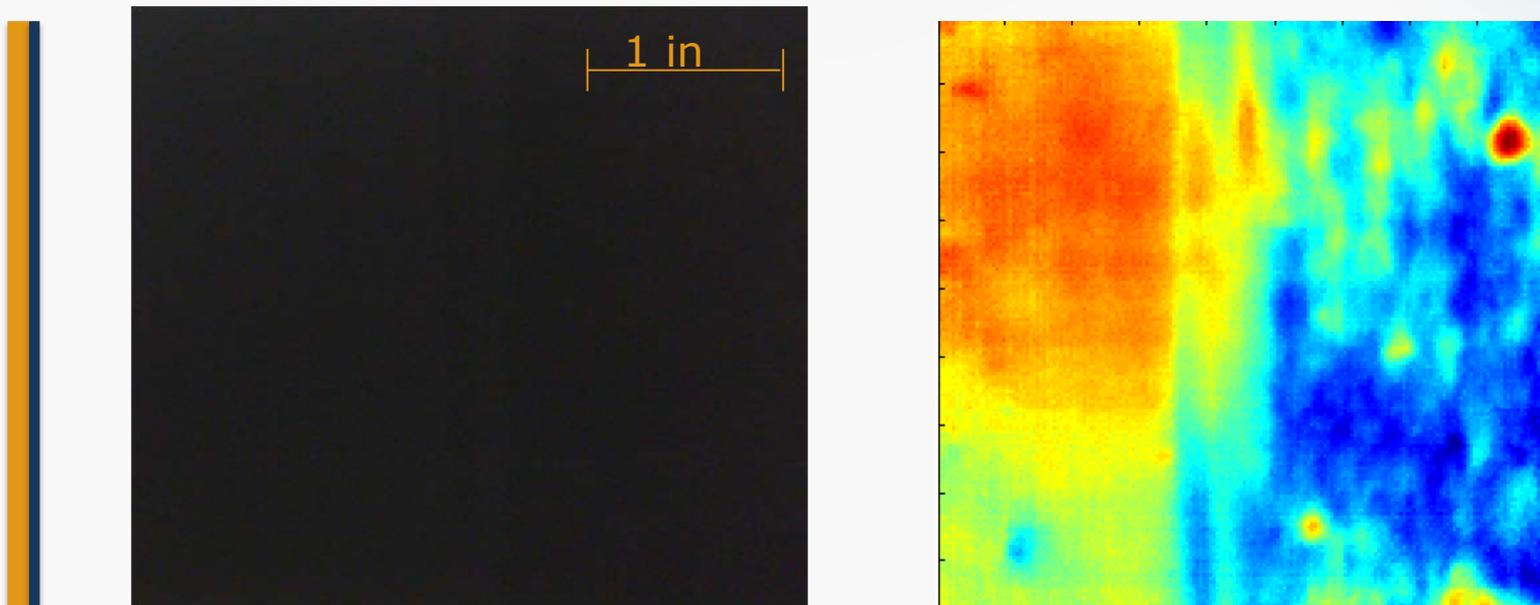
To see what is unseen!

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Is this polymer uniform?

| Material (% wt.)	Control	Test 2
$LiCoO_2$	96	96
PVDF	2	1
Carbon Black	2	3

Sharp, N., Adams, D., and Caruthers, J., "Lithium-Ion Battery Electrode Inspection using Pulse Thermography," 2014, NDT&D International, Vol. 64, pp. 41-51.

Full-Field Imaging to Diagnosis the Composite Material State In-Line
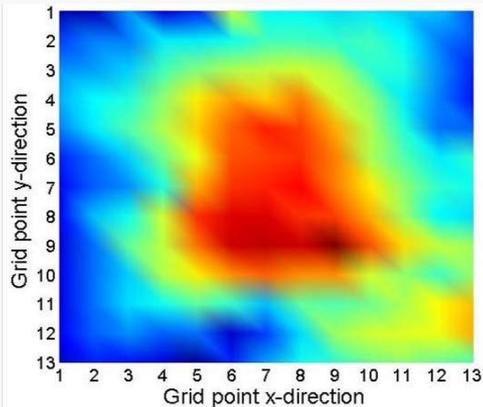
- In < 0.5 second, we can detect variations in both chemistry and geometrical flaws for use in adjusting process controls.
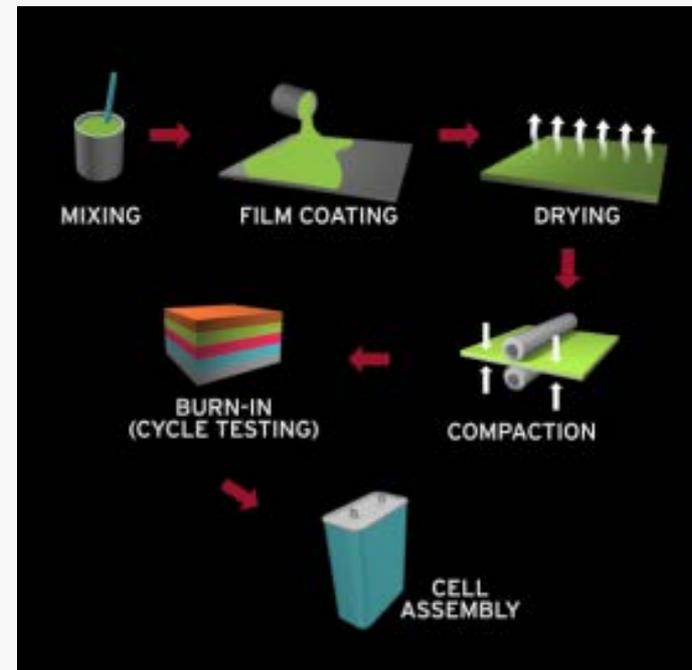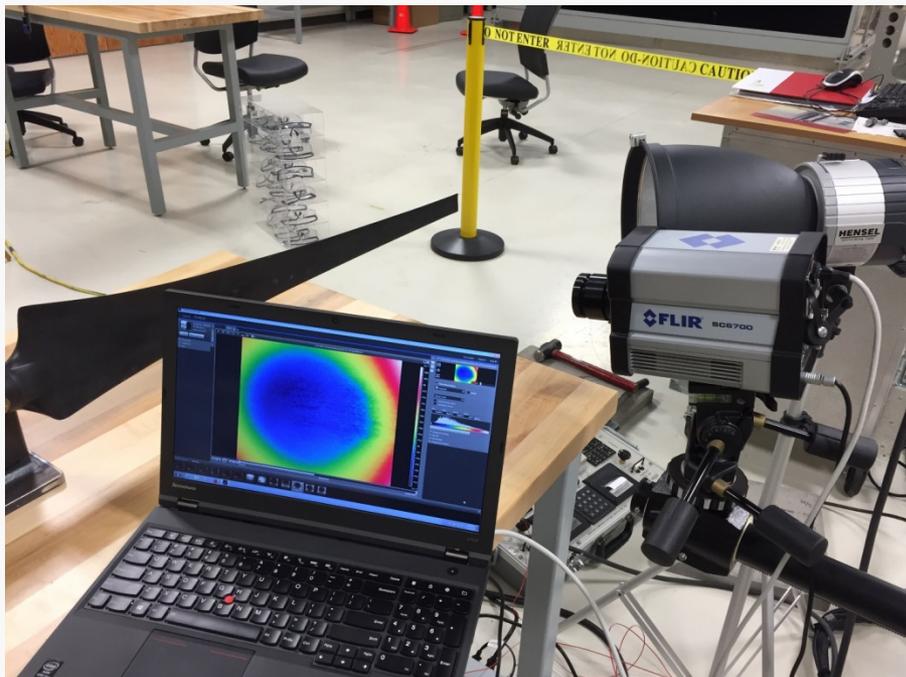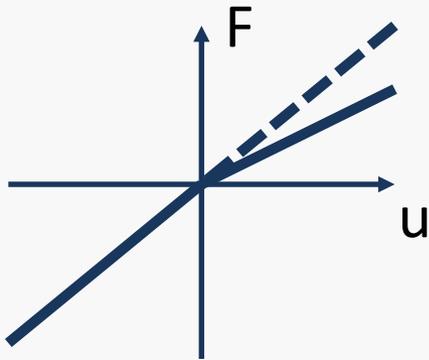
NDE Sensors Now in Reach for Wide Scale Deployment

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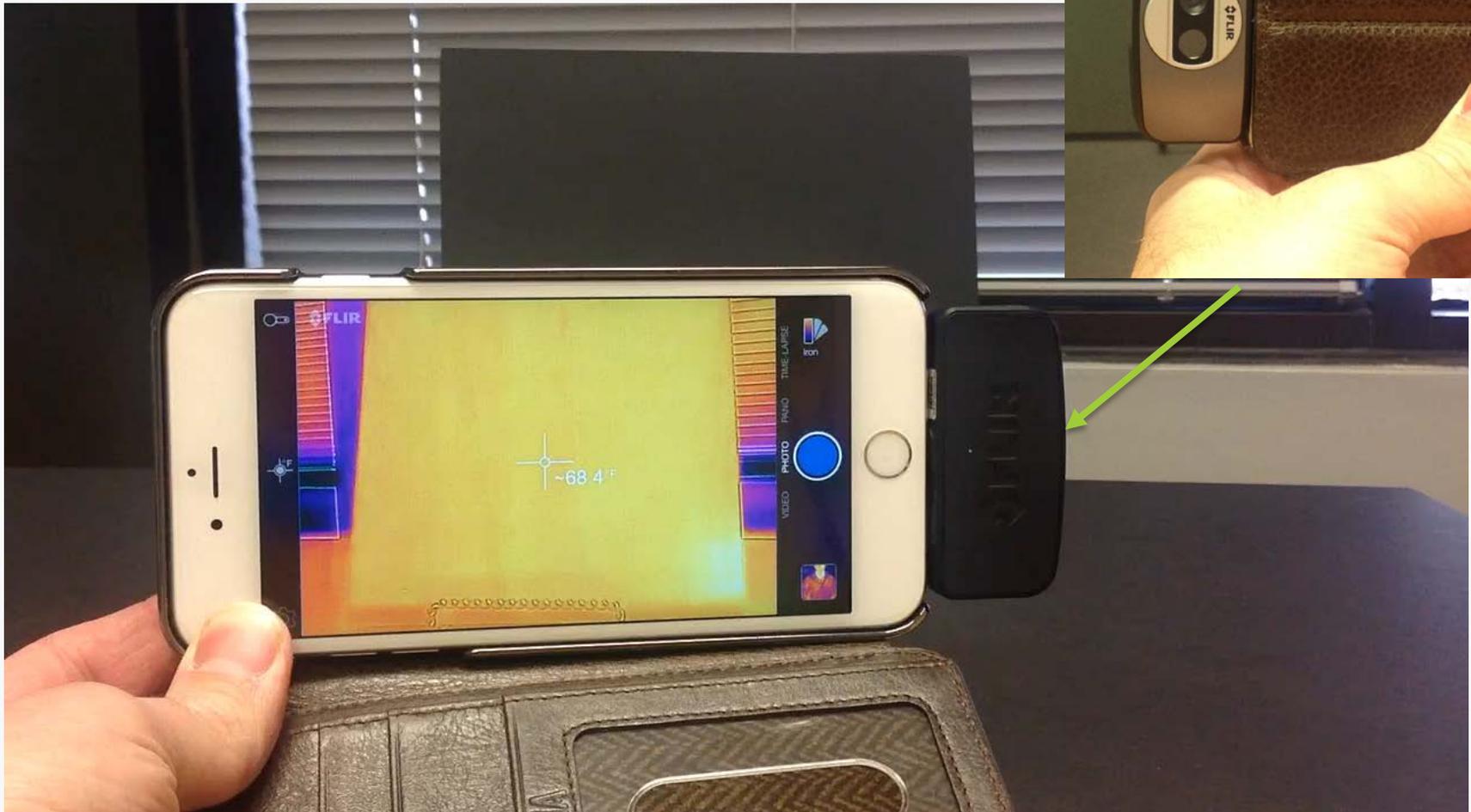
Innovation

Use nonlinearity to overcome barrier to inspecting large complex structures

Implementation


NDE Path to Innovation

Industry Need

Inaccessible bond line
Advanced joining concepts

Bond, R., Underwood, S., Cummins, J., and Adams, D. E., "Structural Health Monitoring-Based Methodologies for Managing Uncertainty in Aircraft Structural Life Assessment," *Structural Health Monitoring*, October 9, 2014, doi: 10.1177/1475921714553733.
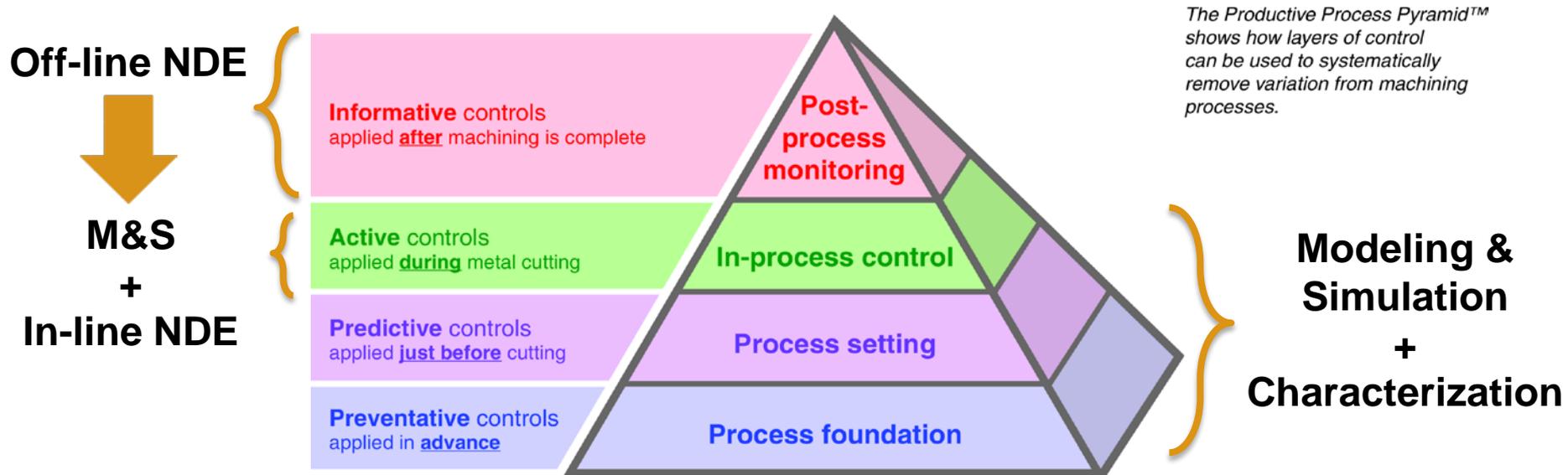
The Cost of Composite Part Variation

Part frequency

Part performance

Low performance dictates value
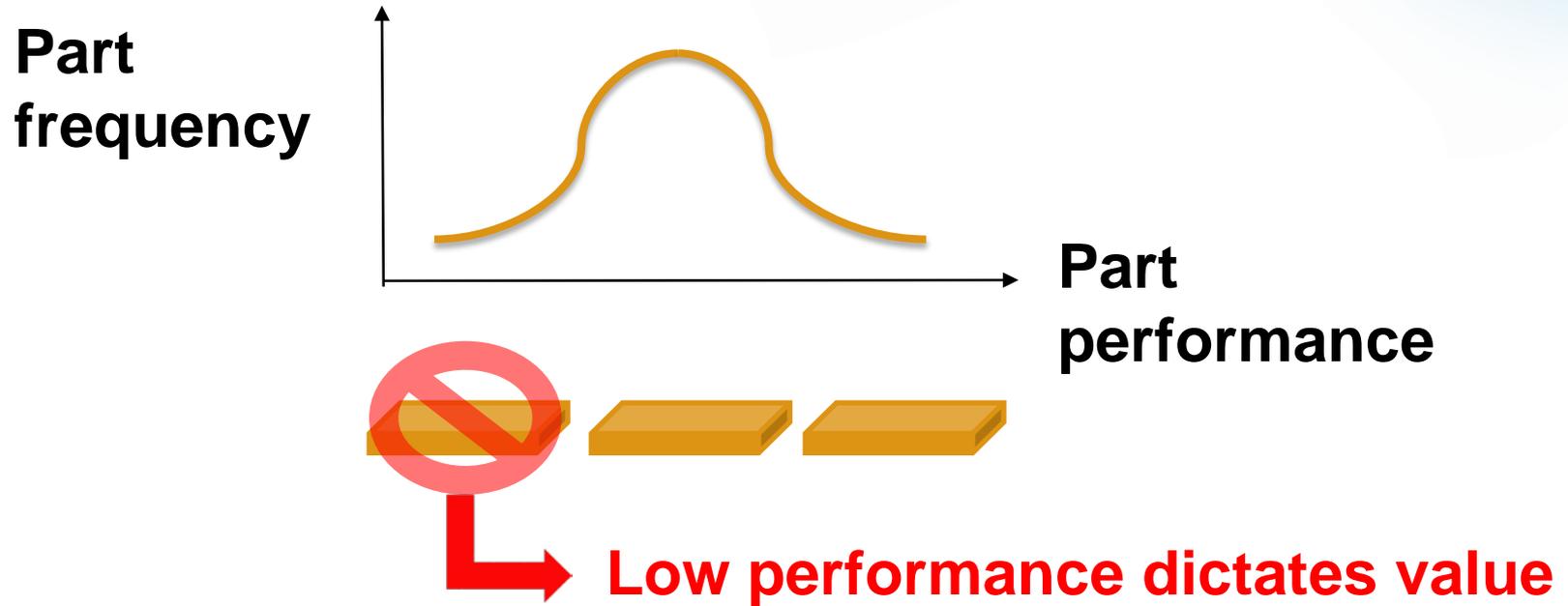
Question

What price will you pay for this batch of parts?

Combine Modeling & Simulation with NDE & Characterization for Decision Making to Enable Speed and Quality

Off-line NDE

M&S + In-line NDE

The Productive Process Pyramid™ shows how layers of control can be used to systematically remove variation from machining processes.

Informative controls applied **after** machining is complete — Post-process monitoring

Active controls applied **during** metal cutting — In-process control

Predictive controls applied **just before** cutting — Process setting

Preventative controls applied in **advance** — Process foundation

Modeling & Simulation + Characterization

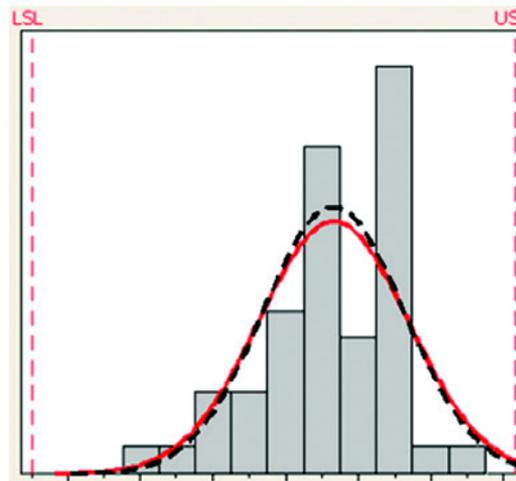*Source Renishaw plc, New Mills, Wotton-under-Edge, Gloucestershire GL12 8JR, U.K.*

Case Study Showing Benefits for Metals Machining Process
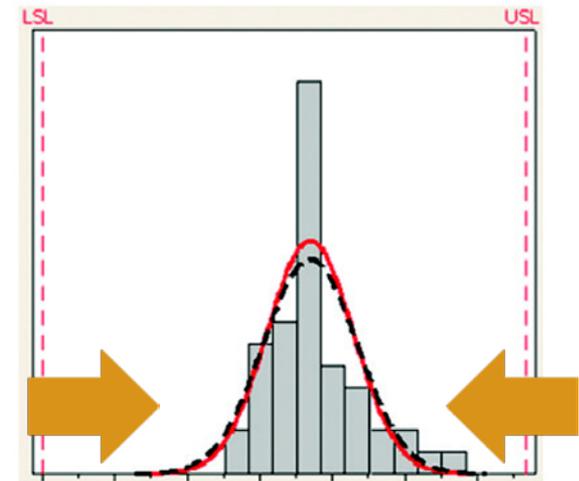

Process setting only
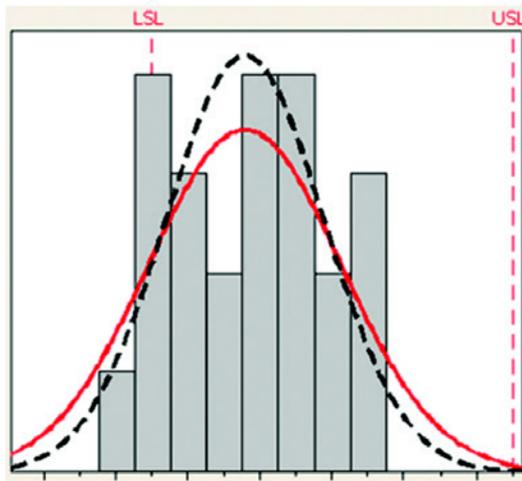
$C_{pk} = 0.32$
$P_{pk} = 0.39$
Scrap/rework = 12.1%

Process setting & post-process monitoring

$C_{pk} = 0.81$
$P_{pk} = 0.86$
Scrap/rework = 0.5%
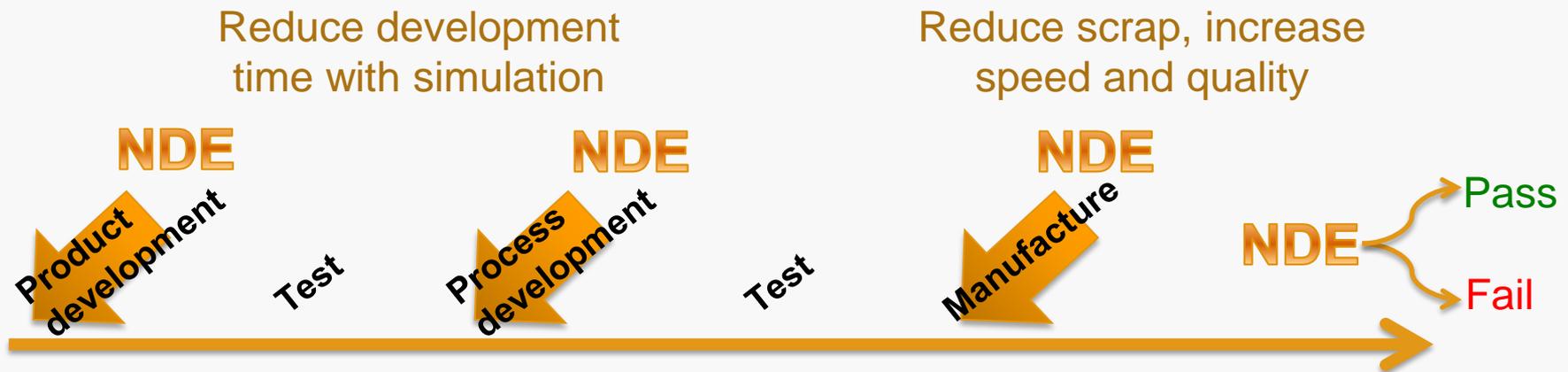
Process setting & in-process control

$C_{pk} = 1.66$
$P_{pk} = 1.55$
Scrap/rework = 0.0002%

60,000 times less scrap and rework!

Source: Renishaw plc, New Mills, Wotton-under-Edge, Gloucestershire GL12 8JR, U.K.

Vision for NDE in Composites Manufacturing

- In cost and energy efficient high-volume manufacture of composites, NDE can:

  – <u>Diagnose the material state in-line to support process</u> decisions in order to reach speed & quality targets.

  – <u>Characterize the material state to support simulation</u> in order to innovate and improve upon process.

Reduce development time with simulation

Reduce scrap, increase speed and quality

NDE NDE NDE

Product development   Test   Process development   Test   Manufacture

NDE — Pass
      — Fail

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What it means in practice: e.g. NDE in-line diagnostics

- Processes are dynamic.

- NDE methods rely on dynamic signatures.

- So, we will use process dynamics for NDE!

Assemblies

Components

Products

Intermediates

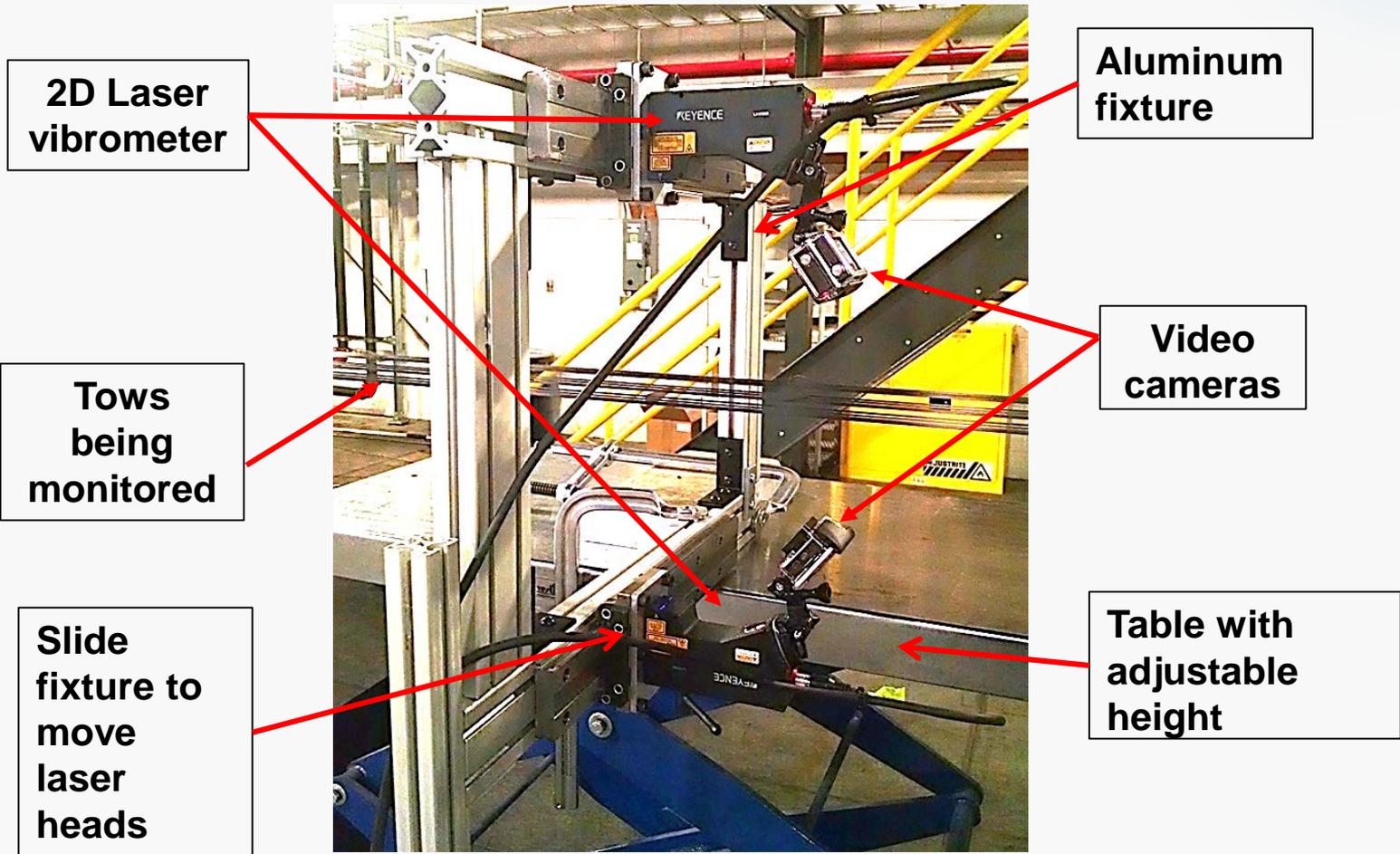**Process Dynamics**

Resins
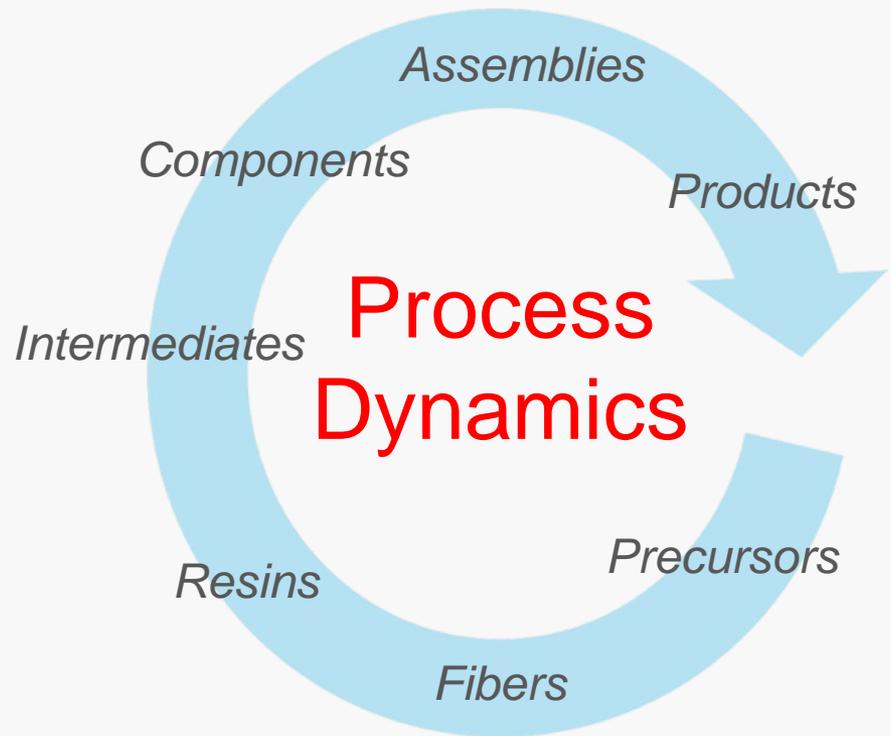
Precursors

Fibers

Mobile NDE Lab at Oak Ridge National Lab Carbon Fiber Technology Facility

Precursor tow band exhibits fuzz which is observed with two 2D laser profilometers to render 3D tow form
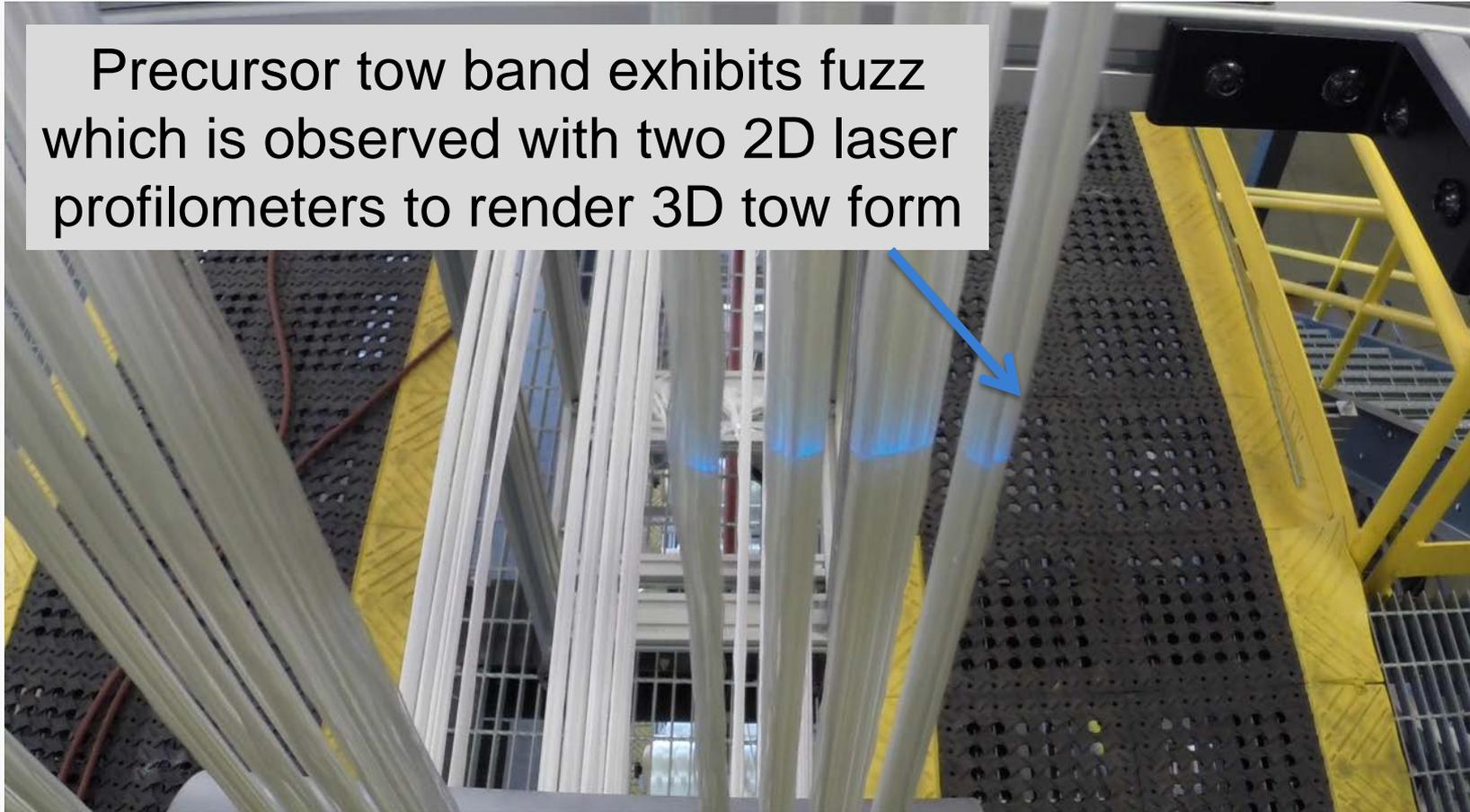
12 tows total of 24k precursor (4 tows shown)

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Setup of Real-Time, Non-Contact, Profilometry NDE System at CFTF

2D Laser vibrometer

Aluminum fixture

Tows being monitored

Video cameras

Slide fixture to move laser heads

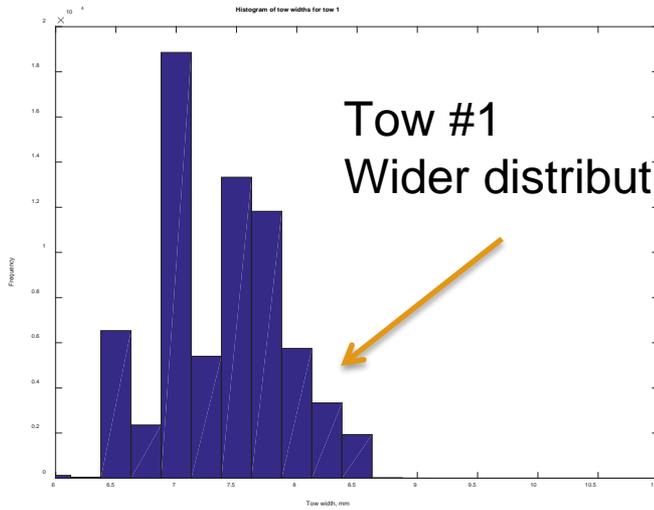**Table with adjustable height**

2D laser specs: Z Range: +/- 48 mm, X Beam Width: 62 mm, Sample Rate (max.) : 62500 Samples/sec. , Resolution: X: 100 μm, Z: 1 μm

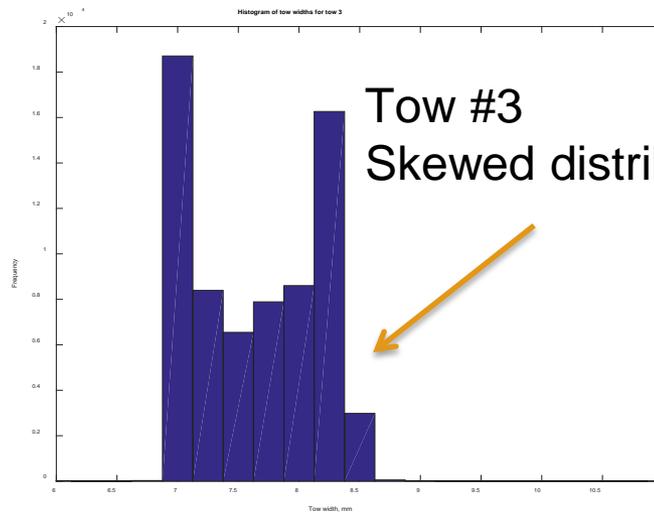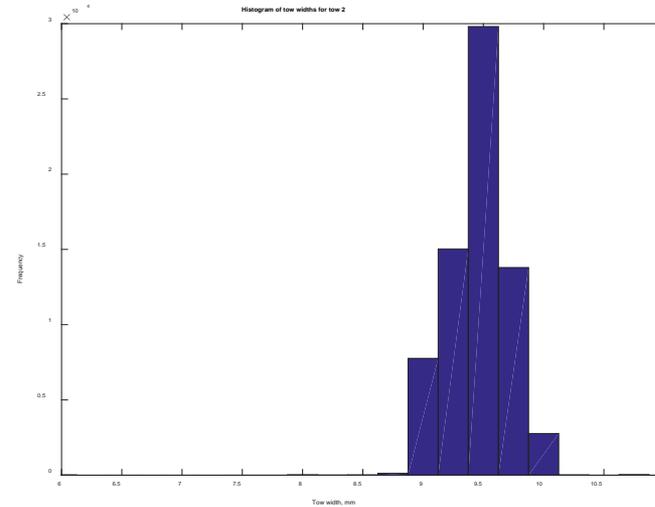# Profile along Tow for In-Line Fuzz Detection of Precursor
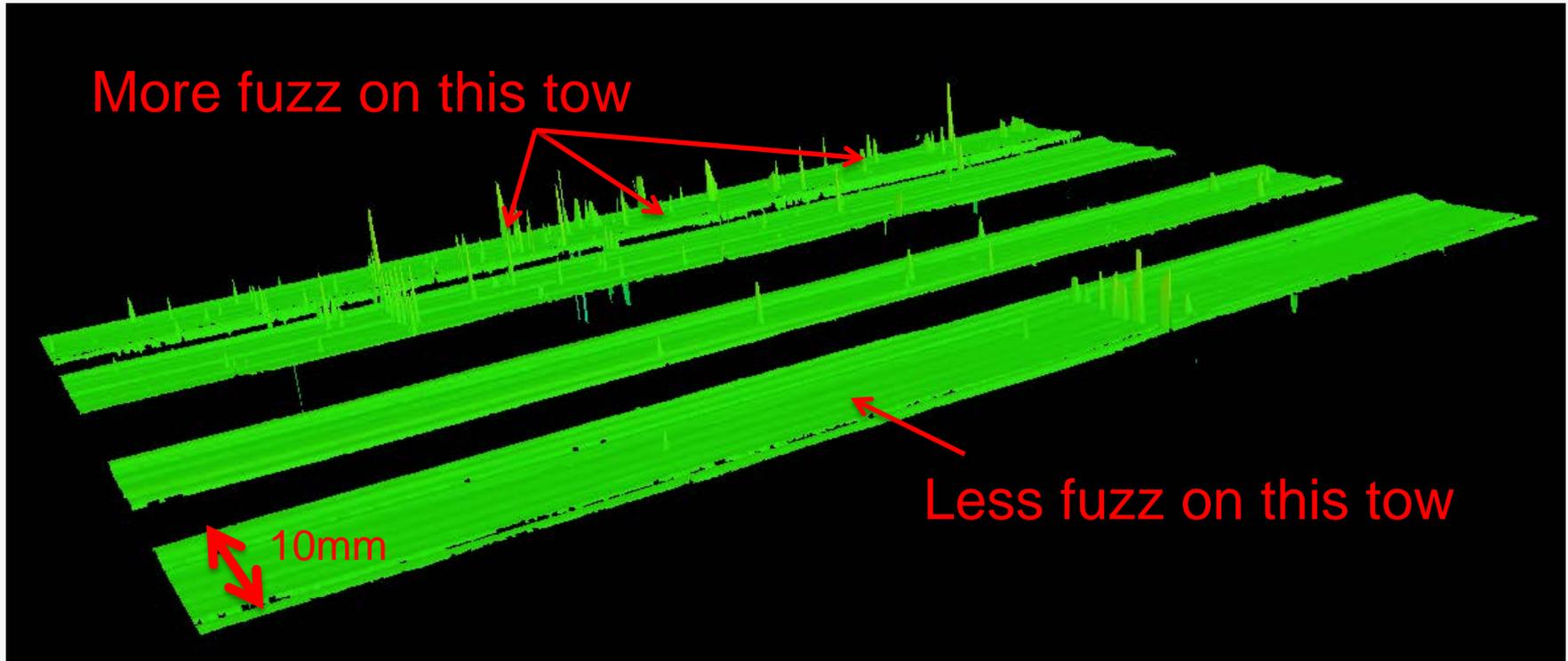
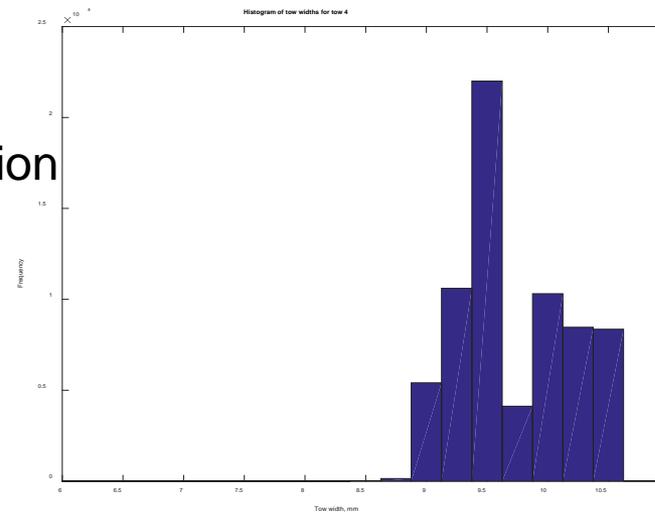Combining the 2D data through time after correlating top and bottom lasers, we can create a 3D profile.

Statistical Analysis of Carbon Fiber Tow Form - Width Distributions
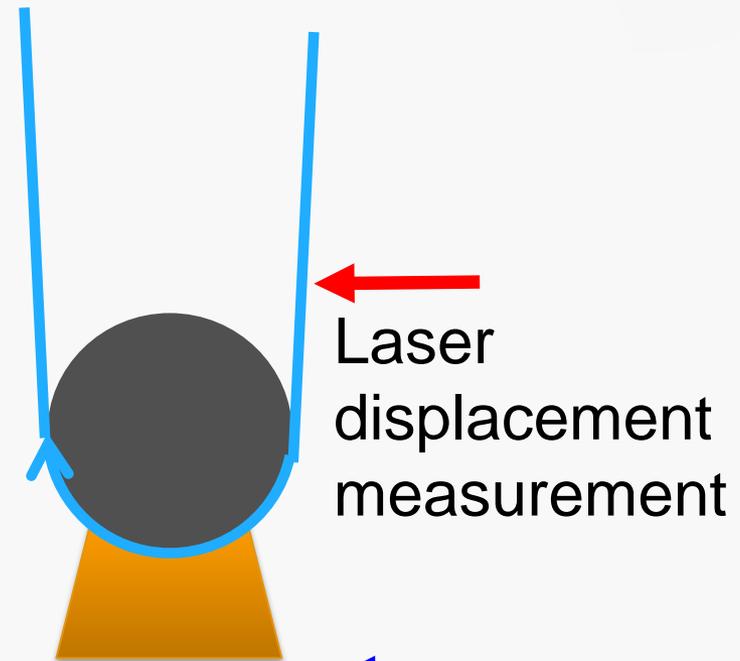

Tow #1
Wider distribution

Tow #3
Skewed distribution

Tow Dynamics for In-Line Diagnostics of Carbon Fiber Properties

- Oscillations of tow are a "fingerprint" with which to diagnose state of fiber
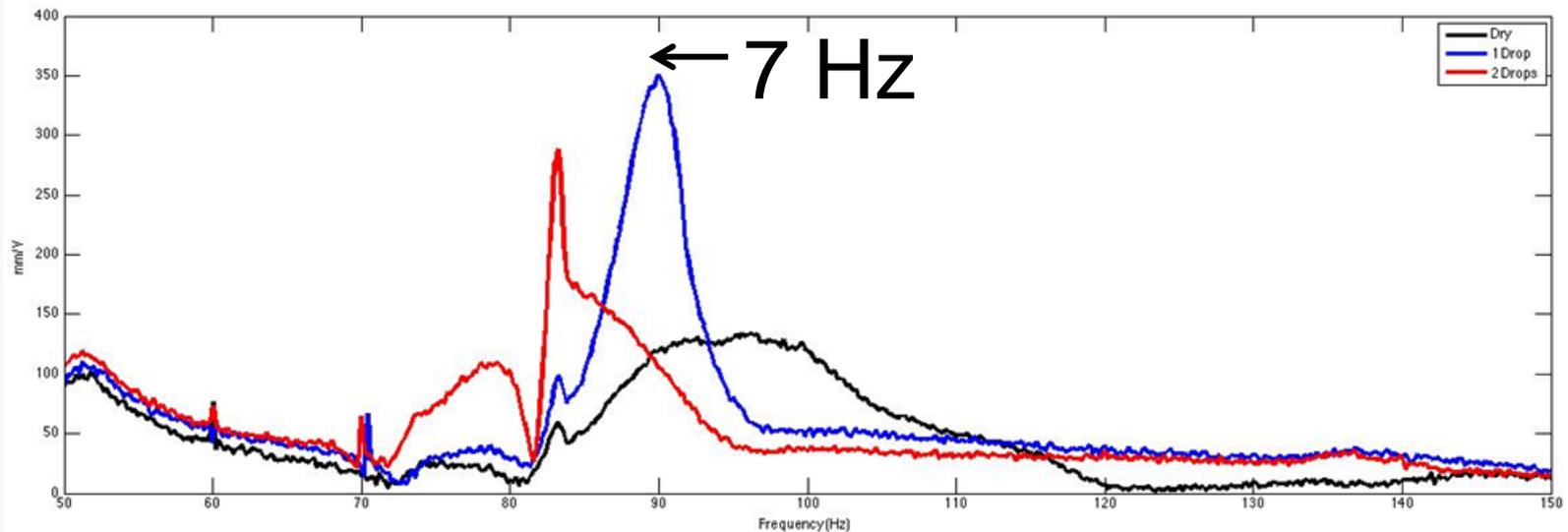
$$m\ddot{x} + kx = f(t)$$

Laser displacement measurement

Excite the machinery or tow fibers to make a coherent measurement

Change in Linear Density Detected in Carbon Fiber using Resonance

- Droplet: 0.036 grams; Tow: 0.461 grams

$$f = \frac{n}{2L}\sqrt{\frac{T}{\rho}}$$

Similar Ideas for In-Line NDE of Material State for Composite Manufacturing

- Composites manufacturing relies on uniform flow, cure, etc.

- Variations occur in the process due to material batch and the environment, e.g., humidity.

- Improve process speed and quality using in-line NDE.

Courtesy: Wind Turbines Tech Area
Derek Berry, NREL
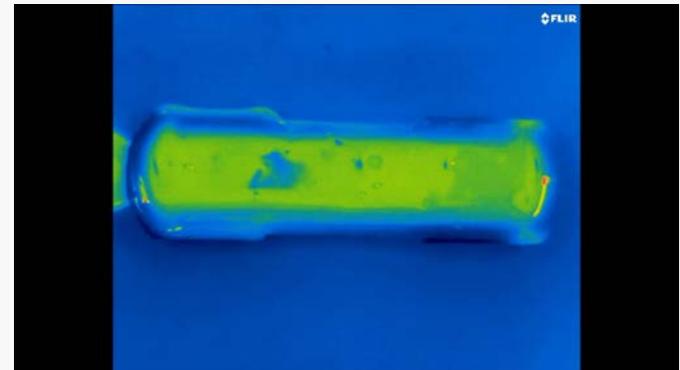
Infrared imaging to monitor full-field temperature of two-part epoxy as it reaches full cure

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What it means in practice:
e.g. NDE to Support Simulation

- Processes are simulated to account for multi-physics effects on material state.

- In-process and post-process NDE can estimate material state.

- So, we will use NDE to inform simulation to close the loop around simulation models.
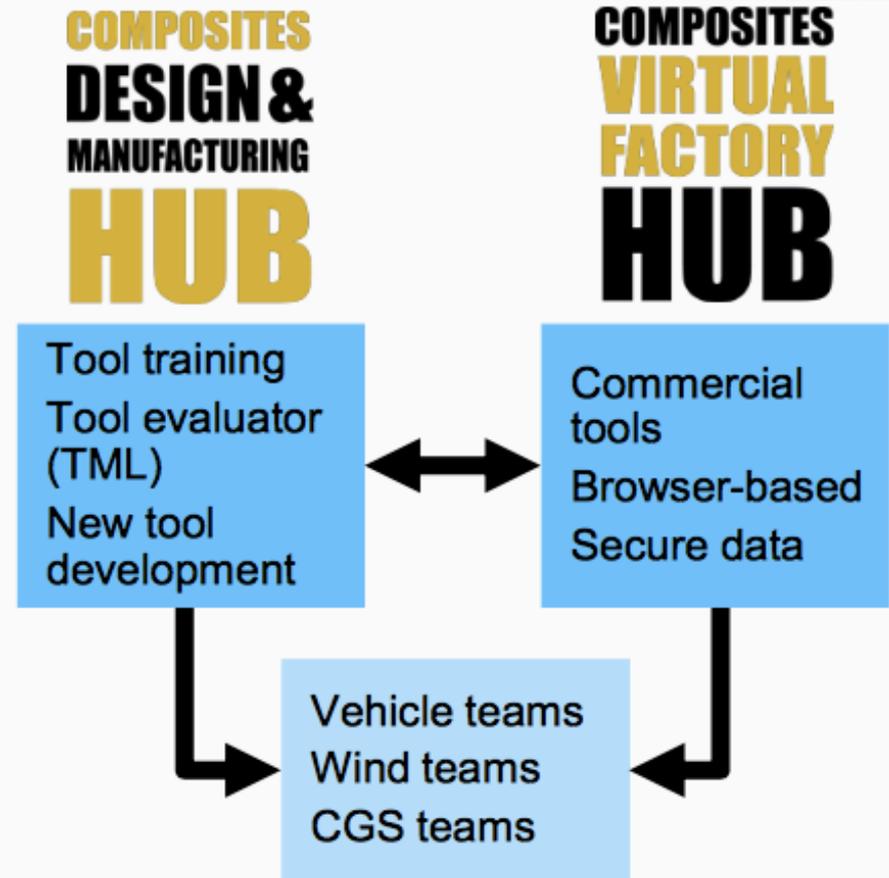
Courtesy: Design, Modeling and Simulation Tech Area
R. Byron Pipes, Purdue University

NDE Overview

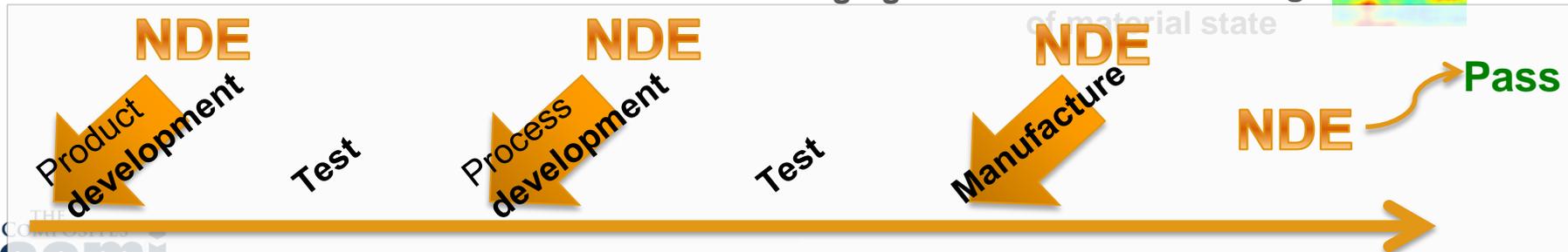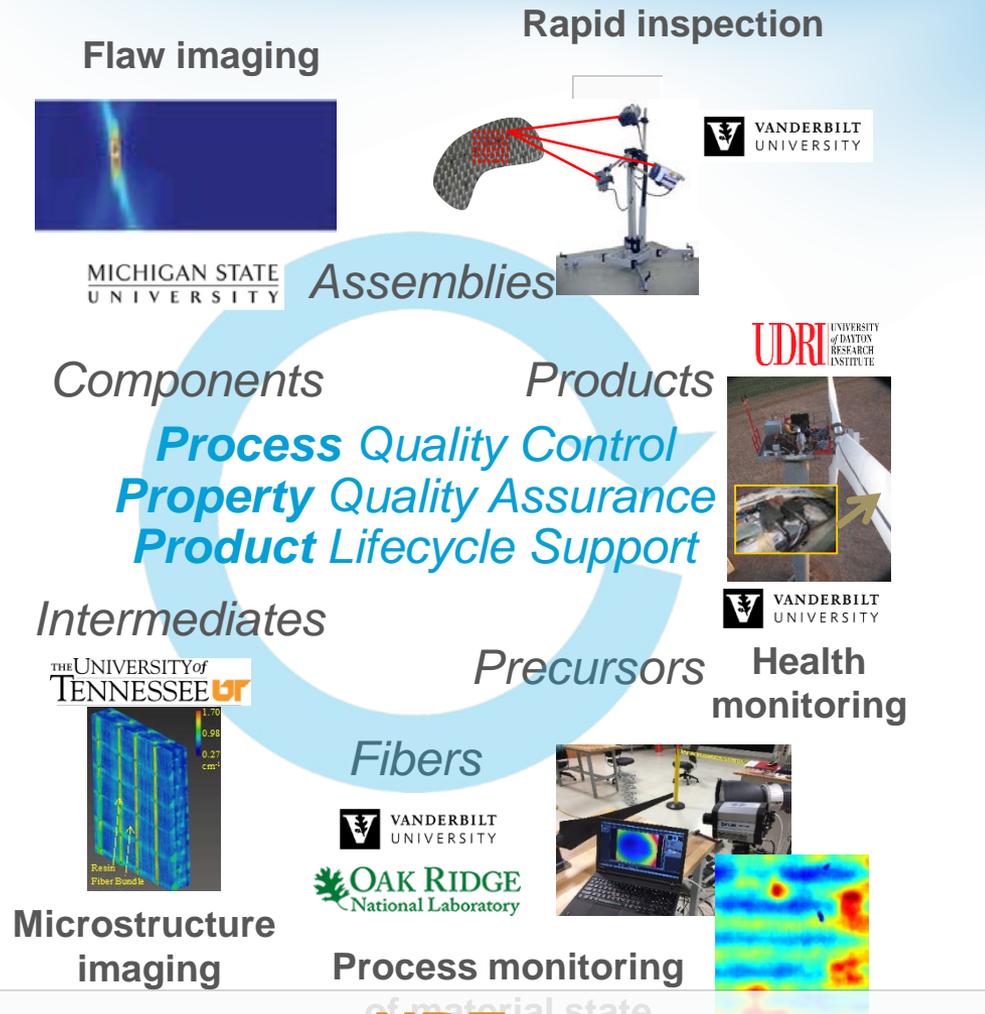- <u>Use</u> NDE data to help meet IACMI metrics for speed and quality by closing the loop around process design and control.

- <u>Deploy</u> technology across supply chain through a mobile NDE lab.

Flaw imaging

Rapid inspection

VANDERBILT UNIVERSITY

MICHIGAN STATE UNIVERSITY

Assemblies

Components   *Products*

Process *Quality Control*
Property *Quality Assurance*
Product *Lifecycle Support*

UDRI — UNIVERSITY of DAYTON RESEARCH INSTITUTE

VANDERBILT UNIVERSITY

Intermediates

THE UNIVERSITY of TENNESSEE ut

Precursors   **Health monitoring**

Fibers

VANDERBILT UNIVERSITY

OAK RIDGE National Laboratory

Microstructure imaging

Process monitoring of material state

NDE — **Product development**   Test   NDE — **Process development**   Test   NDE — **Manufacture**   NDE → **Pass**

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24

Acknowledgements of Our Team

David Koester
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Janette Meyer
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Solution Spinning

Dayakar Penumadu,
UTK
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characterization

R. Byron Pipes, Purdue
Design, Modeling and
Simulation Director

Derek Berry, NREL
Wind Turbines
Director

Acknowledgements of Our Team

Carbon Fiber Technology Facility Staff
Oak Ridge National Laboratory

The Institute for Advanced Composites Manufacturing Innovation

Innovations in NDE for Composites Manufacturing

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Tech Fellow in NDE,
Daniel F. Flowers Professor,
Vanderbilt University

January 13, 2016