AFRL

Nondestructive Evaluation for Quality Assurance and Surveillance of Cold-worked Fastener Holes

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Materials State Awareness Branch

Materials and Manufacturing Directorate

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Acknowledgments – Contractor Team

Hill Engineering

- Josh Hodges
- Bob Pilarczyk
- Dallen Andrew
- Adrian DeWald

Southwest Research Institute

- Clint Thwing
- Adam Cobb
- Nathan Richter
- Nikolay Alimov

Outline

- Motivation / Impact
- Challenges
- Technical Approach
- Testing
- Results
- Summary
- Way Forward

Photograph by author

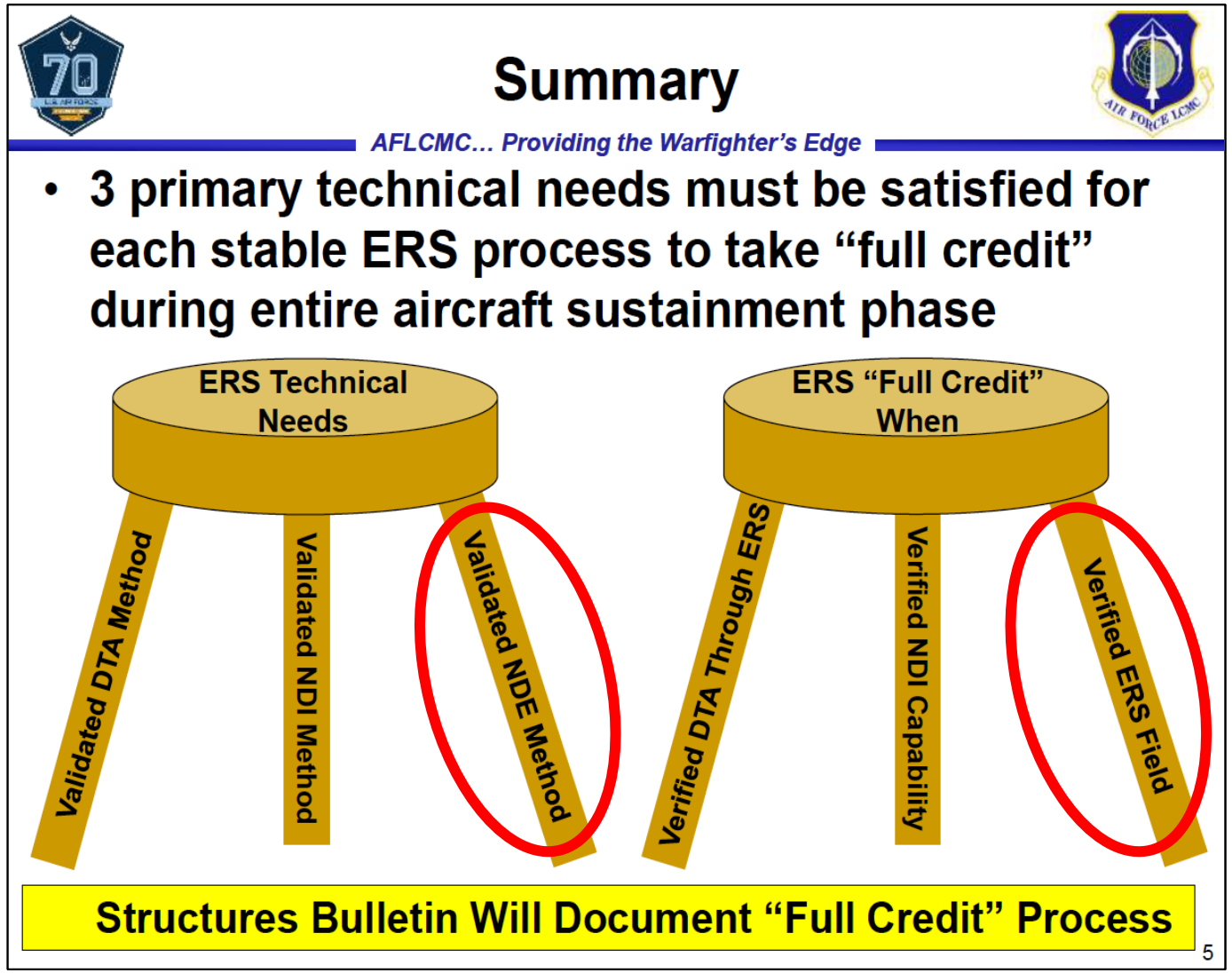
Motivation / Impact

Motivation

- QA of Cx process to ensure residual stresses are present
- Verification residual stresses remain present during life

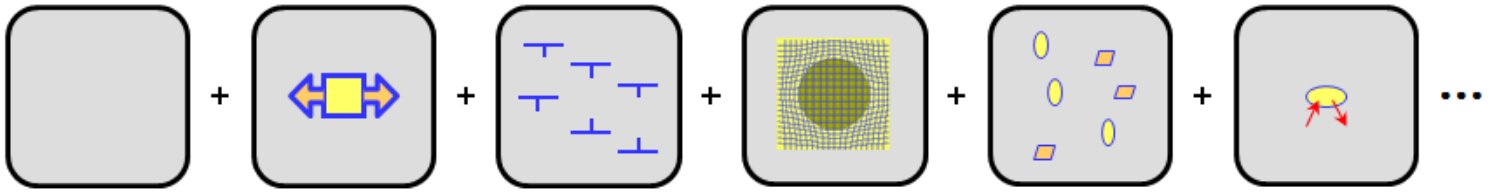
Impact

- Enhanced life management
- Extended inspection intervals



Briefing chart from Charles Babish, available at: http://www.meetingdata.utcdayton.com/agenda/asip/2017/proceedings/presentations/P13677.pdf

NDE of Residual Stress: Challenges



conducting matrix T	residual stress τ_{res}	dislocation density η_{disl}	coherency strain ε_{ii}	precipitate size V_f	solute partitioning x_n
<< 1%*	1-1.5%	up to 3%	% ?	% ?	% ?

*Temperature controlled environment

- **Lots of factors affect measurement in addition to residual stress**
  - **Microstructural complications simplified with aluminum alloys**
  - **Macro-scale considerations: temperature and geometry**
  - **USAF considerations: manufacturing (e.g. fit-up stresses), maintenance, modification, repair, use**
- **Deconvolve or control as much as possible**
- **Maximize sensitivity analysis**

Technical Approach

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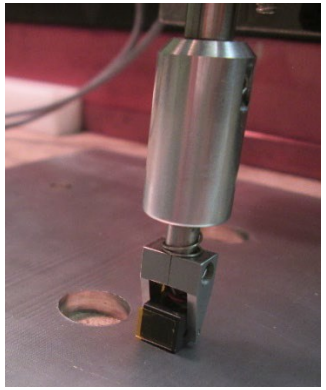
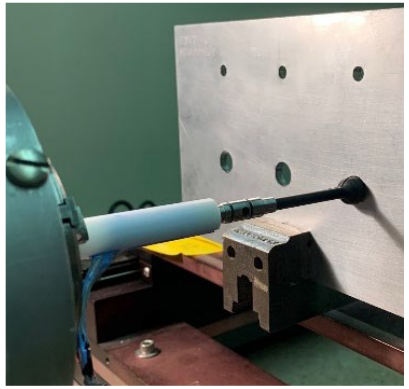
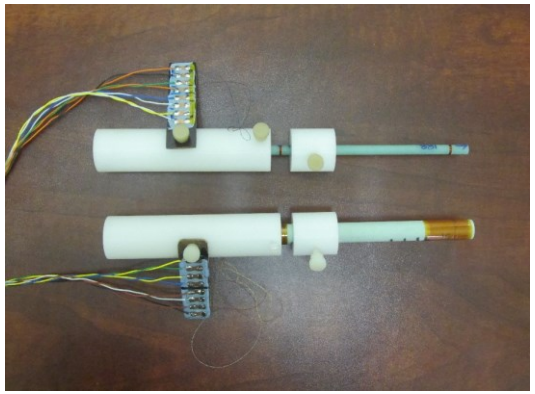
- Develop NDE techniques for quantifying the residual stress state at Cx holes
- Evaluate and rank NDE techniques for quantifying the residual stress state at Cx holes
- Investigate key confounding factors and their influence on NDE response
- Optimize NDE techniques for evaluation Cx holes
- Demonstrate the NDE techniques for evaluation of Cx holes
- Verify the NDE techniques for evaluation of Cx holes
- Sensing approaches explored:



Eddy Current Surface Probe



Low Frequency Eddy Current



Four Coil In-hole Eddy Current Probe

Ultrasonic Longitudinal Critically Refracted Wave Probe

Program Goals

Desired performance:

- Geometry: open holes – 0.25” and 0.5”
- Materials: aluminum alloys: 2024-T351 and 7075-T651
- Environment: field and Depot (plus manufacturing)
- Surface condition: minimal preparation
- Rapid data acquisition: prefer less than one minute
- Equipment: minimize specialize equipment
- Sensitivity: 90% detection of detect cold-worked holes (applied expansion of 3%)

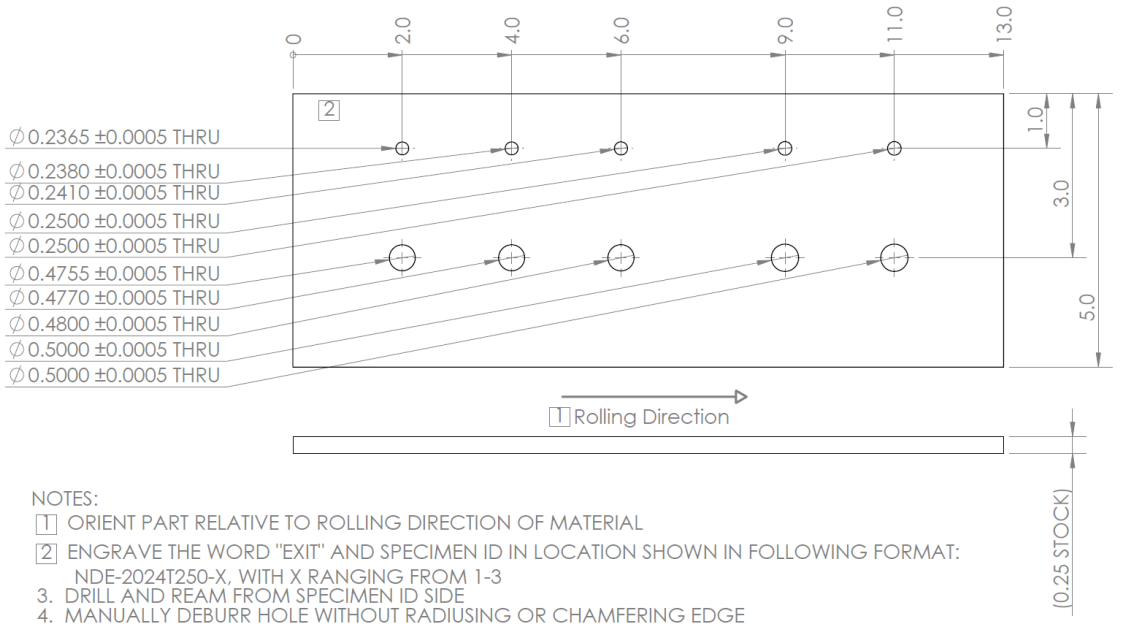
Representative Depot Maintenance

Representative Manufacturing

Testing (Lots of Testing!)

Testing matrices included:

- Levels of cold work
- Hole diameters
- Confounding factors
- Variability
- Coupons
- Extracted components
- In-Depot demonstration



Representative multi-hole coupon machining drawing (0.250” thickness)

Evaluated Confounding Factors

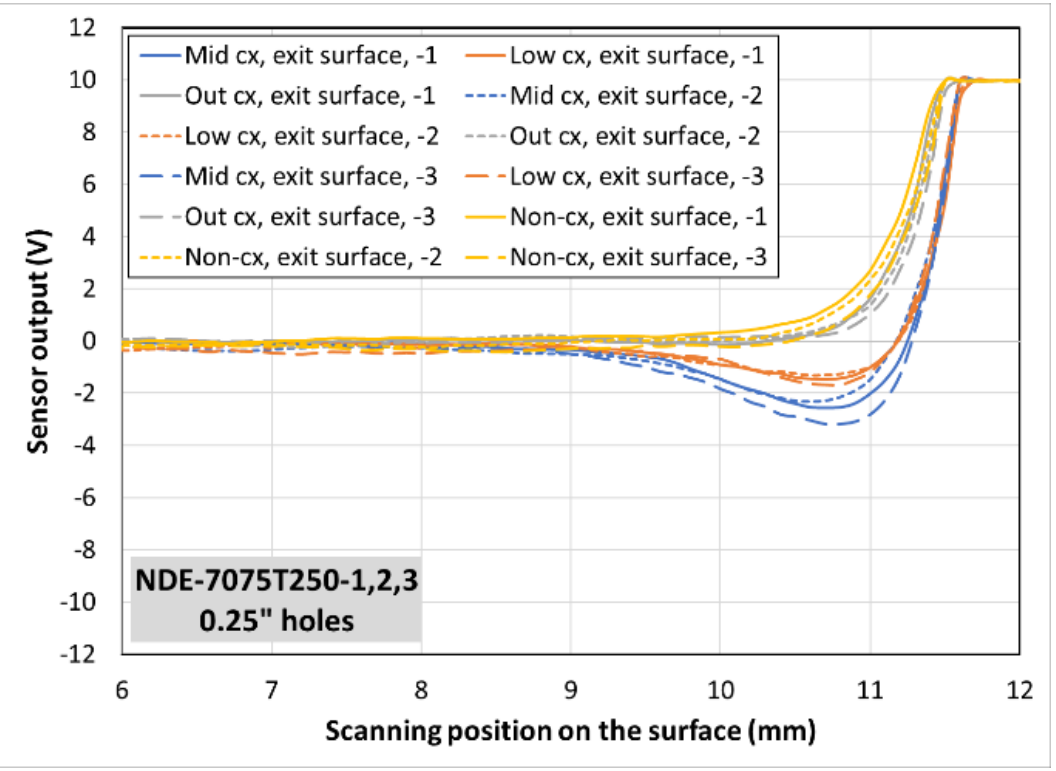
- **Eddy Current centric**

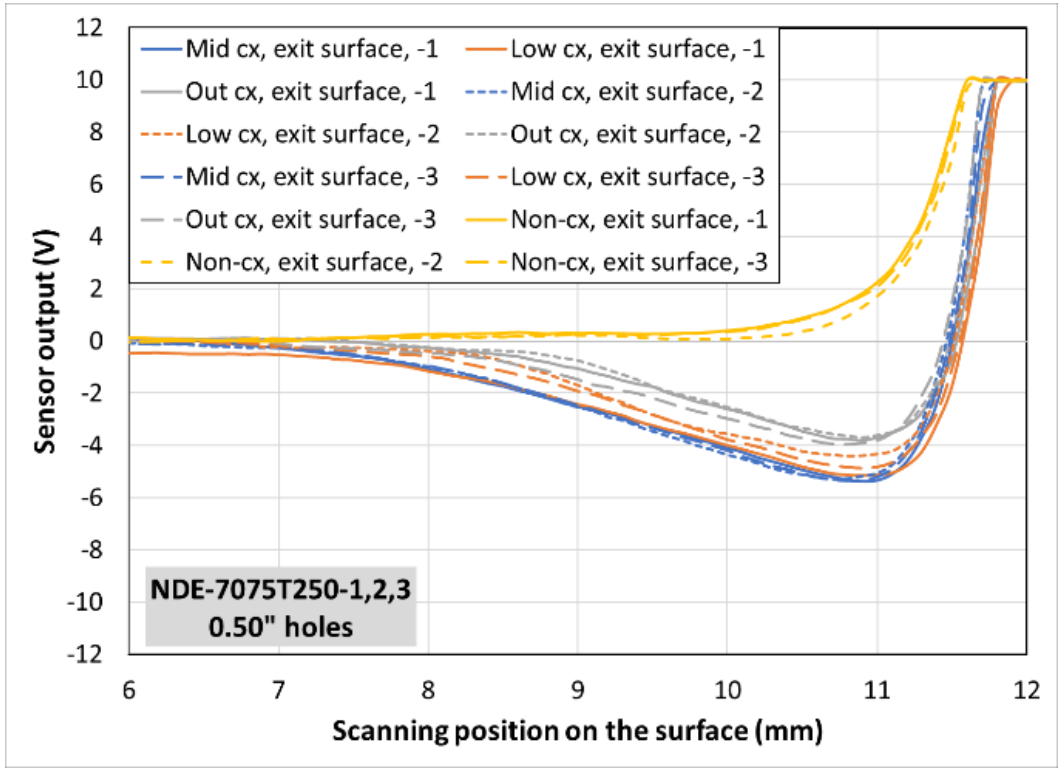
Factor	Influence on NDE response – ET
Electrical Conductivity: Global	High
Electrical Conductivity: Through Thickness Variation	Medium
Hole Diameter	Medium
Plastic Strain	Medium
Coatings/Paint	Medium
Hole Skew	Medium or Low
Operational Overloads	Medium or Low
Temperature Variation – Long Term Changes	Medium or Low
Temperature Variation – Short Term Fluctuation	Medium or Low
Acoustoelasticity	Low
Chemical Composition	Low
Cross-Section Changes	Low
Hole Edge Margin	Low
Hole Pitch	Low
Hole Roundness	Low
Microstructure – Global	Low
Microstructure – Local	Low
Static Loads	Low
Surface Corrosion	Low
Surface Flatness	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Conductivity	Low
Thermal Exposure	Low

- **Ultrasound centric**

Factor	Influence on NDE response – UT
Acoustoelasticity	High
Coatings/Paint	High or Low
Chemical Composition	Medium
Hole Diameter	Medium
Hole Edge Margin	Medium
Hole Pitch	Medium
Microstructure – Global	Medium
Microstructure – Local	Medium
Operational Overloads	Medium
Surface Corrosion	Medium
Surface Flatness	Medium
Temperature Variation – Long Term Changes	Medium
Temperature Variation – Short Term Fluctuation	Medium
Cross-Section Changes	Medium
Thermal Conductivity	Low
Electrical Conductivity: Global	Low
Electrical Conductivity: Through Thickness Variation	Low
Hole Roundness	Low
Hole Skew	Low
Plastic Strain	Low
Static Loads	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Exposure	Low

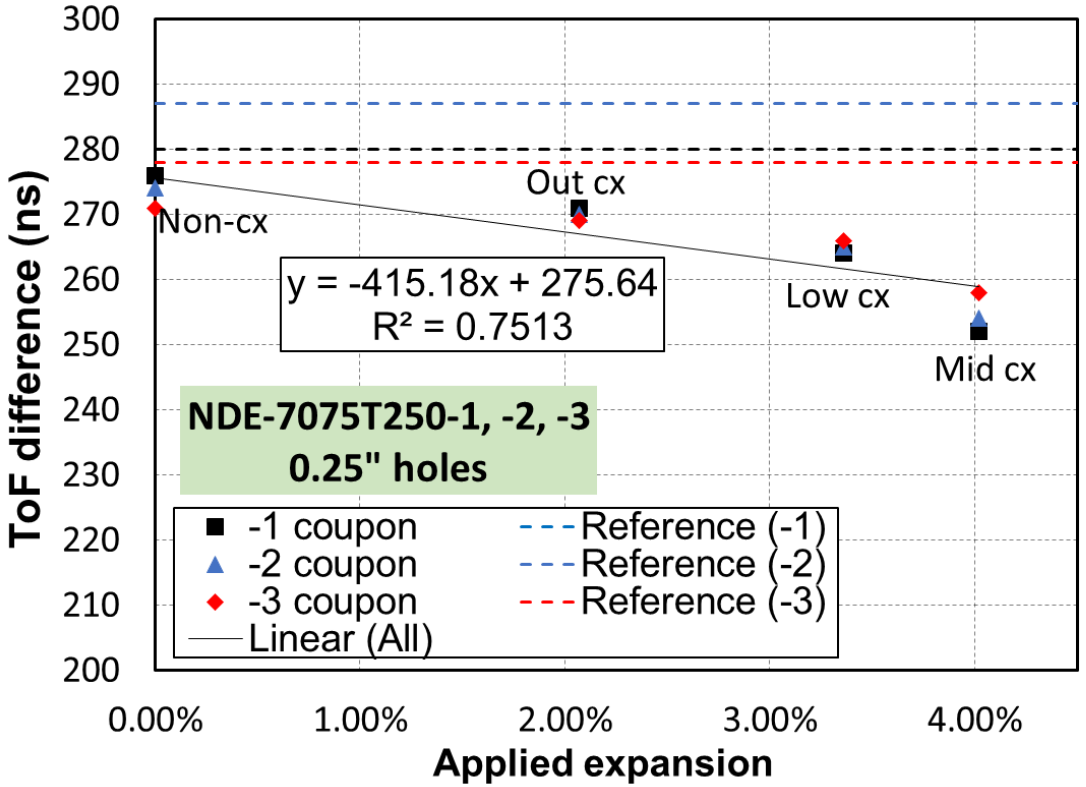
Representative Result: Eddy Current Surface Probe

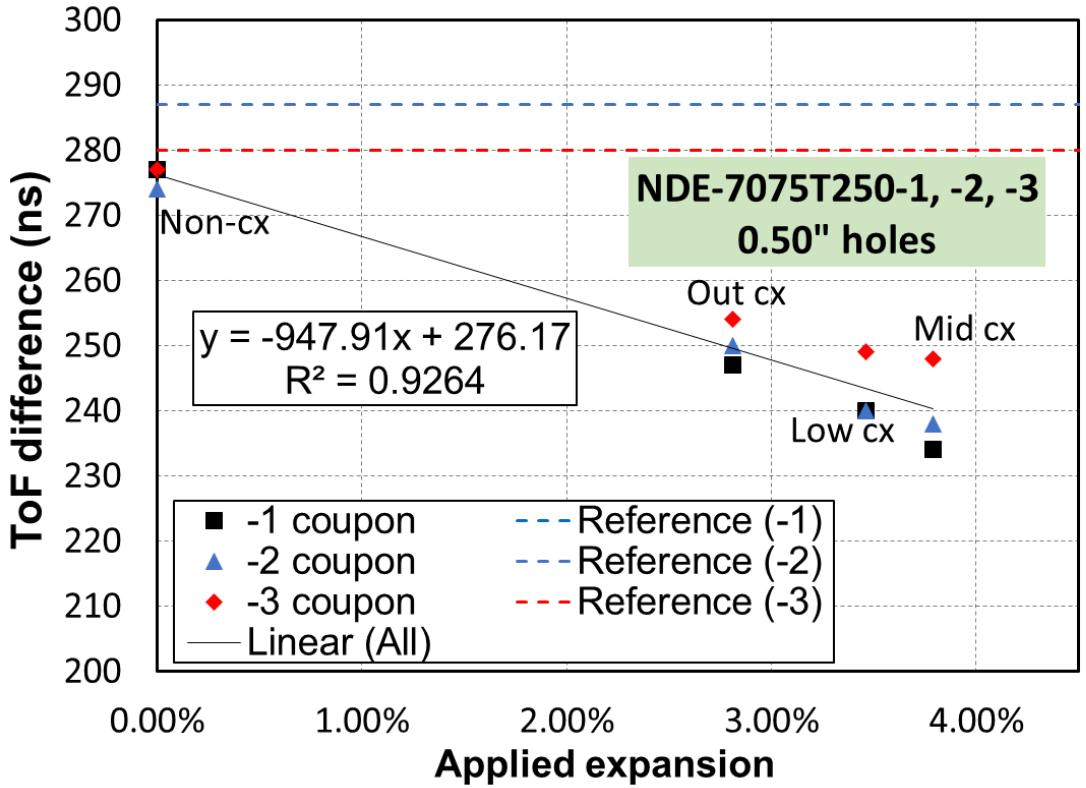




- **Left: 7075 coupons with 0.250 inch thickness, 0.25 inch holes**
- **Right: 7075 coupons with 0.250 inch thickness, 0.50 inch holes**

Representative Result: Ultrasound LCR Probe





- **Left: 7075 coupons with 0.250 inch thickness, 0.25 inch holes**
- **Right: 7075 coupons with 0.250 inch thickness, 0.50 inch holes**

Way Forward – Remaining Challenges

- Address effect of cold-work volcano
  - Impact of surface eddy current results
  - Potential effect on LCR time-of-flight
- Probe optimization
  - Frequency, geometry, durability, fixturing
- May need both approaches
  - Eddy current for QA post cold work of fastener hole
  - Ultrasound for quantitative surveillance during in-service
- Validation study
- Simplified integration into current NDE practice
- Data capture and storage (other programs underway to address this capability)

Summary

Current 6.2 funded effort realized objectives

- Leveraged NDE experience detecting residual stress

Two potential approaches identified

- Surface scanning eddy current with differential coil
- Longitudinal critically refracted (LCR) ultrasound probe

Lots of testing to support identified approaches

- Confounding factors, e.g. surface and sub-surface
- Reproducibility: repeated measures on similar conditions
- Variability: hole diameter, magnitude of cold work, and material

Solutions look favorable, but more development required:

- Probe optimization
- Volcano effect
- Validation

} Need for follow-on program

Discussion

Caelum Domenari

Photograph by Author

The IMx+: A Digital Thread Tool to Enable Effective ASIP

Presented by: Dallen L. Andrew, Ph.D.

Co-Authors: Robert Pilarczyk & Josh Hodges

Hill Engineering LLC

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Predict. Test. Perform.

Digital Thread Definition

What is a Digital Thread?

- Two-way line connecting engineering and maintenance (Mx) in a common data stream
- Required to extend from Mx action through Aircraft Structural Integrity Program (ASIP) engineering processes to development of an inspection interval published in tech data

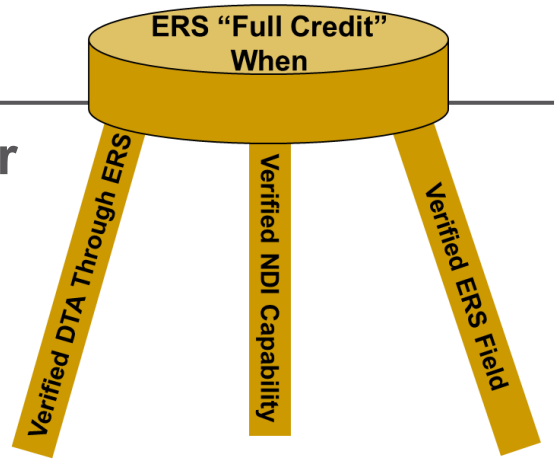
What does a digital thread look like?

- *It depends…*
- Different scenarios require different levels of need for data capture
- Customized Data Fidelity Level (DFL) should be developed for different levels of need

Category	Source	Data Description
Cold Expansion	DigitalEx	Correlation to residual stress
		Pressure profile
		Go/No-Go indication (in/out spec)
NDE	UT/ET Probe	Cx Applied % Expansion
		UT/ET response data
		Go/No-Go indication (in/out spec)
NDI	NORTEC	Screen capture
		Probe settings
		Clock position
		% screen height
		Final cleanup indication
Location	iGPS	(xyz) coordinates for each device

DFL 1: One-off type repairs
DFL 2: Depot-level repairs
DFL 3: Major modification programs

Digital Thread Definition



For cold expansion (Cx) of fastener holes, digital thread data must answer critical ASIP questions to qualify for full credit:

1. ***Was Cx accomplished at the correct location?***
2. ***Was Cx accomplished (go/no-go)?***
3. ***Is the ERS validation traceable?***
4. ***Has NDI/NDE been accomplished?***
5. ***What are analysis requirements for full credit?***

For NDI process, digital thread data must provide essential data for evaluating inspection:

- Automatically capture and store inspection data (not just pass/fail) to support NDI and engineering
- Identify critical layers and crack locations for stack-ups
- Identify correct location of Mx in aircraft coordinates

Category	Source	Data Description
Cold Expansion	DigitalEx	Correlation to residual stress
		Pressure profile
		Go/No-Go indication (in/out spec)
NDE	UT/ET Probe	Cx Applied % Expansion
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DFL 1: One-off type repairs
DFL 2: Depot-level repairs
DFL 3: Major modification programs

Digital Thread Tools to Enable Effective ASIP

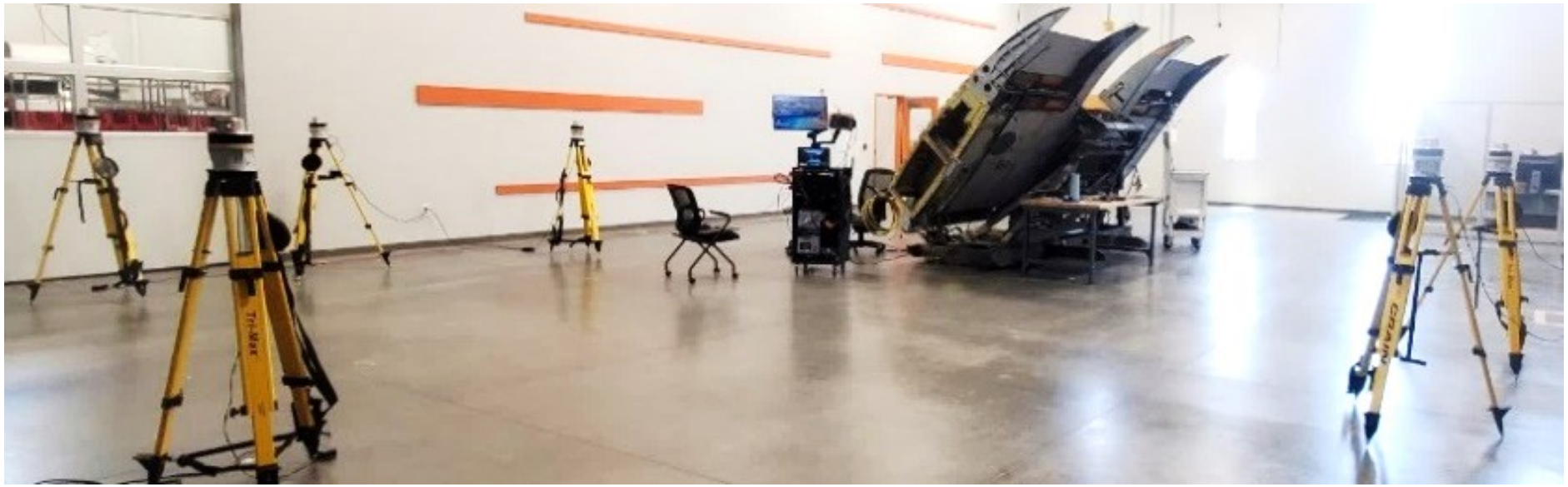
Hill Engineering continues to support multiple USAF-sponsored programs targeted to support digital thread tools to enable an effective ASIP

- Data Spatial Positioning → Integrated Maintenance System (IMx+)
- Digital Thread Tools for NDI Applications of IMx+
- Spatial Registration of NDE Sensors in Enclosed Locations

Digital Thread Tools to Enable Effective ASIP

IMx+

Integrated Maintenance System+



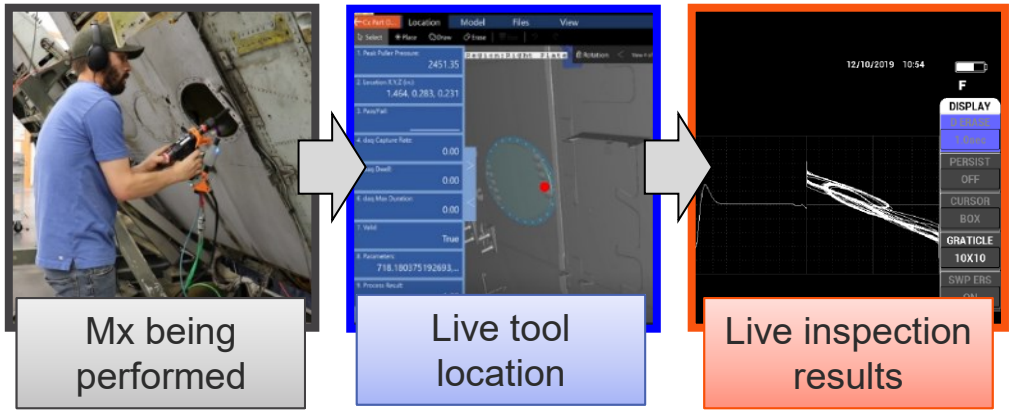
Digital Thread Tools: IMx+ System

Stated Need

"Current challenges include an automated method for digital procedural compliance, importing digital NDI equipment outputs & interfacing with legacy maintenance processing systems.
In terms of capturing maintenance data, an automated integrated system doesn't exist."
-Lt. Col Gary Steffes, 76 CMXG/CR, ASIP Conference 2020

Objectives

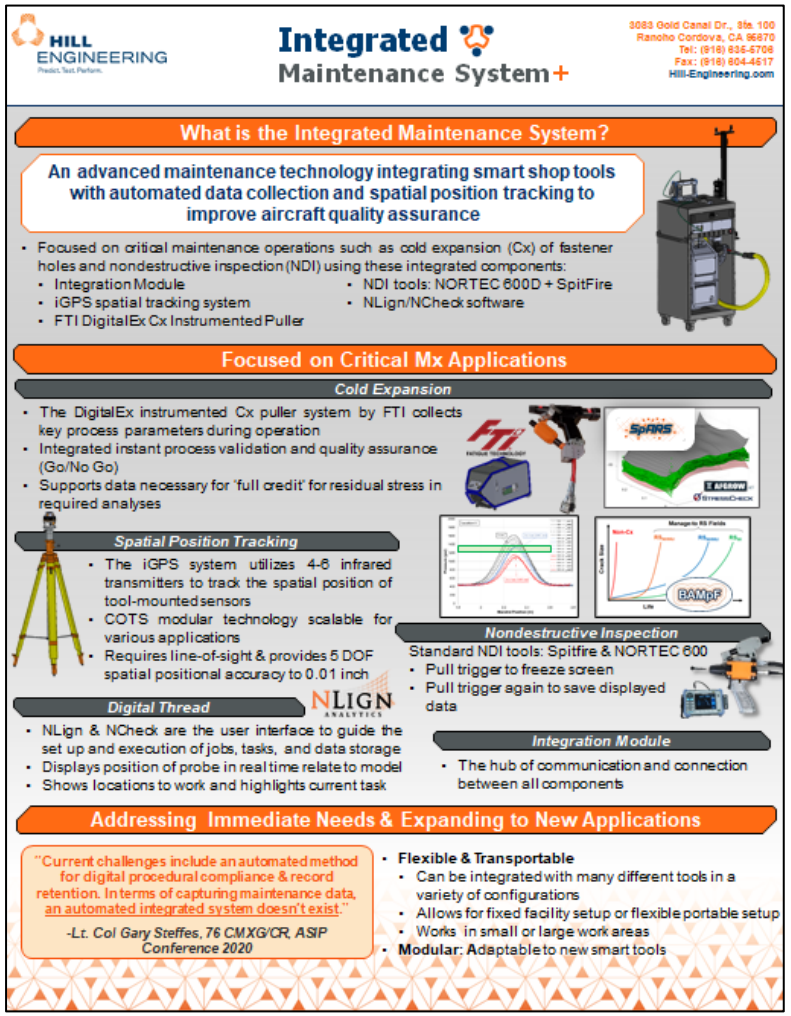
- Create a digital thread for fastener holes that builds & maintains process records for NDI & Cx using commercial Data Spatial Positioning (DSP) technologies to leverage in structural integrity management
- Assist maintainer with real-time position feedback
- Digitally capture NDI and Cx results and submit results automatically
- Cybersecurity accreditation to integrate with the USAF NIPRNet
- **Simplify the maintenance, inspection and reporting process**



Digital Thread Tools: IMx+ System

Introduction to the IMx+ system

- An advanced maintenance technology integrating smart shop tools with automated data collection and spatial position tracking to improve aircraft quality assurance
- Focused on critical maintenance operations such as Cx of fastener holes and NDI using these integrated components:
  - **Integration Module**
  - **iGPS spatial tracking system**
  - **FTI DigitalEx Cx Instrumented Puller**
  - **NDI tools**
  - **NLign/NCheck software**



Digital Thread Tools: IMx+ System

Integration Module [Hill Engineering]

- The hub of communication and connection between all components
- All the physical and digital signals are combined and managed
- Integrates location and maintenance/inspection results for upload to the digital thread directly from within the USAF network
- Adaptable to new smart tools

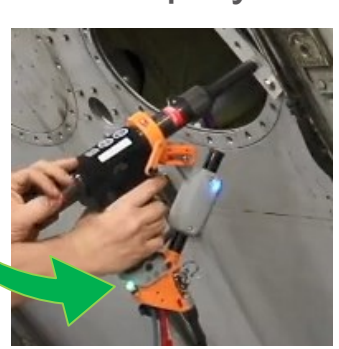
Digital Thread Tools: IMx+ System

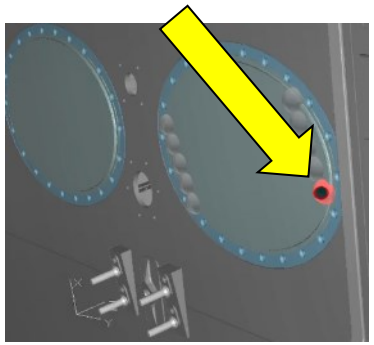
Spatial Position Tracking [7D Kinematic Metrology]

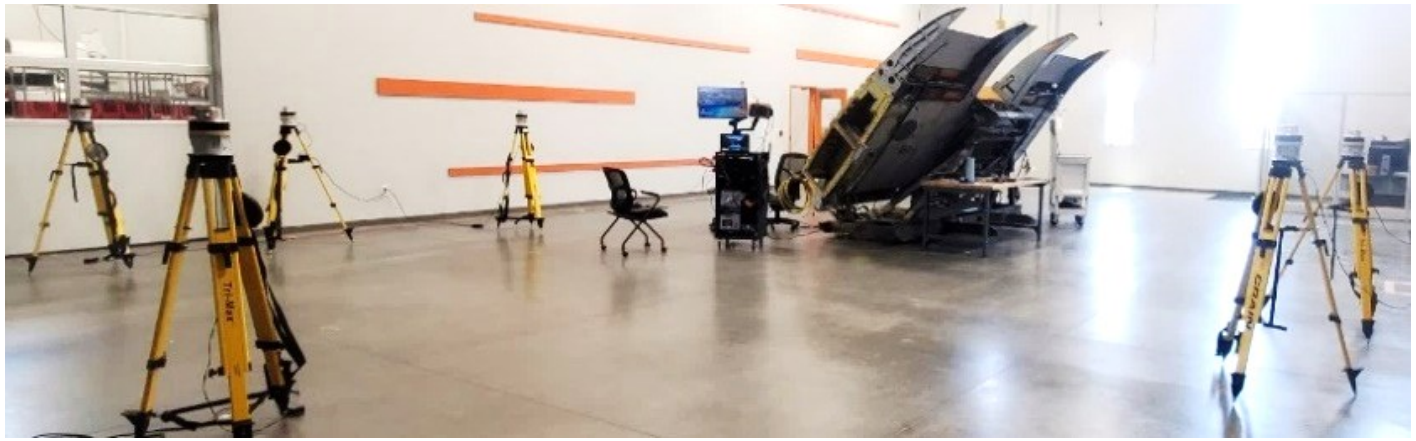
- iGPS infrared laser off-the-shelf modular technology
- Coverage area: Scalable for small to large production facilities
- Utilizes 4-6 infrared transmitters to track the spatial position of tool-mounted sensors
- Requires line-of-sight & provides 5 DOF spatial positional accuracy down to 0.01 inch

Add-on: Integrated Feedback to Maintainer

- LED lights indicate if tool is:
  - In correct fastener hole (green)
  - Within 2 diameters of correct hole (yellow)
- Live display of tool location





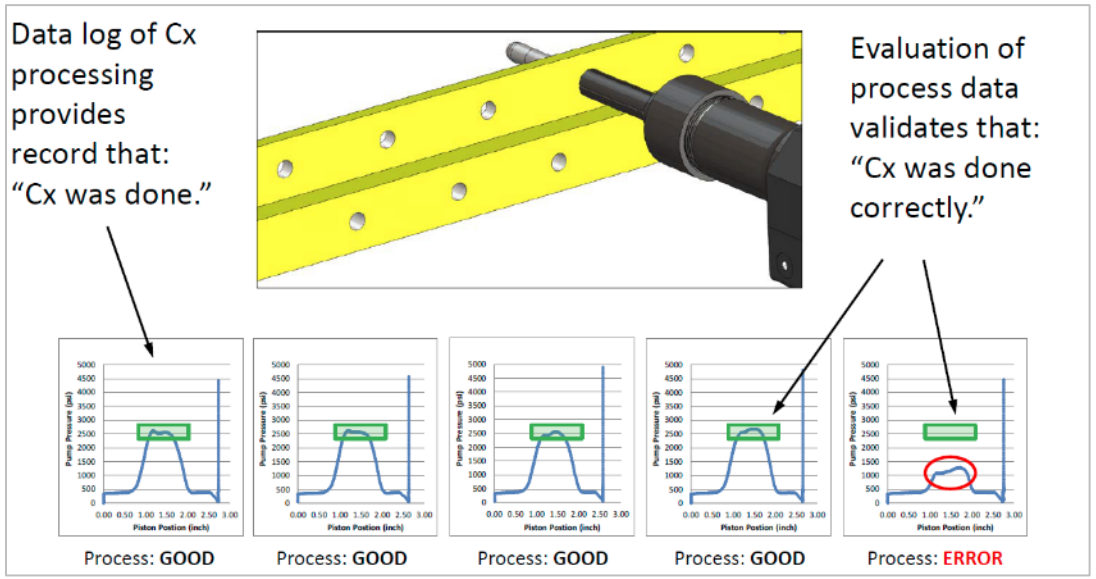


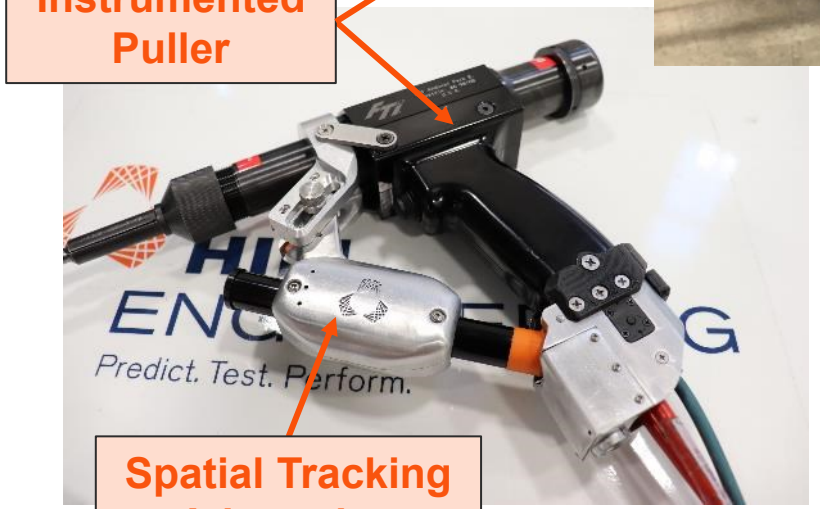
Inclusion of additional modular spatial position tracking technologies

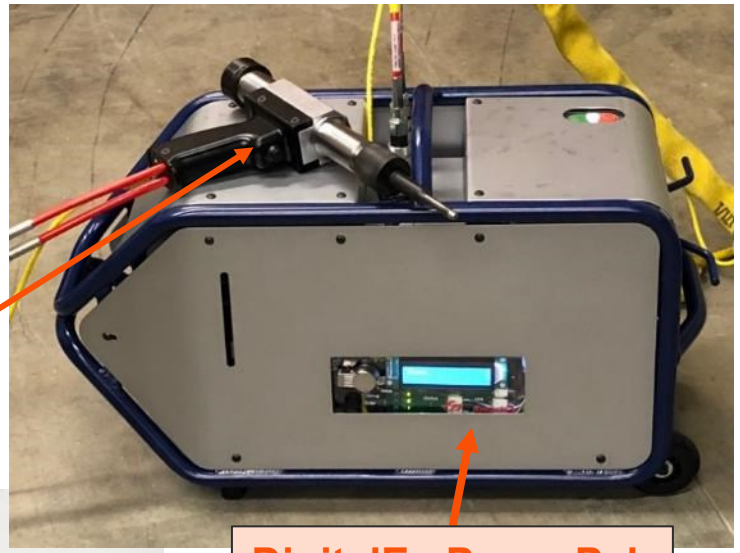
Digital Thread Tools: IMx+ System

DigitalEx Instrumented Cx Puller [FTI]

- DigitalEx physical and digital interface with IMx+ system
- Collects key process parameters during operation
- Integrated instant process validation and quality assurance (Go/No Go)
- Supports data necessary for 'full credit' for residual stress



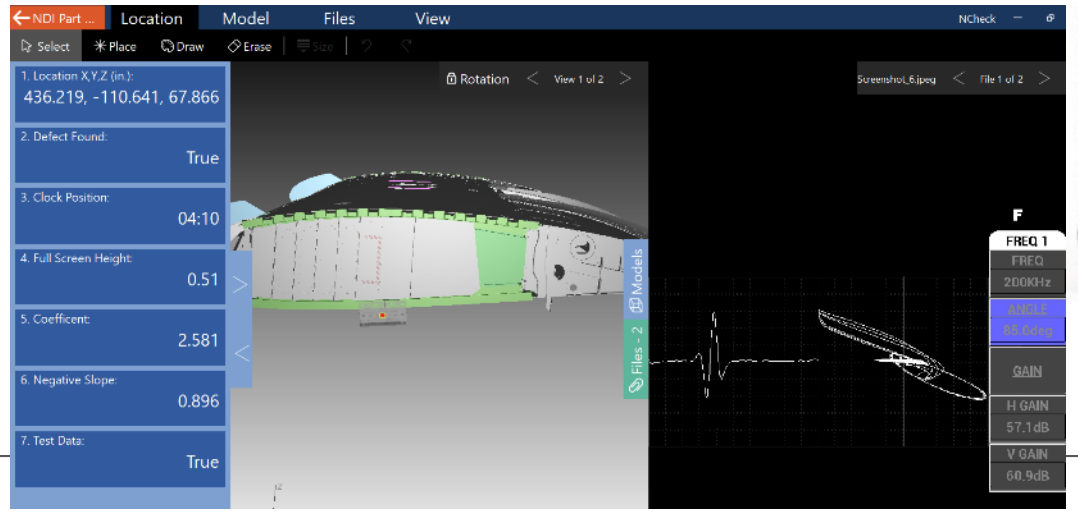




Digital Thread Tools: IMx+ System

NDI Tools

- NORTEC + SpitFire + MiniMite
- EVi + ECS-3 + ECS-5
- EPOCH 650
- Physical and digital interface between NDI tool and IMx+ system
- NDI data stream capture
  - Screenshot automatically saved to hole location with trigger pull
  - Automatically tracks/saves defect layer
  - Automatically populates inspection data based on screenshot

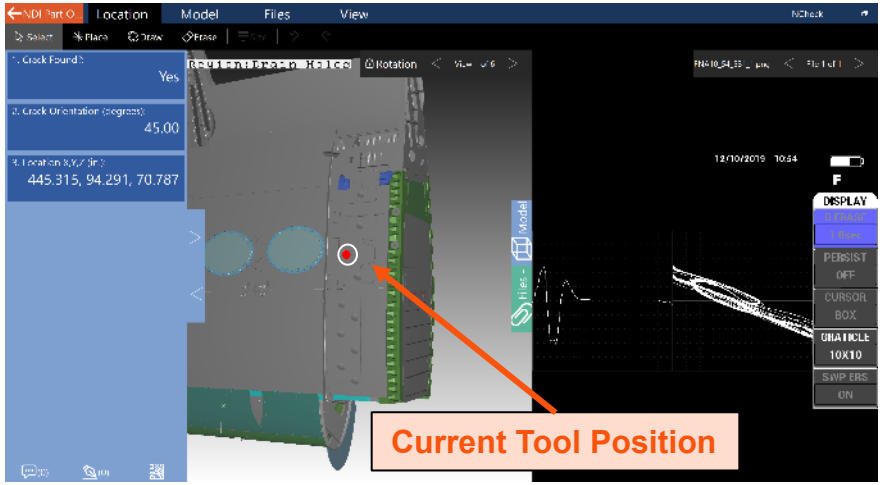


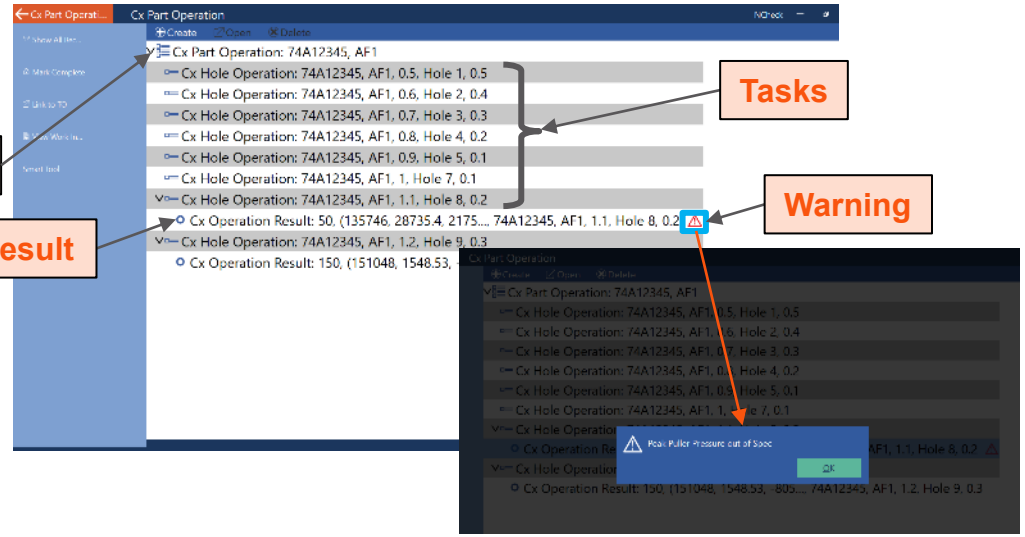
NO MORE SNEAKERNET TO CAPTURE NDI DATA!

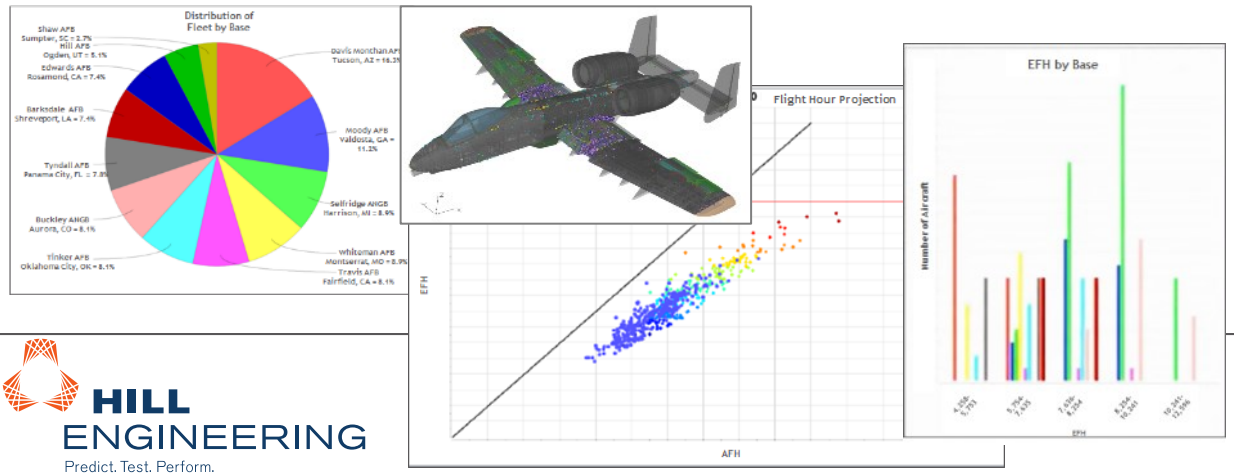
Digital Thread Tools: IMx+ System

User Interface and Digital Thread [NLign Analytics]

- NCheck
  - User interface for maintainers for the execution of jobs and tasks
  - Shows locations to be worked and highlights current task
  - Displays what operations have been completed and the results
  - Captures location and operation results automatically
- NLign
  - User interface for engineering to guide the set up of jobs and tasks
  - Digital thread and full data repository
  - Extensive data analytics, visualization, and mapping capabilities
  - Trending of fleet statistics based on user inputs







Digital Thread Tools: IMx+ System

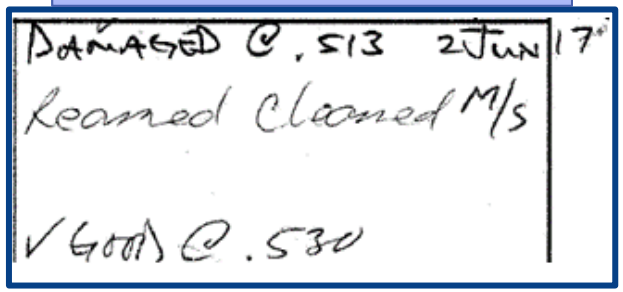
Why IMx+ for NDI?

- Automatically capture critical data to support NDI and engineering
- Identify critical layers and crack locations for stack-ups
- Estimated 50% reduction in time to document inspection results
- Estimated 20% reduction in inspection time through real time feedback

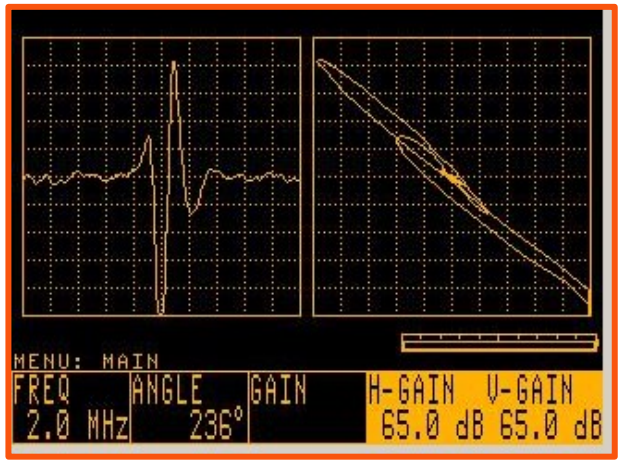
A-10: Why do we want IMx+? ▸▸▸

- Meets MIL-STD-1530D requirements
- Automates data entry and upload (faster and easier for inspector)
- Improves inspection value by saving inspection data, not just pass/fail
- Includes Mx location in aircraft coordinates
- Identifies correct location of Mx

Logbook: Data capture



IMx+: Data capture

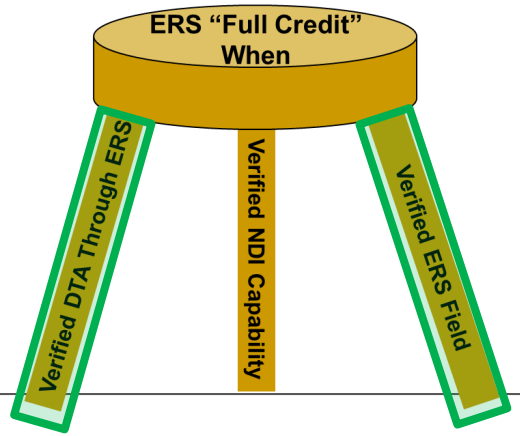


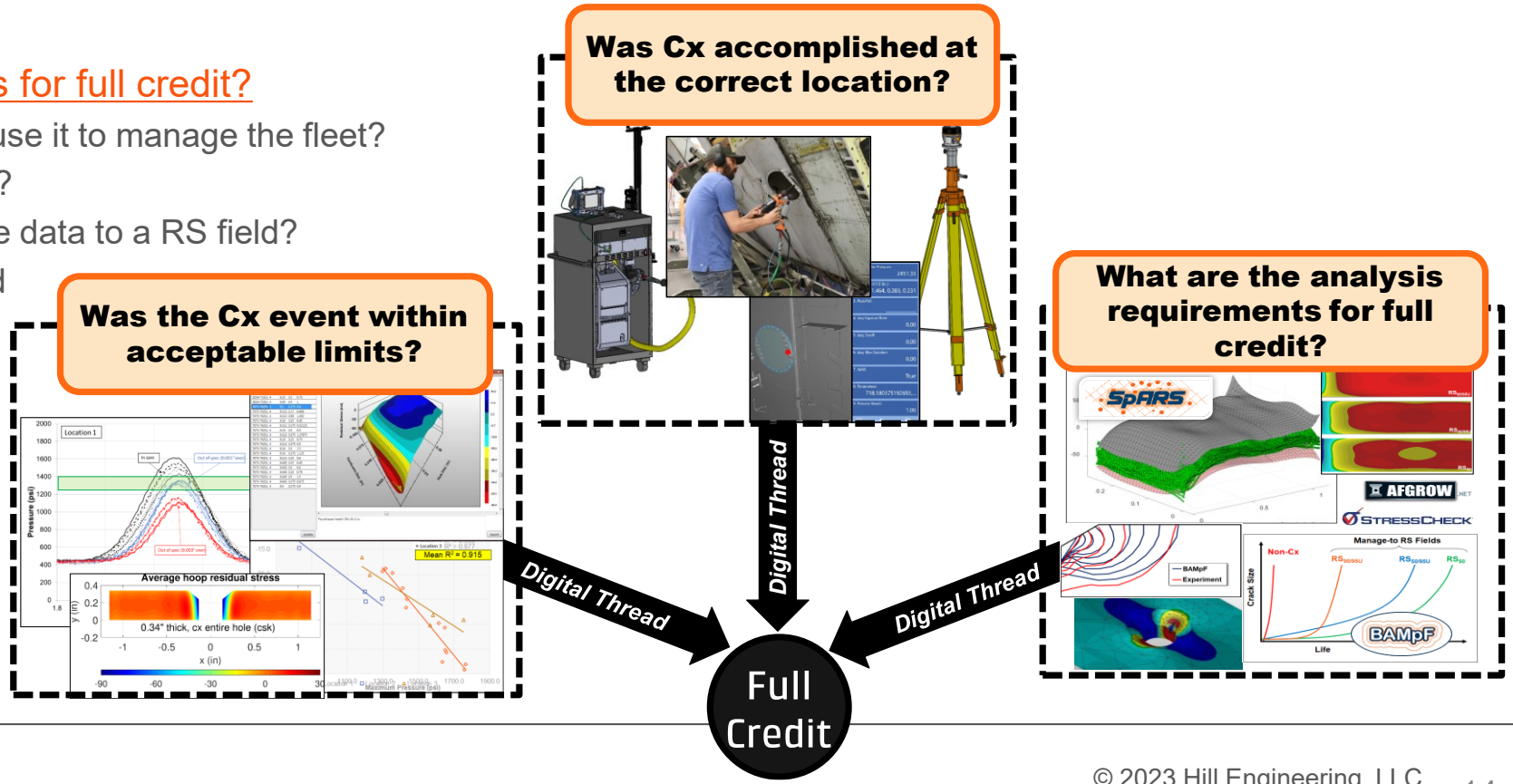
Digital Thread Tools: IMx+ System

Why IMx+ for Cx? ▸▸ Establishing the Cx digital thread ▸▸

Required to extend from Mx action through ASIP engineering processes to development of an inspection interval to be published in tech data

- Address next-step-questions faced by ASIP to develop inspection intervals & answers critical questions required for RS full credit
  - Was Cx accomplished at the correct location?
  - Was Cx accomplished (go/no-go)?
  - What are the analysis requirements for full credit?
    - What do I do with this data and how use it to manage the fleet?
    - What data is needed to perform DTA?
    - How do I correlate Cx pressure profile data to a RS field?
    - How statistically characterize RS field to use explicitly in DTA?

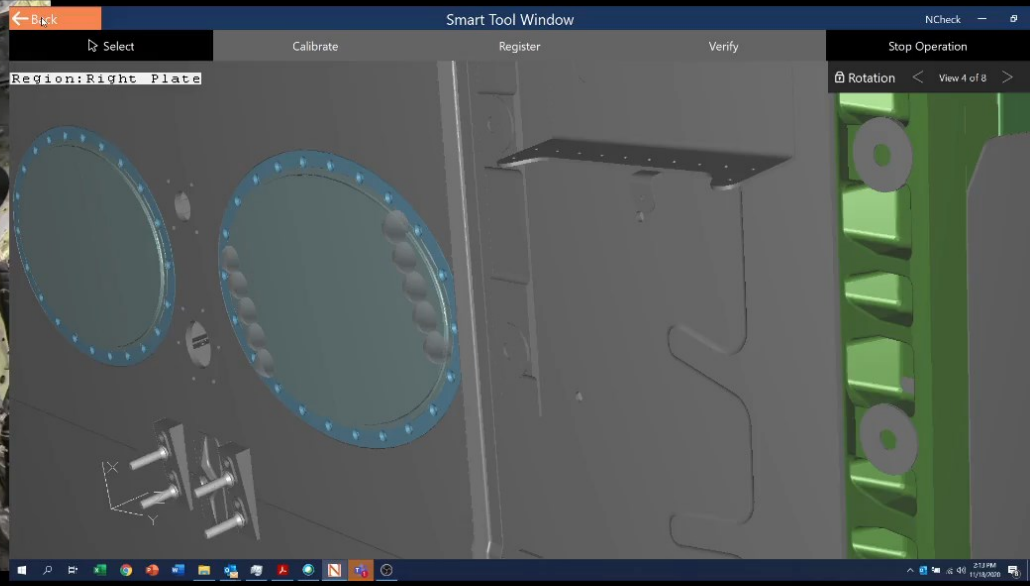




Digital Thread Tools: IMx+ System ▸▸ Cx Demo

Technician working

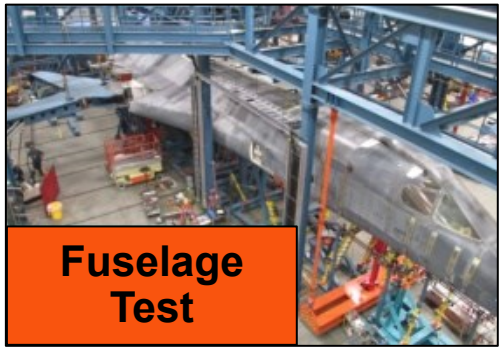
Live display on Integration Module



Digital Thread Tools: NDI Applications of IMx+

Design, develop, test, and demonstrate adaptations of USAF standard NDI tools for use with IMx+

- Automate data capture from the NDI tool
- Retrofit current USAF NDI tools with a spatial tracking sensor
- Output captured NDI data to user-defined database
- Update user interface for expanded use for all users
- Perform on-site demonstrations of NDI automated data capture capabilities and deliver IMx+ system
  - Candidate 1: Hill AFB & A-10 application
  - Candidate 2: B-1 Full Scale Fatigue Test



Integrated Maintenance System+

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Predict. Test. Perform.

Integration and Validation Testing

EVi testing

- Spatial position tracking functioning with ECS-3 and ECS-5

ECS-5 Video w/ Spatial Tracking in Separate File

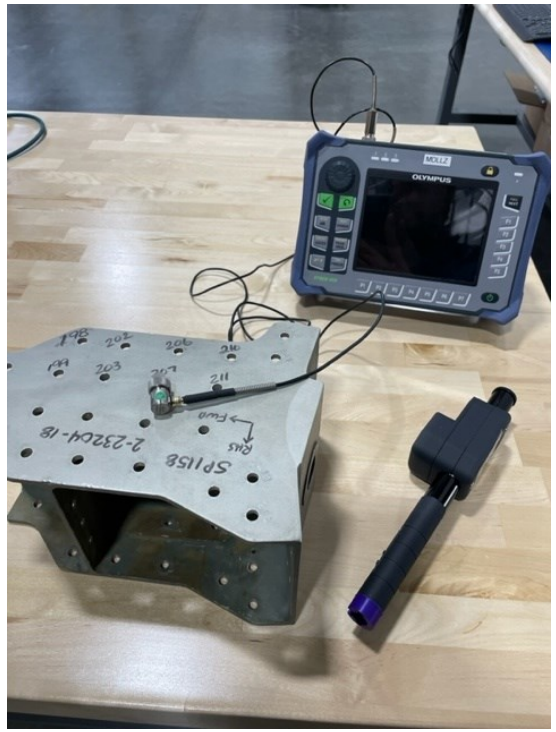
Integration and Validation Testing

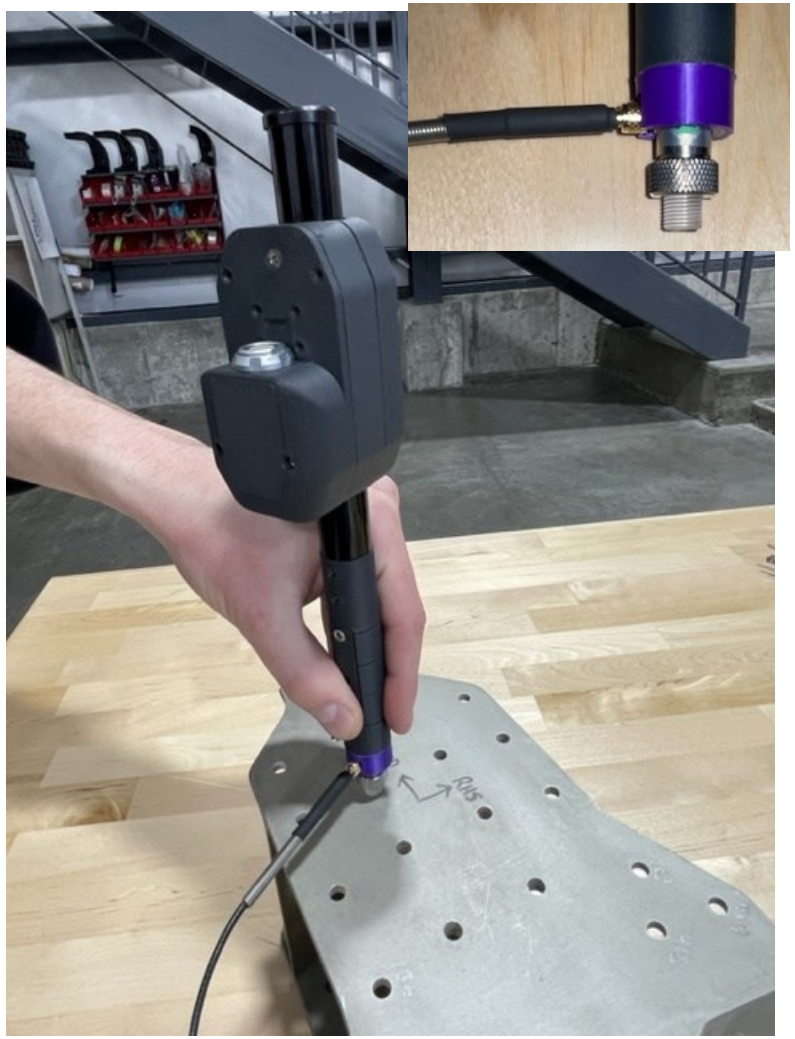
Digital bore gauge testing

Integration and Validation Testing

EPOCH 650 development

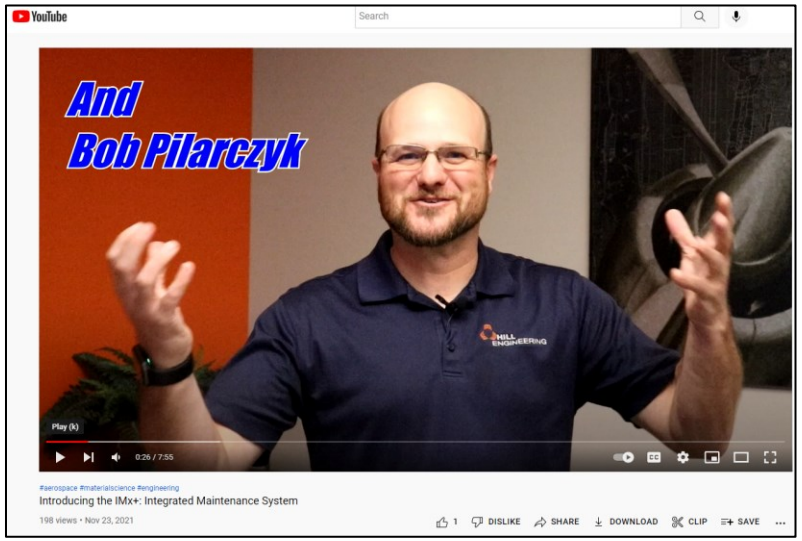
- Leverage existing Space Pencil for spatial tracking
- Adaptable tips for various UT probes
- Real-time tracking of position
- Video and dataset of position of data from EPOCH





Digital Thread Tools to Enable Effective ASIP

QUESTIONS?



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