Model-assisted Methods for Validation of Structural Health Monitoring Systems

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Outline

- Context: Validation of Structural Damage Sensing
- Need for Validation
- Options for Validation
- NDE analogy and approaches: past and future
- Completed Demonstration: approach and results
- Suggested Protocol
- Time Variability
- Summary

Definitions

Structural Health Monitoring includes:

- Structural Models
- Loads and Flight Information
- Structural Damage Sensing (SDS)
- Reasoner to integrate data from the above three components

This talk will focus on ONLY on Structural Damage Sensing

Motivation

- USAF Systems Engineering Process includes:
  - Verification: Laboratory Environment
  - Validation: Operational Environment
- Must validate SDS to enable use of SHM for USAF Structures managed via Aircraft Structural Integrity Program (ASIP)
  - Review ASIP Manual 1530C Requirements
- Provide a capability metric with statistical confidence

Options for Validation

- Demonstration: e.g. flight test
  - Insufficient statistical data
  - Variability for each aircraft
  - Value for lessons learned
- Trust: confidence building through experience
  - Inherent risk for ASIP managed structures
- Statistical Metrics: Probability of Detection
  - Defined in MIL HNBK 1823a

Analogy to NDE

- Structural Damage Sensing Methods are same for NDE and SHM (SDS):
  - Stress Waves: extensional, guided, bulk, vibration, modal, acoustic emission, acousto-ultrasonics, etc.
    - e.g. Ayter, Auld, and Tan, QNDE V1. p595 (1981), Ginzton Laboratory, Stanford University, CA
  - Electromagnetic: eddy current, X-ray, THz, microwave, etc.
  - Thermal: diffusion
- SHM (SDS) has been tried before: AE on KC-135 in the 1980's* followed by recent flight test
  - False calls were present

*Airlift Tanker: History of U.S. Airlift and Tanker Forces, C0lin Bakse, Turner Publishing, 1996, p63

Model of NDE Reliability

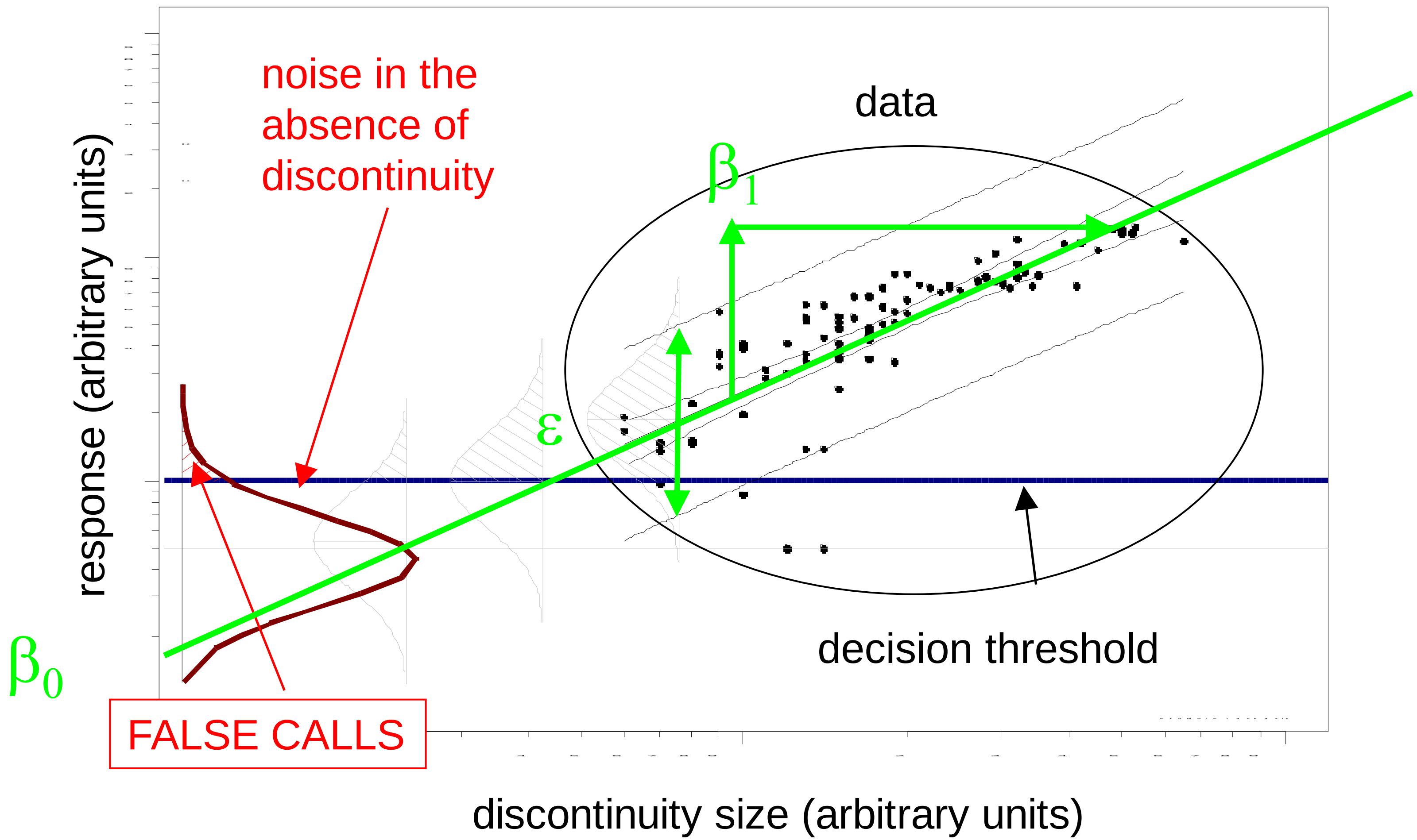
- If NDT system produces a signal,
  - if the signal magnitude is correlated to discontinuity metric
  - if error (noise) in fit is random, normal, zero mean
  - THEN

$$\ln \hat{a} = \beta_0 + \beta_1 \ln a + \varepsilon$$

$$POD(a) = 1 - Q\left[\frac{\ln a - \mu}{\sigma}\right] \quad \text{where } \mu = \frac{\ln(y_{th}) - \beta_0}{\beta_1} \text{ and } \sigma = \frac{\delta}{\beta_1}$$

D. Forsyth, et al., “Development and Validation of the Model Assisted Probability of Detection Method,” QNDE 2009, Providence RI

Graphical Representation of MIL-HDBK-1823 model



D. Forsyth, et al., “Development and Validation of the Model Assisted Probability of Detection Method,” QNDE 2009, Providence RI

Probability of Detection: Myths and Misconceptions

- Myth 1: POD is math
  - POD is statistics and does not become a "plug and chug" formula
- Myth 2: 29 of 29 is sufficient
- Myth 3: Binominal distribution is the most conservative analysis method
- Misconception: results are results
  - Errors will be made if you do not understand process and the data from the inspection

MIL HNBK 1823

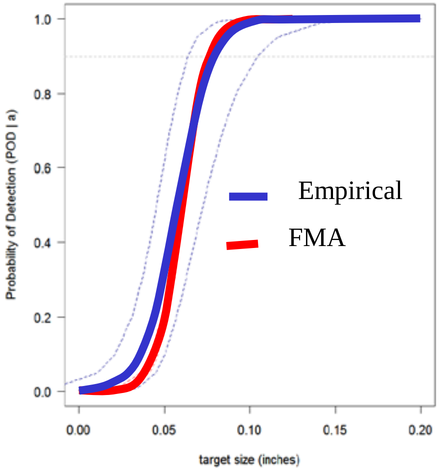
- Defines recommendations required to perform POD Study
  - Currently defined as 100% empirical, revision under review will allow ***modeling***
- Key component: statistically significant number of samples with a statistically significant number and range in size of representative damage
  - Statistically significant means at least 60 samples with damage of different sizes
  - Also requires 120 samples without damage
- Can address a component of human factors with multiple operators

Issues with MH 1823 for SHM

- Currently only uses empirical data
  - Time and cost is very high for NDE application
  - Empirical approach not practical for SDS in SHM
  - New revision just released allows modeling
- Focuses only on detection
  - Hit / Miss Analysis
  - Flaw size (a) vs. flaw response (â) analysis
- Does not address Probability of Locating or Characterizing Damage
  - However, statistical basis for determining these parameters can build on POD process

Approach for POD of SDS in SHM

- Model-assisted Probability of Detection
  - Uses models to minimize the need for empirical samples an data
  - Leverages ongoing work: Consensus Protocol developed by international working group
    - Established in 2003
    - Full model-assist, transfer function based, hybrid
    - Significant amount of stored data and minutes of working group at: **www.cnde.iastate.edu/MAPOD/**
  - Feasibility of Approach Demonstrated for Eddy Current Inspection (Aldrin, et. al., QNDE 2006, 2008)
  - Project under contract (SBIR) to demonstrate feasibility for Ultrasonic Inspection

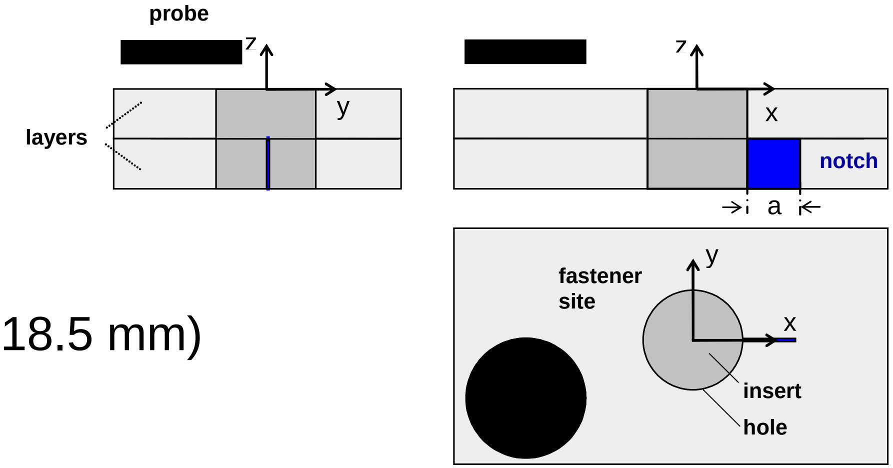


Crack detection in second layer of two-layered structure

This approach will work for SDS in SHM with appropriate models

Demonstration Study for MAPOD

- Classic Two-layer Fatigue Crack from Fastener
  - first layer thickness: 0.156" (3.96 mm)
  - second layer thickness: 0.100" (2.54 mm)
  - total for two layers: 0.256" (6.50 mm), center of layers (3.25 mm)
  - material: aluminum (7075-T651)
  - exterior coat: 0.004"-0.006" (0.10 – 0.15 mm)
  - faying surface: sealed with polysulfide and chromate corrosion inhibitor
- Fastener Site:
  - countersunk fastener
  - diameter: 0.250" (6.35 mm)
  - 100 degree (cone) flush head
  - material: steel and titanium
  - distance between holes: ~0.73" (18.5 mm)



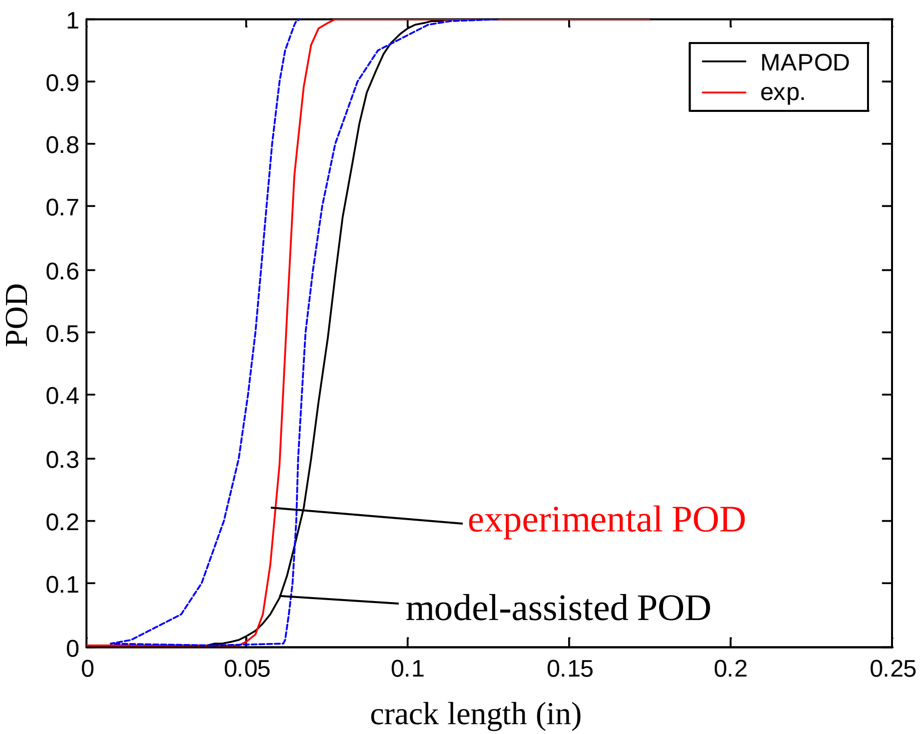
[Knopp, Aldrin, Lindgren, and Annis, “Investigation of a model-assisted approach to probability of detection evaluation”, *Review of Progress in Quantitative Nondestructive Evaluation*, (2007)]

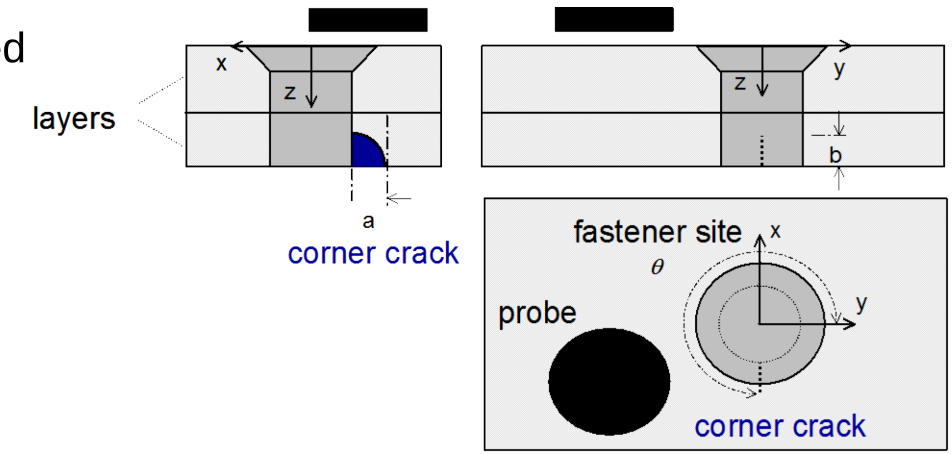
Demonstration Results

Demonstration of model-assisted probability of detection (MAPOD)

Experimental Comparison with Model-Assisted

1^{st} layer – faying surface – corner cracks





Successes:

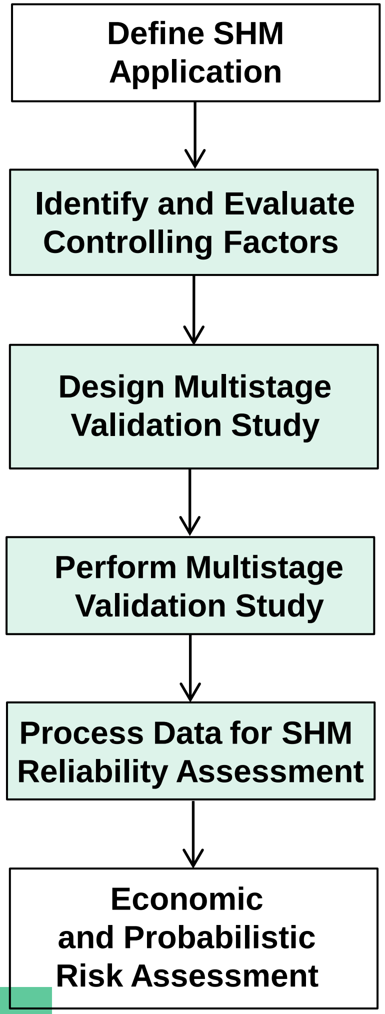
- First demonstration of (MAPOD) in the literature for structural problem.
- Eddy current models were able to simulate eddy current inspection of 2^{nd} layer fatigue cracks around fastener holes

[Knopp, Aldrin, Lindgren, and Annis, "Investigation of a model-assisted approach to probability of detection evaluation", *Review of Progress in Quantitative Nondestructive Evaluation*, (2007)]

NDE MAPOD Process
(Thompson, 2008)

1. Identify the scope of the POD study
2. Identify factors that control signal / noise
3. Evaluate quality of physics-based models
4. Acquire / develop / validate simulation tools
5. Acquire input parameters / parameter distributions
6. Partition factors to simulated and empirical studies
7. Simulate flaw signal distribution simulations and noise signal distribution simulations (stochastic)
8. Acquire remaining information on factors empirically
9. Acquire marginal information on independent factors and covariance information on dependent factors
10. Evaluate *full signal* and *noise distributions* from simulated and experimental data [regression model f(crack length)]
11. Compute Probability of Detection (POD) and of False Call

SDS (SHM) Protocol



For Damage Detection, will work for SDS in SHM

Variability and Modeling

System Variability

- No two aircraft are exactly identical
- Changes can occur as a function of:
  - Design, Assembly, Maintenance, Repair, Modification, Usage
- Baselines for aircraft are not stable: change as a function of variables above, which can change flight to flight
  - Example is boundary conditions between layers*
- Models need to address these variables, or at least define the probabilistic effect of their variance on the output from an inspection process
  - Approach could (should) integrate empirical data and/or expert knowledge

*"Ultrasonic Guided Waves for Fatigue Crack Detection in Multi-layered Metallic Structures," Lindgren, et. al., SPIE March 2007

Example: Factors that will Affect NDE of Two-layered Structure

A. NDE method:

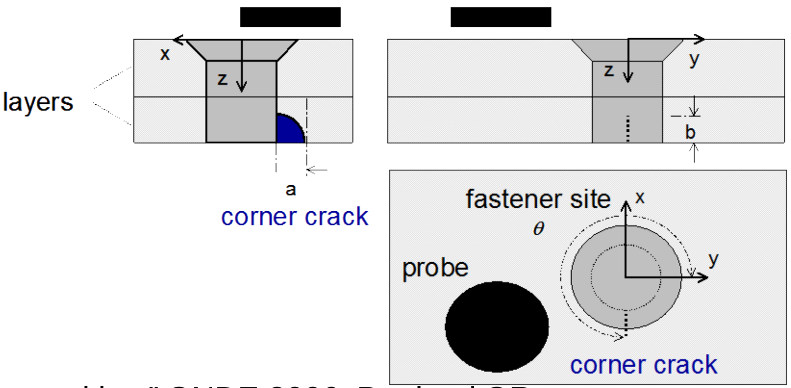
1. **NDE technique**
2. **Transducer/probe design**
3. **Contact condition with part (direct, immersion, air-coupled)**
4. **Scan plan (directions, resolution, orientation)**

B. Part geometry, material and condition:

1. **Layer material, number, and thickness (shims)**
2. **Outer layer surface condition (paint, very thick coatings, corrosion)**
3. **Fastener material / type / head condition**
4. **Hole geometry (oblong, off-angled, surface conditions, scratches, chatter, tool marks)**
5. **Fastener hole fit (asymmetric fit, irregular contact conditions / loading, sealant)**
6. **Gaps / sealant between layers (aging)**
7. **Presence of metal shavings**
8. **Bushings, residual stress around holes**
9. **Proximity of adjacent fasteners and edges**
10. **Presence and condition of repairs**

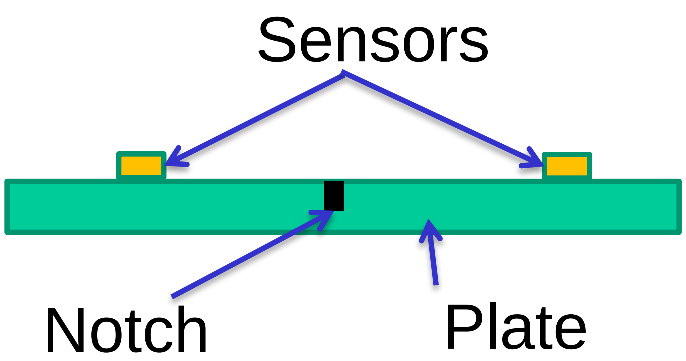
C. Flaw characteristics:

1. **Flaw number (number of cracks per fastener site)**
2. **Flaw type (cracks, EDM notch)**
3. **Flaw location (layer, location in layer: surface, mid-bore, eye-brow cracks)**
4. **Flaw orientation (around fastener site, skew angle from normal)**
5. **Flaw dimensions**
6. **Material within flaw (none, use of filler material, filled with sealant/paint/fluids)**
7. **Flaw morphology (regular, irregular)**
8. **Flaw conditions at faces (contact conditions, residual stress)**



Lindgren, et. al., "Aging Aircraft NDE: Capabilities, Challenges, and Opportunities," QNDE 2006, Portland OR

Research Challenge



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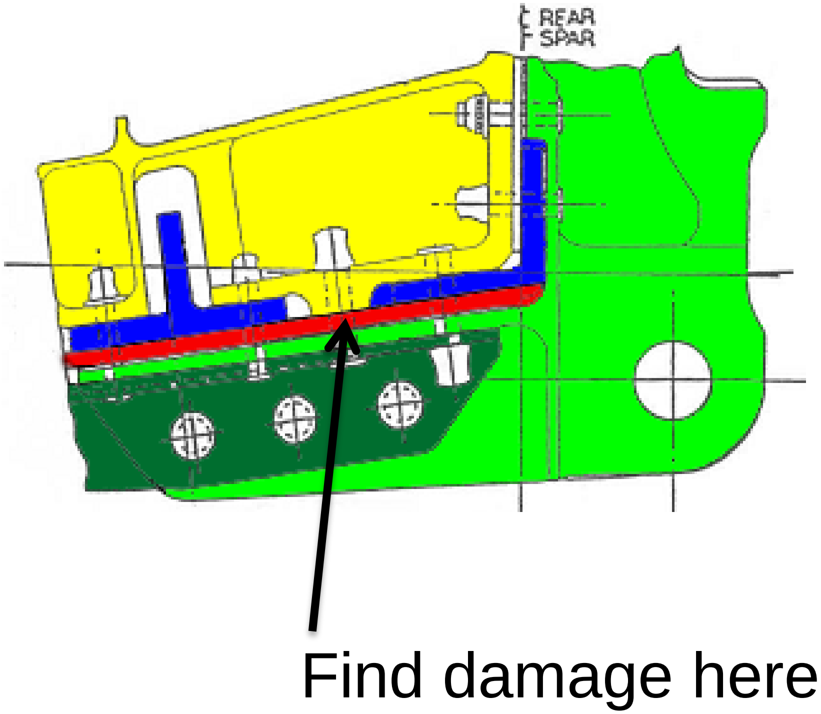

Laboratory Success Does Not Often Translate to Operational Environment without Extensive Investment of Time and Funds

Additional Details

- Approach: See Medina et. al., "Toward a Validation Methodology for Structural Health Monitoring," ISHM 2009 and Aldrin et. al., Rev. Prog. QNDE 2009 Proceedings
- Variability: See Lindgren and Derriso, "Challenges for the Validation of Structural Health Monitoring Systems: an Approach," ISHM 2008

Summary

- Validation Process Critical to Implementation Success of SDS in SHM
  - Leverage experience and lessons learned from NDE of aircraft structures
- Model-based Methods show Significant Promise to Enable Validation of SDS component of SHM
  - Demonstration for Eddy Current Successful
  - Demonstration for Ultrasound underway
- Challenges Remain
  - Model Development and Validation

Acknowledgments

- MAPOD Working Group Members
  - DoD: Air Force, Navy, Army
  - Federal Labs/Agencies: NASA, FAA, DOE, NRC
  - Academia: ISU, others…
  - Industry: P&W, others…
  - International Collaborators: DSTO, QinetiQ, CNRC, more to join this year
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