Project 3.13 (October 2021)

Development of NDE/NDT Tools for High-Volume & High-Speed Inspection of CFRP Structures in Automotive Manufacturing

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Institute for ADVANCED Composites Manufacturing INNOVATION

3.13 Development of NDE Tools for High-Volume, High-Speed Inspection of CFRP Structures in Automotive Manufacturing

CHALLANGES

- Destructive mechanical tests of CFRP parts are inefficient & costly
- Existing “off-the-shelf” NDE techniques are not optimized for high-speed industrial environments
- New sensors arrays & NDE hardware need to be developed & validated

APPROACH

- Multiple NDE technologies evaluated in Project 3.8 (MSU & Vanderbilt)
- **Air Coupled Ultrasound (ACUT) & Electromagnetic (EM) NDE** down selected for Project 3.13 (MSU)
- Development of NDE robotic platform with a target goal of <3 min inspection per part (MSU)
- International collaboration & knowledge exchange (TACOMA UK Project, X-Ray NDE)

IMPACT

- High-speed NDE for high volume production of advanced composite components & structures
- Increased use of advanced composite materials in auto body structures (integrity, safety & quality)
- Lightweighting & improved strength for fuel efficiency & crashworthiness

Executive Summary: I. Array Probe Development & Optimization for High-Speed NDE of CFRP Parts

NDE TECHNIQUES

AIR COUPLED ULTRASONIC (ACUT) NDE

- Through-Transmission (TT) ACUT
- Single-Side Access (SSA) ACUT

ELECTROMAGNETIC (EM) NDE

- Eddy Current Testing (ECT)
- Capacitive Imaging (CI)
- Dual-Mode Imaging (DMI)

KEY ACCOMPLISHMENTS

- Array probes developed using commercial single-element ACUT transducers
- Frequency, spacing, angle of attack, focusing cones, excitation optimized for CFRP

- Array probes developed & fabricated by MSU
- FE models of sensors developed & validated
- Multiple sensing topologies tested
- Inspection parameters optimized for CFRP

Executive Summary: II. Hardware & Software Development & Integration for High-Speed NDE of Automotive CFRP Parts

HARDWARE

MSU ROBOTIC PLATFORM

- Two synced Fanuc ArcMate 100iB arms
- Active scan envelope of ~6 ft^3

MSU GANTRY SYSTEMS

- XYZ gantry for TT-ACUT & SSA-ACUT
- Portable gantry for EM NDE

NDE MODULES

- Sonoair 4-channel pulser-receiver (ACUT)
- Ectane 2 system with 64 channels (EM)

SOFTWARE

MSU SCAN SOFTWARE

- Dual-robot & gantry control
- Robotic path planner for curved parts
- Stereovision for part's surface reconstruction
- Synced data acquisition with NDE hardware

MSU SIGNAL PROCESSING

- Signal & image filtering algorithms for enhanced defect detection
- 3D point cloud rendering for robotic NDE

Development of Multimodal NDE Platform for Rapid Inspection of Automotive CFRP Parts

- **Robotic Platform & Scan Software**
- Air-Coupled Ultrasonic (ACUT) NDE
- Electromagnetic (EM) NDE

Robotic Workcell at MSU/CVRC

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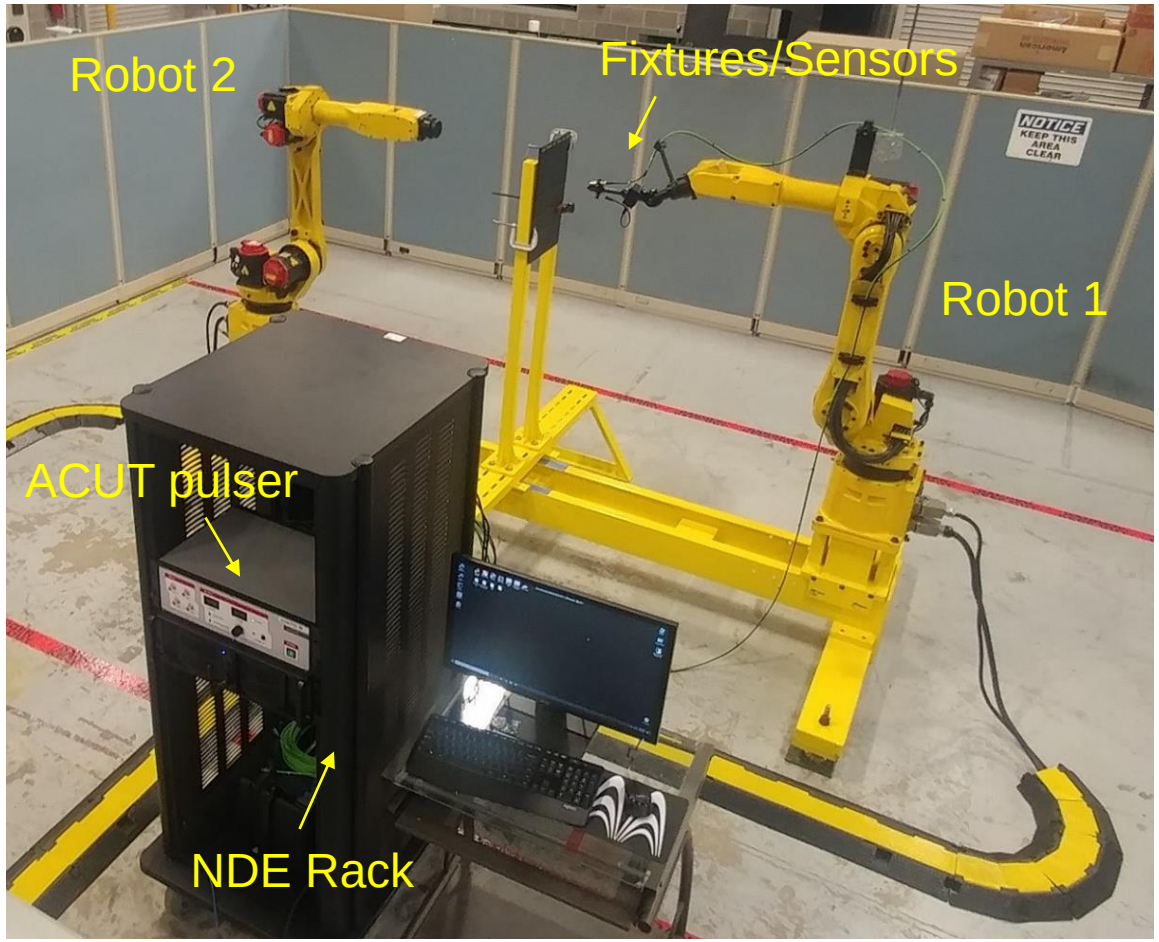
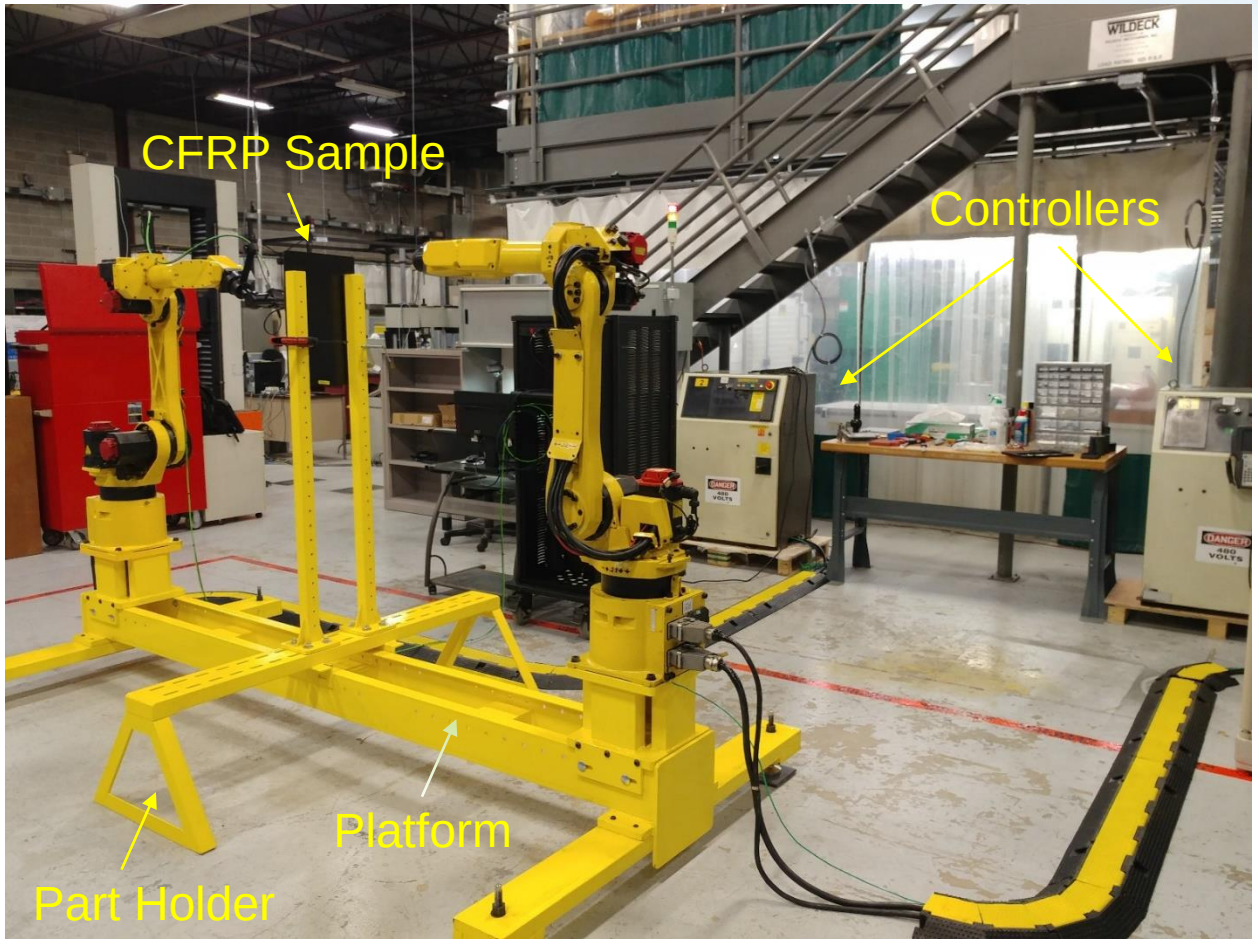


Top View



Side View

Robotic NDE Pipeline

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1. IDENTIFY PART GEOMETRY

- Acquire CAD model
- Use stereo-camera reconstruction

2. GENERATE TOOLPATH

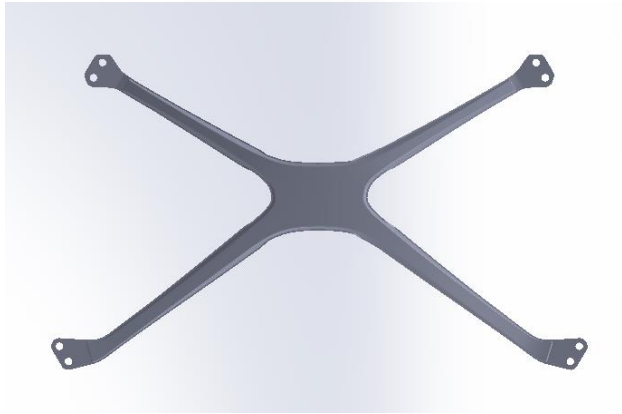
- MSU 3D zig-zag path planner
- Position constraints for NDE probes

3. RUN SCAN

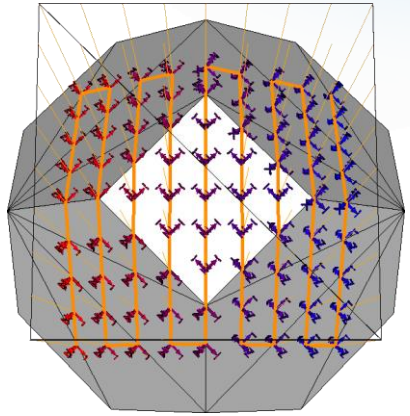
- Execute KAREL program
- NDE data synced with coordinates

4. PROCESS & VISUALIZE DATA

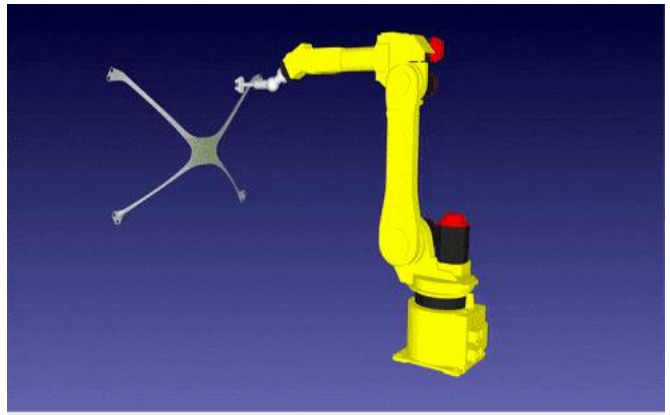
- Image filtering, defect detection
- 3D data rendering



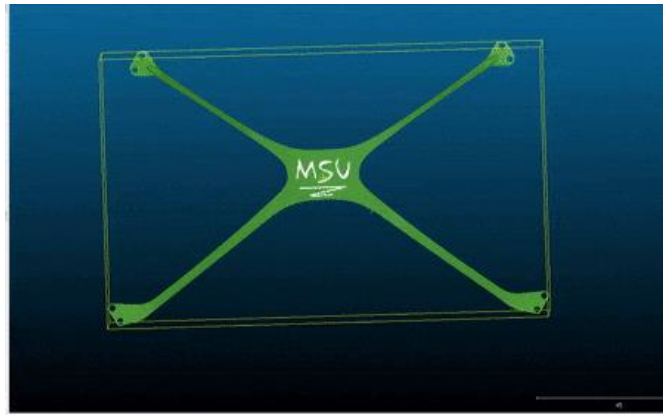
1. CAD model



2. Zig-zag scanpath in 3D



3. Simulation of scan process



4. Data visualization

Development of Multimodal NDE Platform for Rapid Inspection of Automotive CFRP Parts

- Robotic Platform & Scan Software
- **Air-Coupled Ultrasonic (ACUT) NDE**
- Electromagnetic (EM) NDE

Robotic SSA-ACUT (1CH): Validation on CFRP Panel #1

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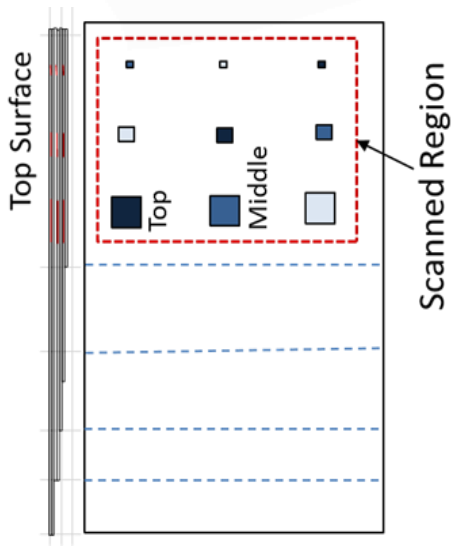
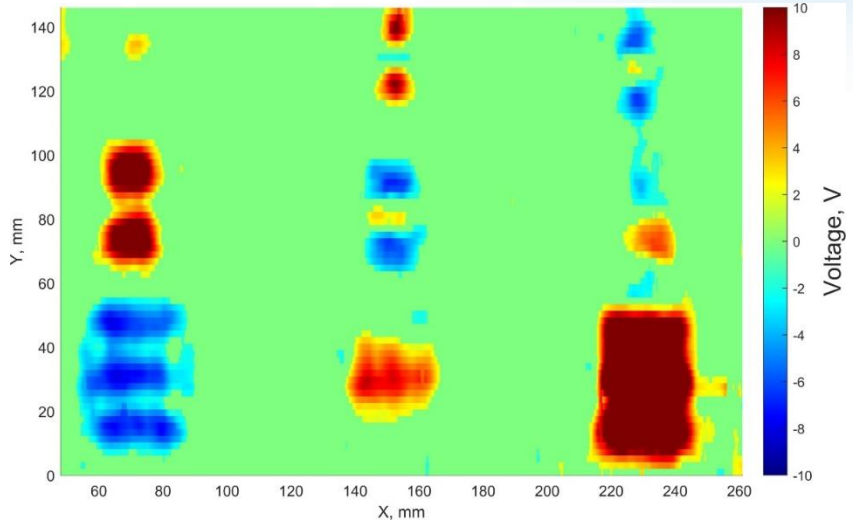
SSA-ACUT scan on robotic platform

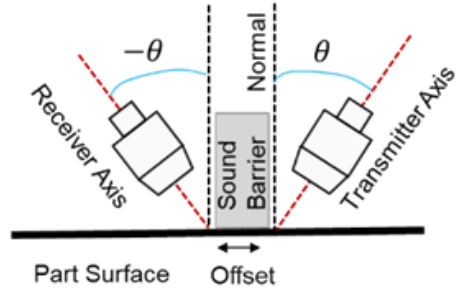


Calibration Panel #1 with 9 delaminations



Typical Scan + Image Processing (delaminations shown as blue, orange and red)

- SSA-ACUT showed good capability for robotic NDE
- Interlaminar delaminations successfully detected using guided waves
- Inspection frequency: f = 200 kHz, bandpass filtering applied
- Scans can be acquired at higher robot speeds



SSA-ACUT approach

Robotic SSA-ACUT (3CH): Validation on X-brace #3

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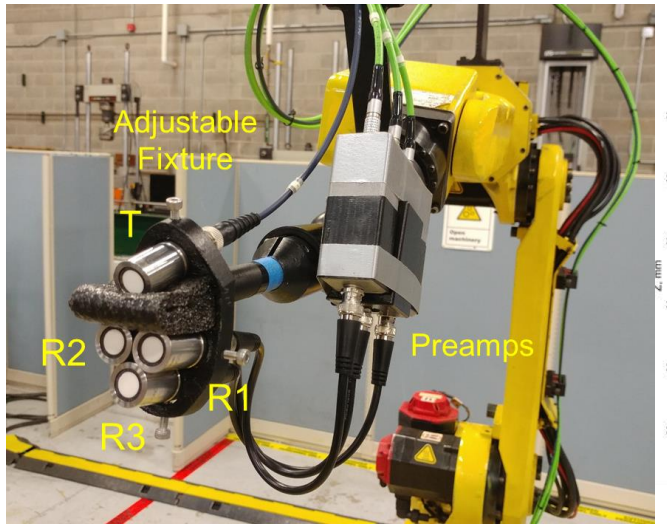
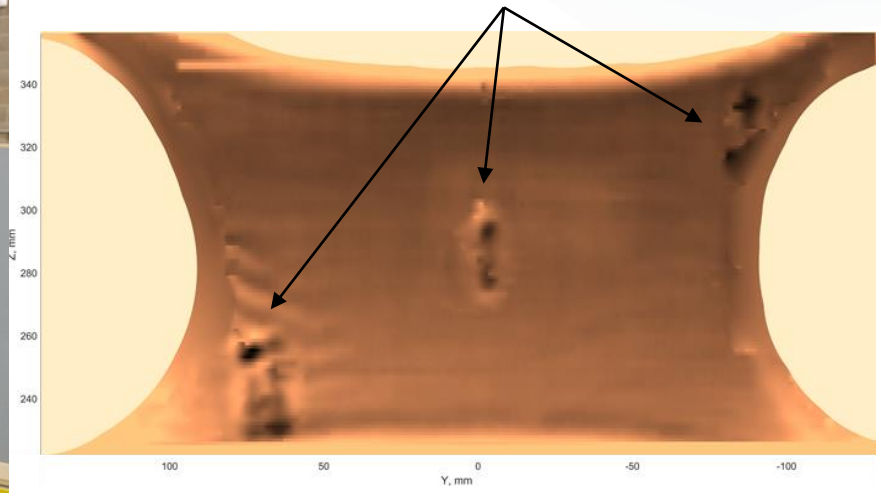
SSA-ACUT scan on robotic platform



ACUT Fixture

Interlaminar delaminations



Corresponding ACUT C-scan (unprocessed 3D point cloud)

- SSA-ACUT performed on CFRP part with curved geometry
- Three delaminations were successfully detected: 16x16 mm^2, 9x9 mm^2 and 6.7x6.7 mm^2
- Inspection frequency: f = 200 kHz, bandpass filtering applied
- Scans can be acquired at higher robot speeds

High-Speed 4-CH ACUT Gantry: Validation on X-Brace #3

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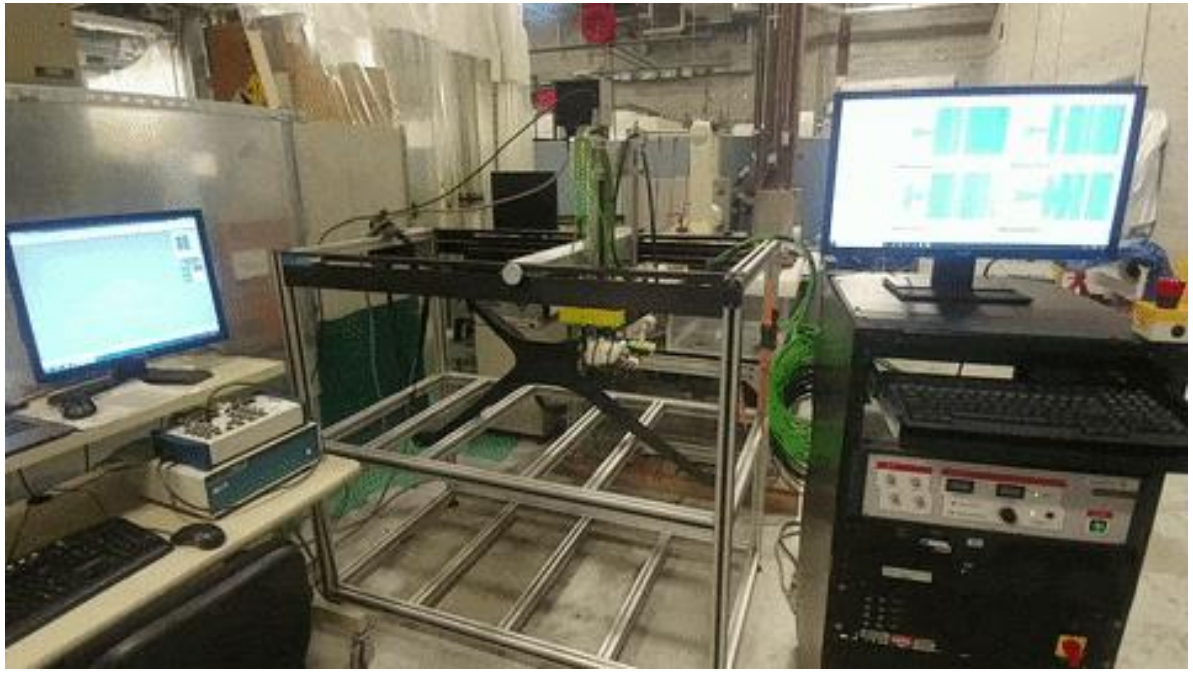
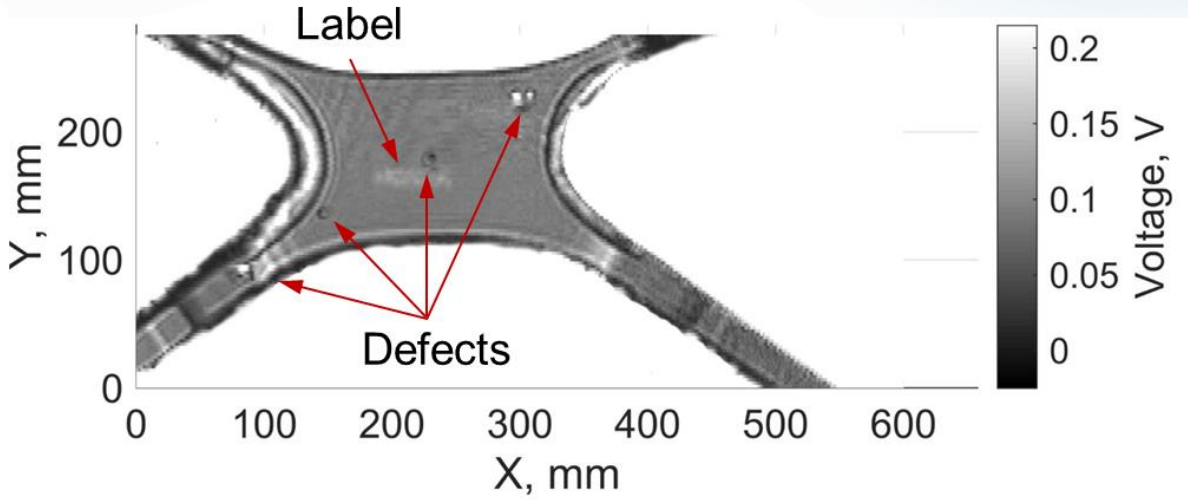
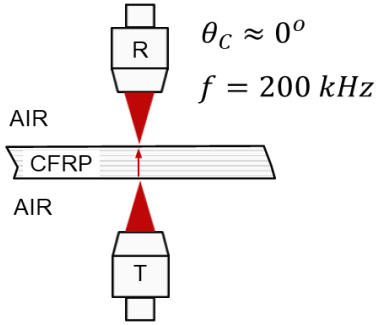


TT-ACUT scan on gantry system

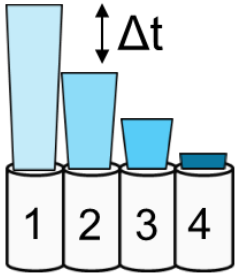


Typical scan + Image processing (1 min 30 s)

- UT waves propagated through the test sample
- ACUT transducers were excited sequentially with time delays in order to avoid cross-talk
- Embedded defects successfully detected



TT-ACUT approach



Time-gated excitation

High-Speed 4-CH ACUT Gantry: Validation on Door Panel #3

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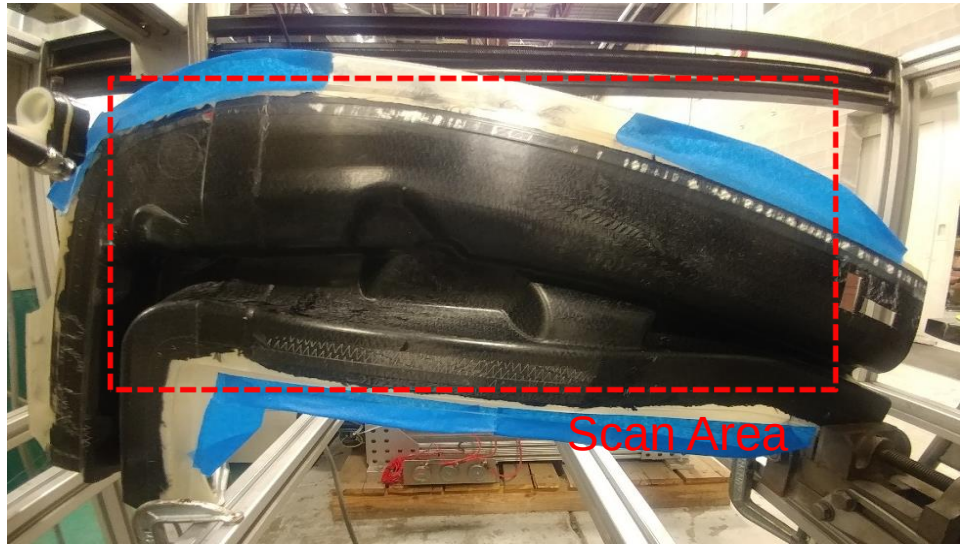
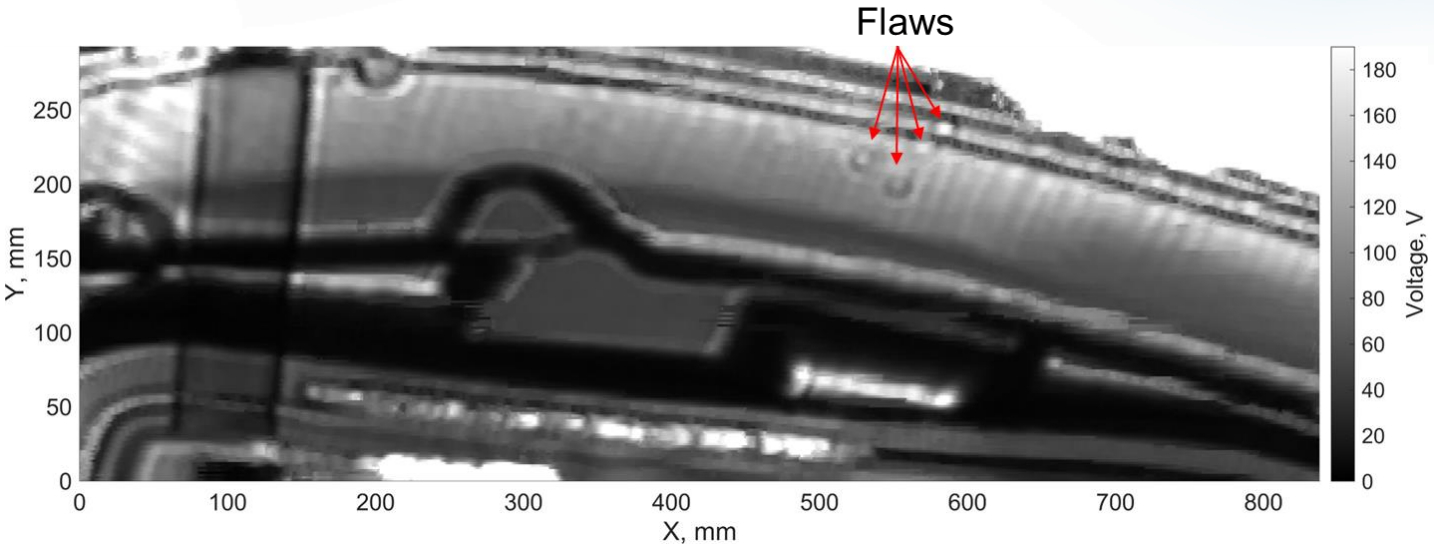
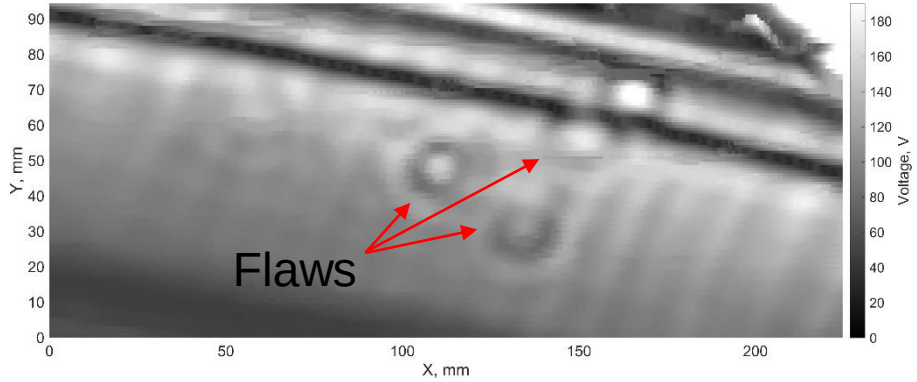


CFRP Door Panel #3



- Real manufacturing defects
- Dry fibers and/or agglomerations of air bubbles
- Approximate flaw sizes [1-4] mm

Region with defects



TT-ACUT C-scans of Door Panel #3

Development of Multimodal NDE Platform for Rapid Inspection of Automotive CFRP Parts

- Robotic Platform & Scan Software
- Air-Coupled Ultrasonic (ACUT) NDE
- **Electromagnetic (EM) NDE**

MSU Designed EM Array Probes: Printed Circuit Board

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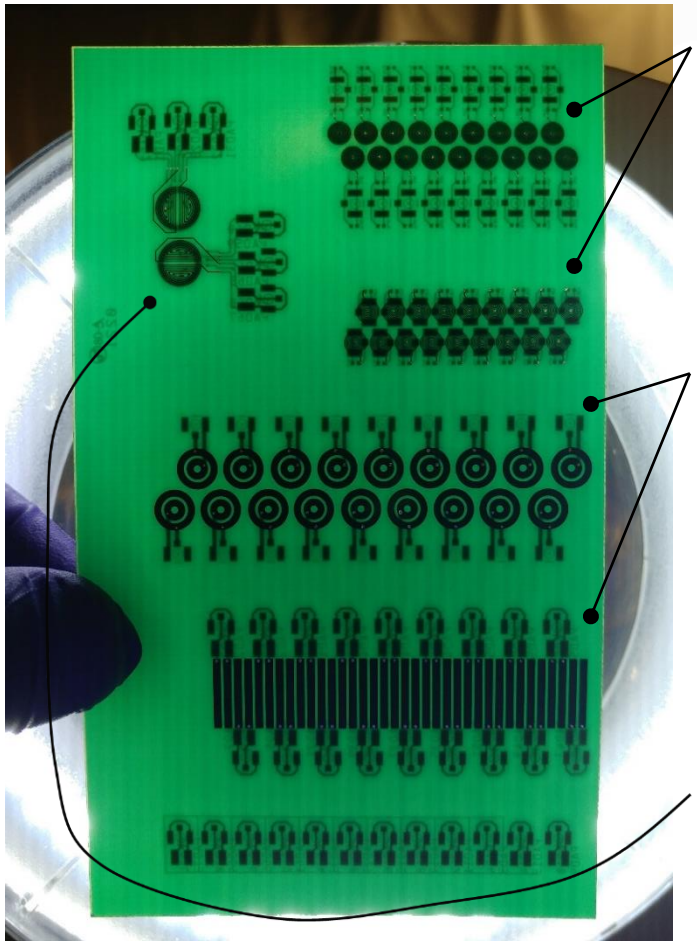

Flex PCB with coil, capacitive & dual-mode sensors

Eddy current sensors (multi-layer coils)

- Sensitive to local variations of electrical conductivity (carbon fiber damage & irregularities)

Capacitive sensors (rect- or circ-electrodes)

- Sensitive to local variations of dielectric permittivity (matrix damage & irregularities, fiber damage)
- Allow for NDE of CFRP & GFRP

Dual-mode sensors (inductive+capacitive)

- Hybrid sensors that can be configured as coil or capacitive sensors

ECT: Staggered Array of 18 Coils

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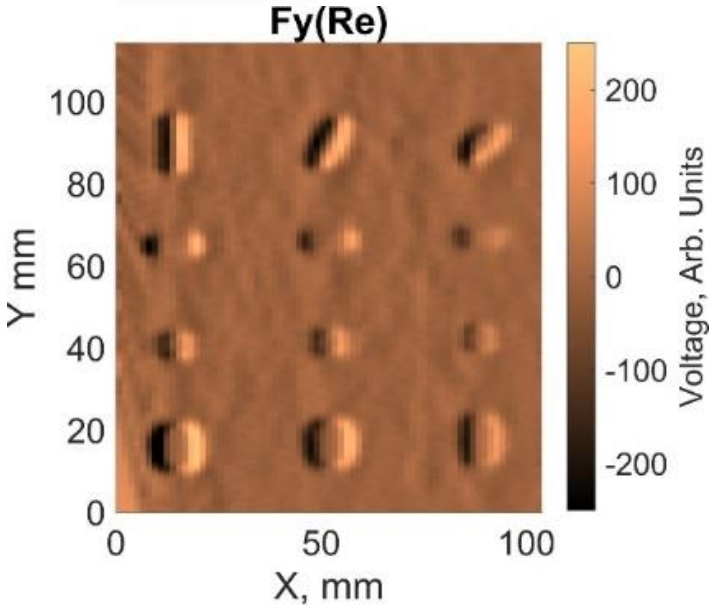
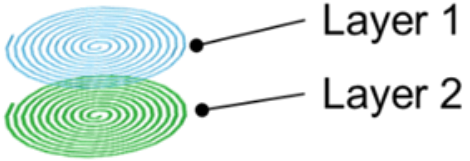
ECT scan of CFRP Panel #7 (10 s)



Typical C-scan + Image processing

MSU 18-channel coil array probe

- ECT measurements acquired using absolute configuration of coil sensors
- Frequency: 2 MHz; spatial resolution: 2 mm; lift-off: 1 mm
- Calibration defects in the form of notches in CFRP panel successfully detected



Double layer coil design

CI: Validation on CFRP Panel #1 with Delaminations

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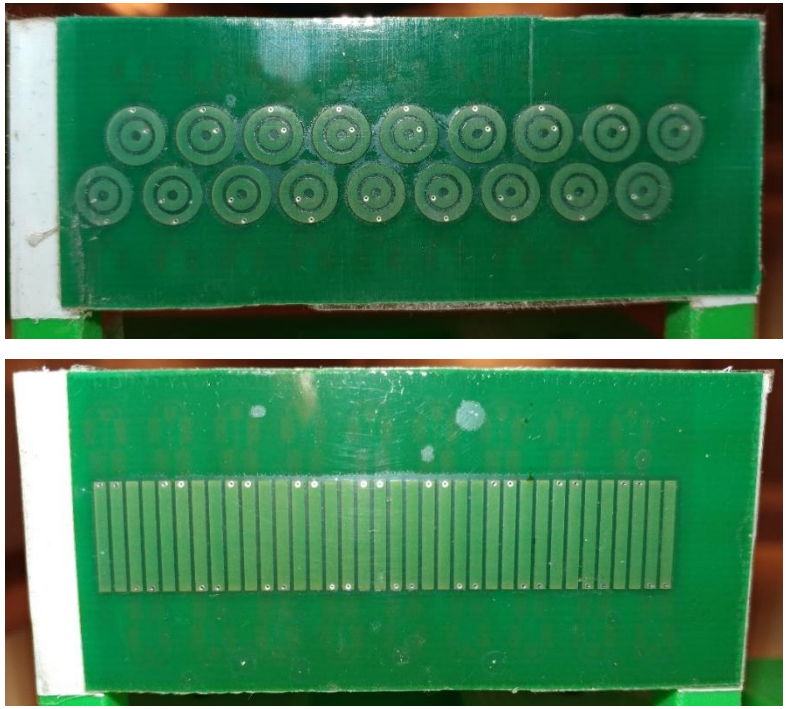
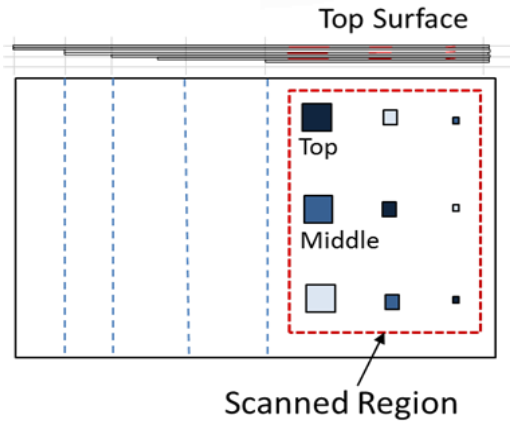
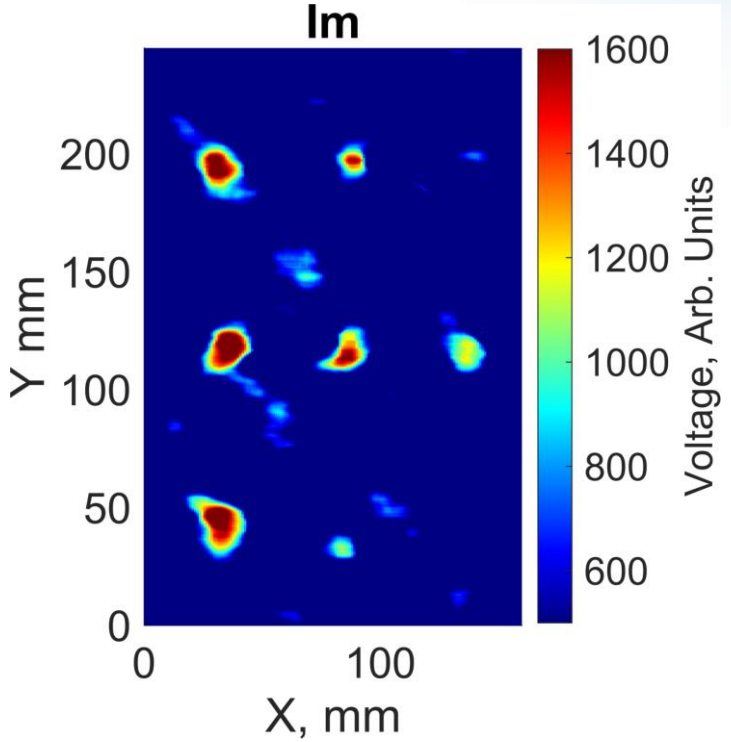


Array capacitive probes with annular & rectangular electrodes



Calibration panel #1 with 9 delaminations



Typical C-scan + Image processing

- Experimentally verified sensitivity to volumetric flaws in GFRP & interlaminar delaminations in CFRP
- Arrays driven in absolute mode at f = 5 MHz

DMI: Hybrid Inductive & Capacitive Sensor

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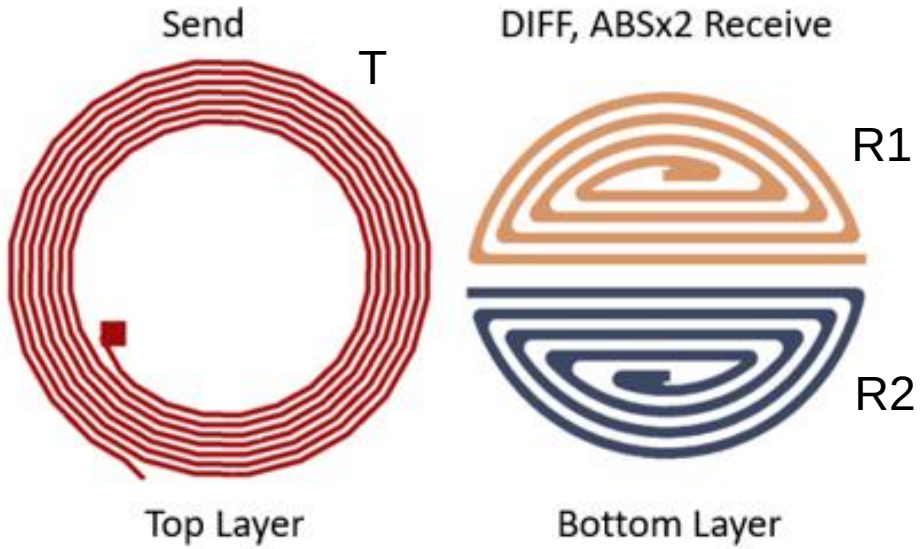
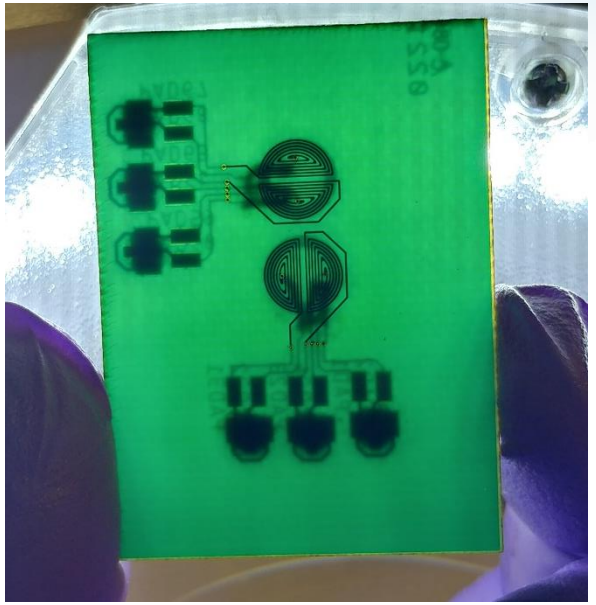


Coils R1 and R2 can be individually shorted to create two electrodes of a capacitor



PCB design of the hybrid probe

Two hybrid probes printed on a flex substrate

Single transmitter [T] / differential receiver [R1-R2] probe (STDR)

- Hybrid (Inductive/Capacitive) probe that can be configured for ECT and CI measurements
- NDE of CFRP (weak electrical conductors)
- NDE of GFRP (electrical insulators)

Future Plans

ACUT system development & integration

- Implement multi-channel TT-ACUT using synced robots

EM system development & integration

- Acquire 64 channel cable & expand probe channel count
- Make probes more flexible & design new probe connectors
- Install Ectane 2 & deploy EM probes on the robot
- Design a dual-mode array probe & interface it to Ectane 2

Robotic platform

- Optimize robot control for enhanced performance
- Upgrade core software of robot controllers
- Debug/improve scripts & GUI

- ACUT & EM NDE techniques need to be further improved/validated on multiple types of defects, part geometries & part manufacturing methods
- The proof-of-concept robotic NDE platform can be scaled by automotive suppliers to a production ready NDE system

Project 3.13: Development of NDE/NDT Tools for High-Volume & High-Speed Inspection of CFRP Structures in Automotive Manufacturing

Questions & Answers