Hybrid Passive/Active Impact Detection & Localization for Aerospace Structures

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Introduction

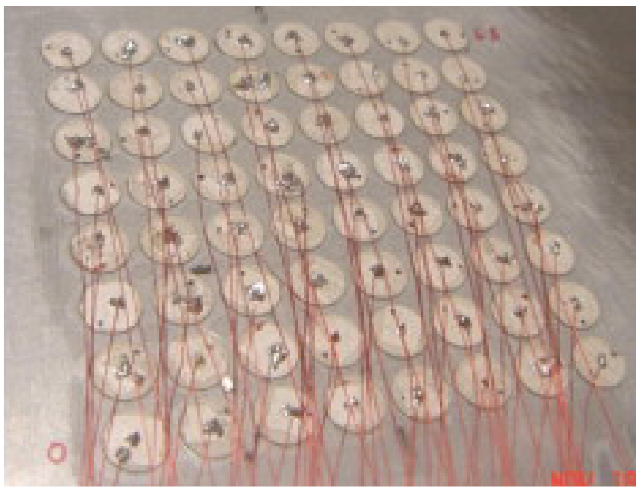
- Aerospace vehicles are subject to impact damage
  - foreign object debris (FOD)
  - battle damage (and bird strike)
  - ground handling (or mishandling)

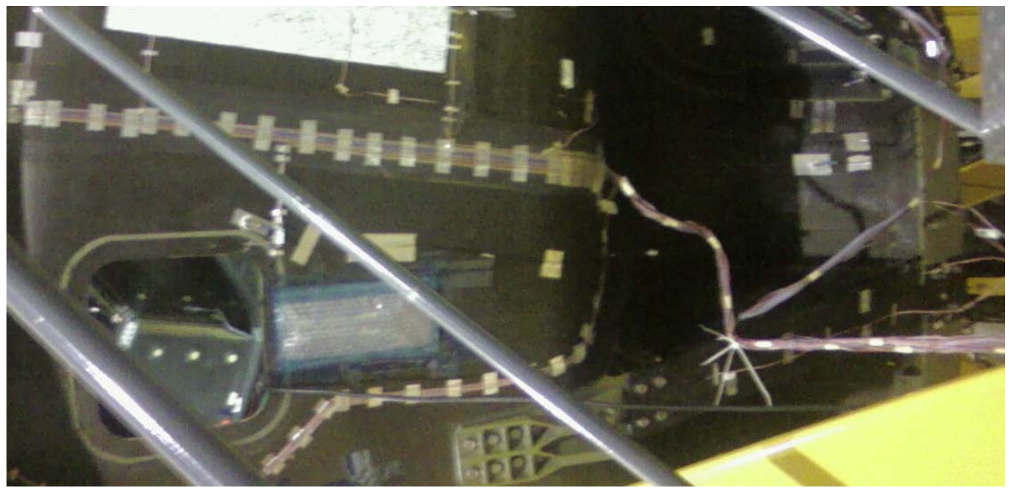
- Recording of damage event and/or resulting damage provides for timely & cost effective repairs (or prevents unnecessary ones)

- MD7 Digital SHM System
  - passive mode (acoustic emission recording)
  - active mode (guided wave propagation)
  - witness mode (differential voltage measurements)

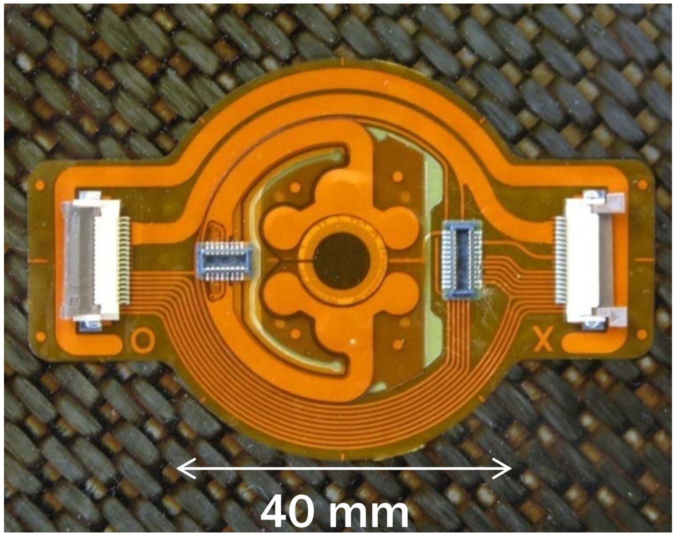
MD7 Motivations: Beamforming

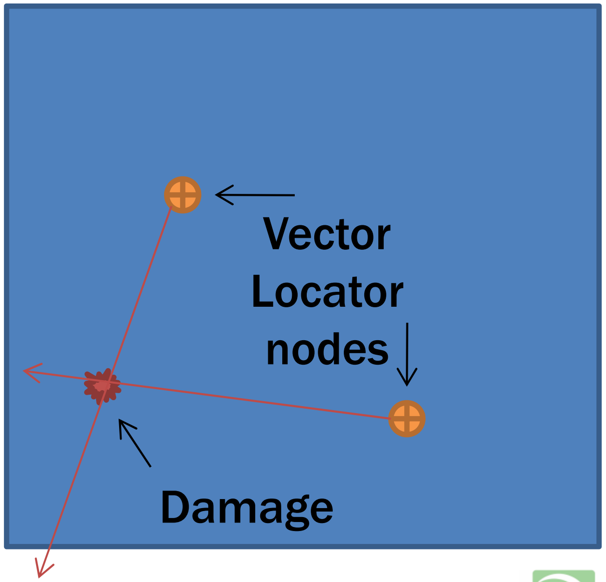
- Traditional SHM methods require high sensor density
  - many methods only detect below sensor (fiber optic, Eddy current, CVM)
  - wave-based methods can cover large areas with small sensors, however acoustic emission & scatter methods need 3+ sensors in close proximity
- Most wave-based methods require knowledge of wave velocity
  - challenging to compensate for velocity in non-isotropic laminates
  - complications arise due to inhomogeneity (tapers, stiffeners, drop-offs)





MD7 VectorLocator™



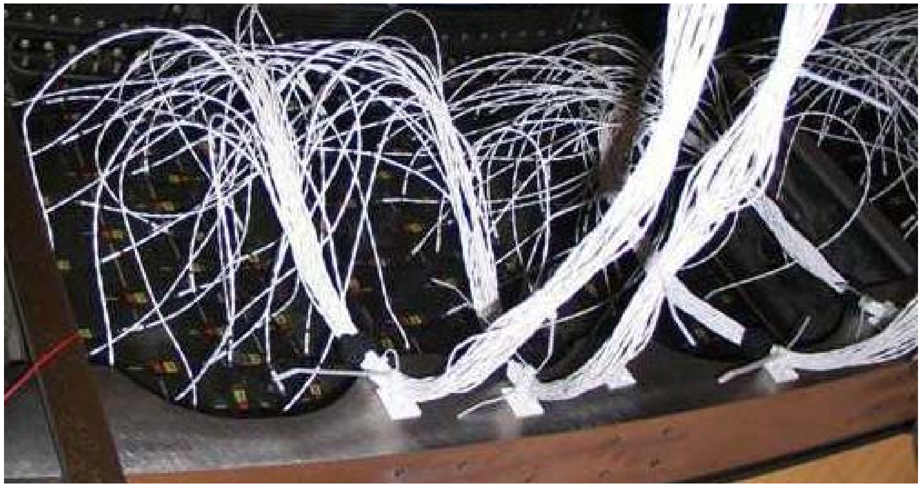


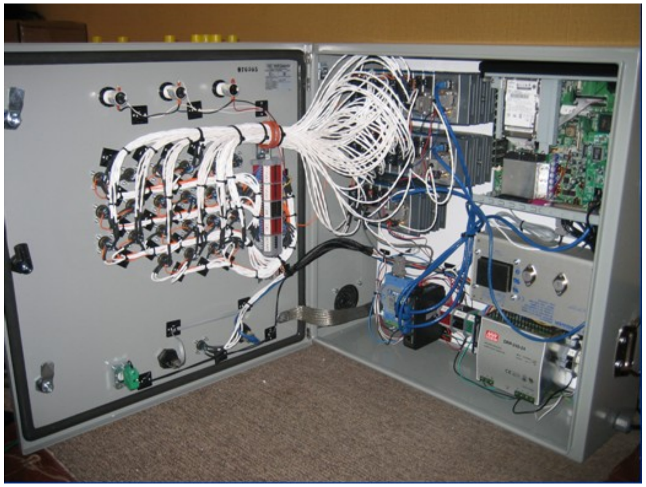
- Analog sensor base for impact/damage detection
- 1 PZT actuator & 6 PZT sensors in small package
- Facilitates both active/passive beamforming

MD7 Motivations: Digital Network

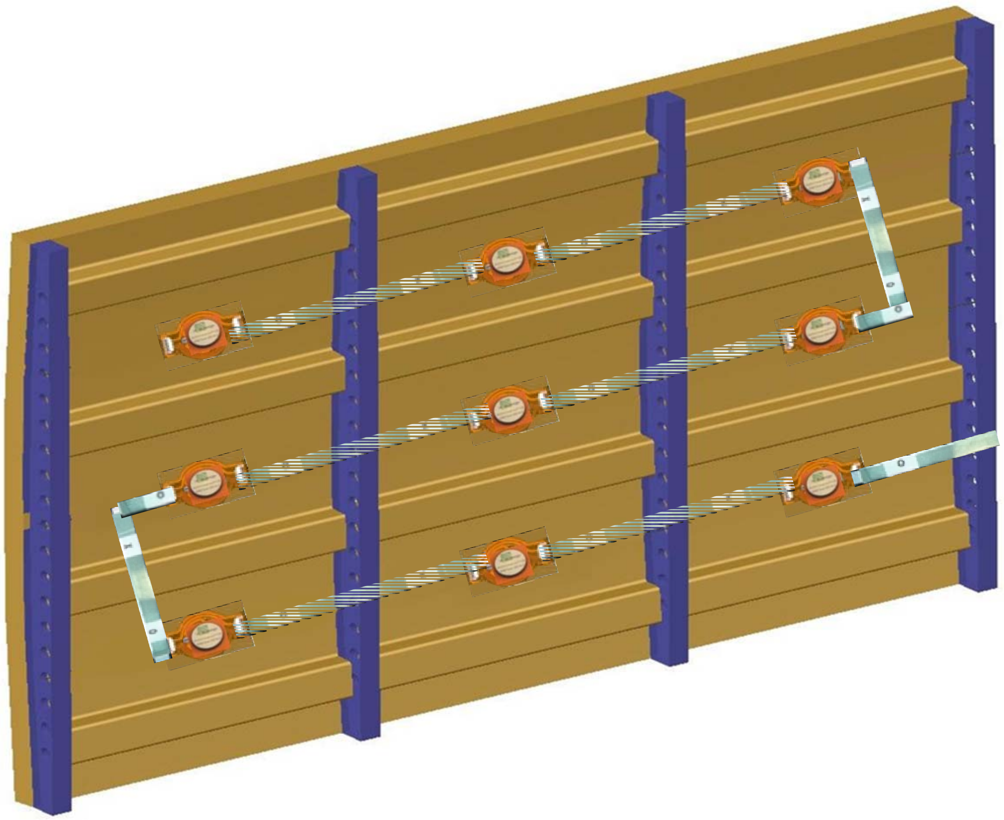
- Current SHM strategies are analog, do not scale practically
  - individual cables to each element adds mass, cost, reliability concerns
  - centralized processing can limit the total quantity of sensors on structure, required to handle significant data volume synchronously

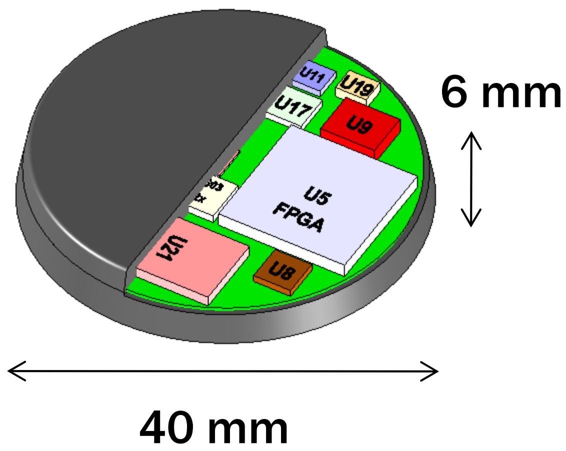
- Analog cables not ideal for precision measurements
  - susceptible to conducted & radiated EMI (long wires = antenna)
  - shielded signals attenuate linearly with length due to stray capacitance





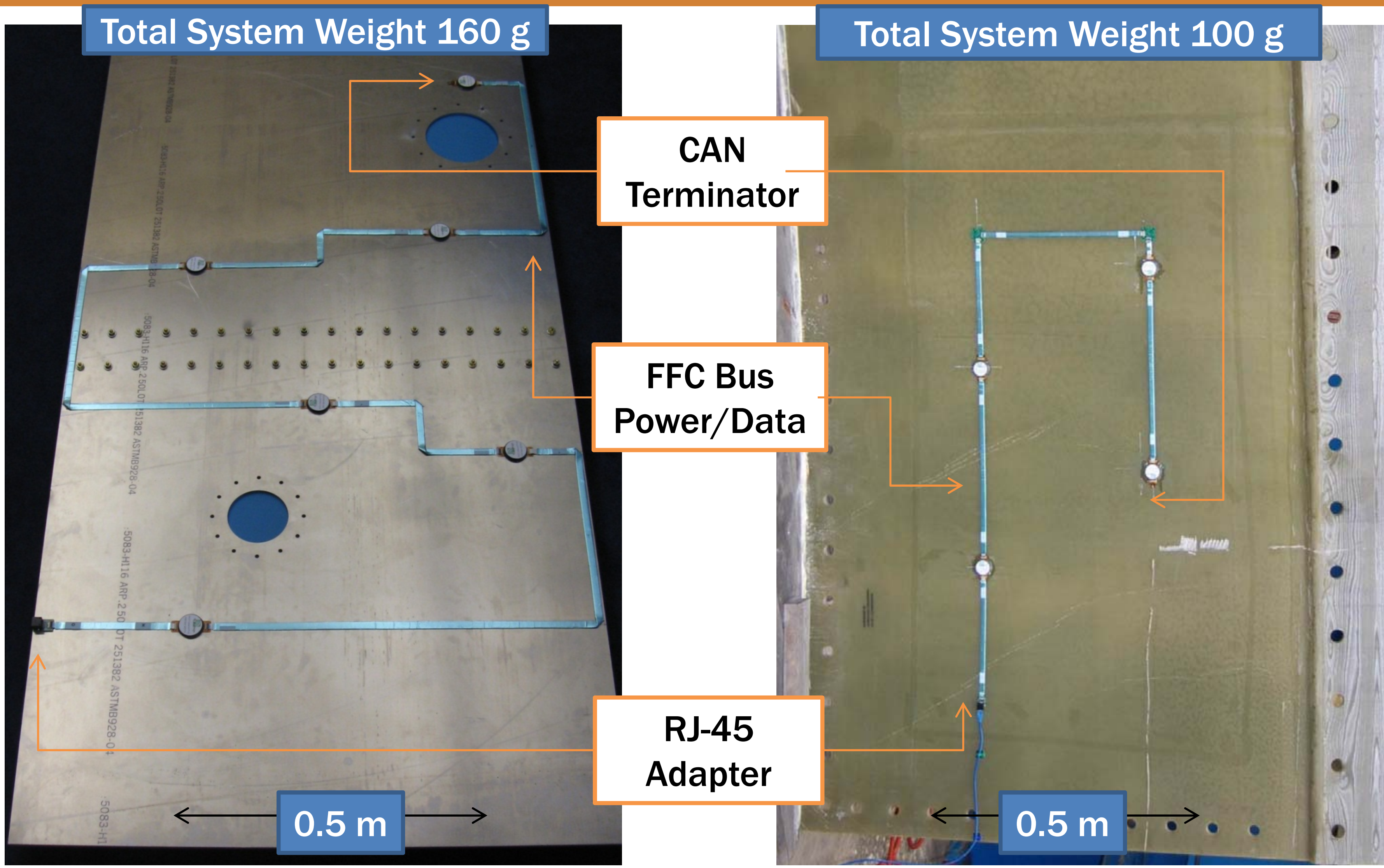
MD7 IntelliConnector™





- Digital node for distributed acquisition & computation
- Facilitates both active/passive detection methods
- Flat Flexible Cable (FFC) bus for up to 200 nodes

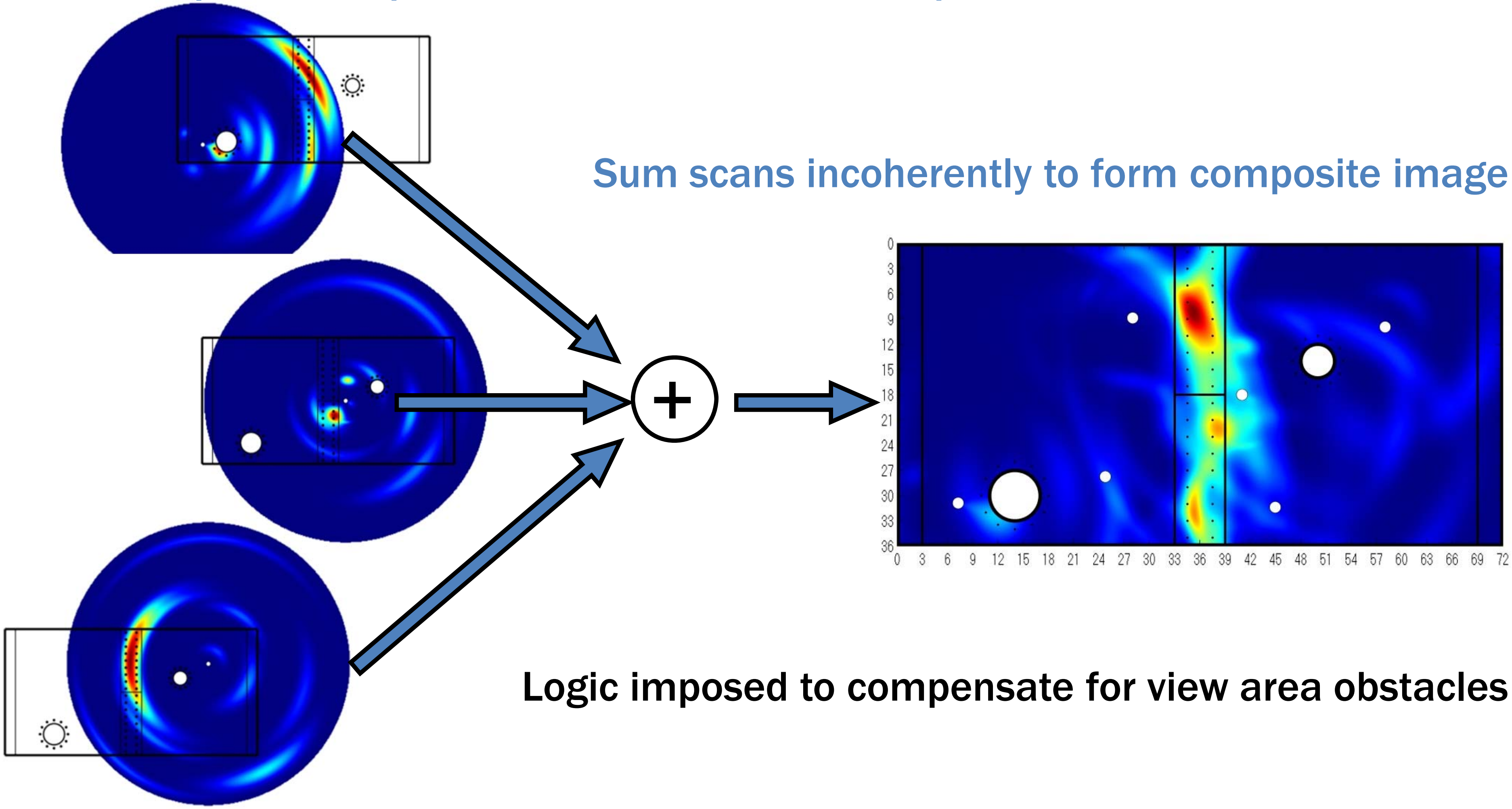
Installed MD7 SHM System



Data Analysis & Reconstruction

Each node processes phase-coherent, location independent "sonar-scan"

Sum scans incoherently to form composite image



Logic imposed to compensate for view area obstacles

color represents # of standard deviations above mean of damage-free data

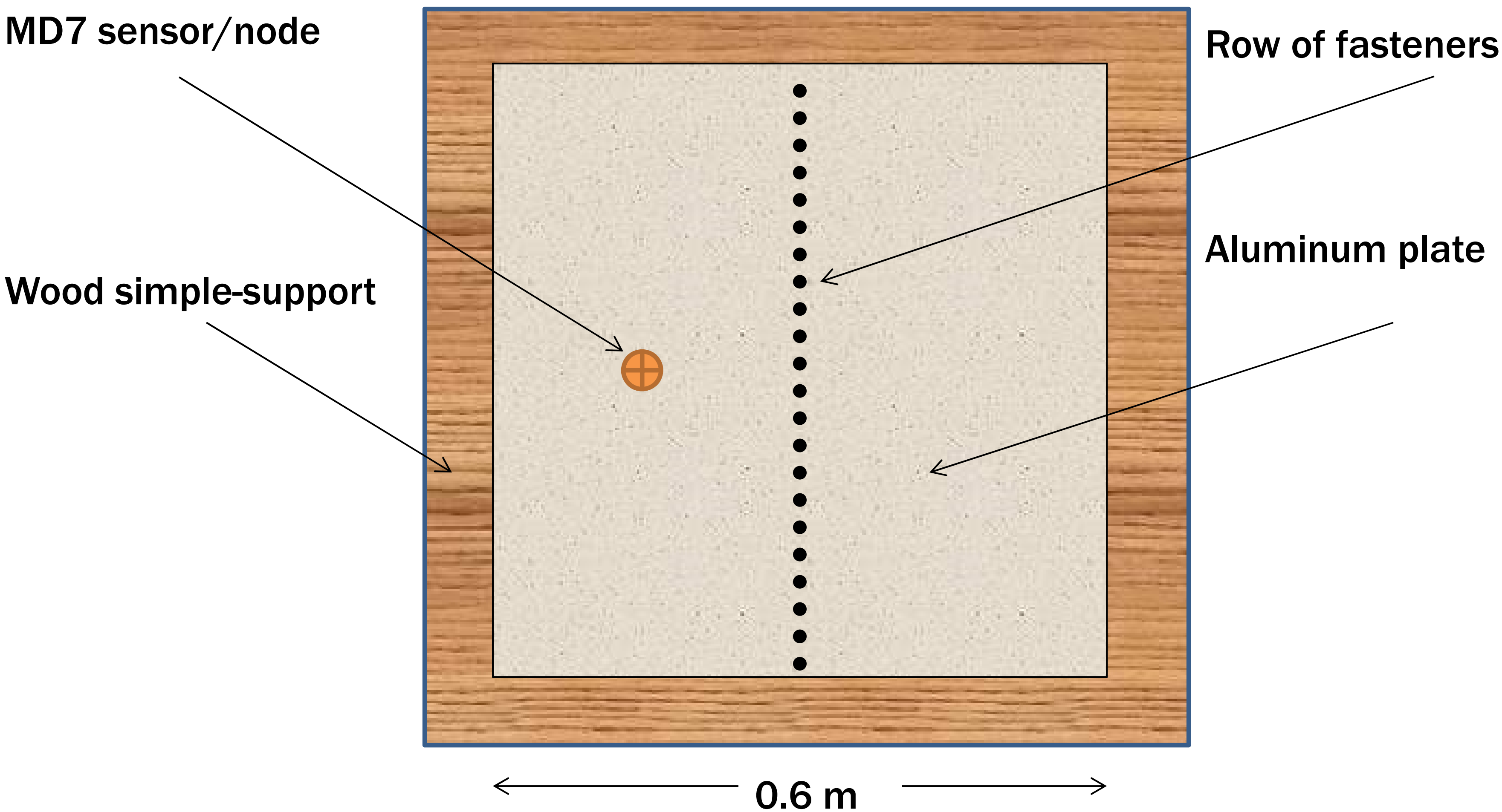
Experimental Performance Evaluation

- Experiment designed to evaluate performance of hybrid system
  - detection/localization of impact events
  - detection/localization of damage induced by impact events
  - detection/localization of loosened fasteners

- Specimen selected to be representative of aircraft/rotorcraft skin
  - Aluminum sheet 2 mm thick, 0.6 x 0.6 m square
  - 20 fasteners evenly spaced across the center, tightened to same torque

- Single MD7 sensor/node used
  - bonded with AE-10 using 24-hour room temperature cure cycle
  - centered half-way between edge of plate and row of rivets
  - flat flexible cable (FFC) used to connect to hub (command & data storage)

Representative Aerospace Specimen



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Test Procedure

- Falling-mass low-velocity impacts
  - 1 cm semi-spherical impact head
  - ~20 J of energy per impact
  - strike on side opposite and at least 2 cm from sensor/node
  - simply-supported perimeter with wooden frame
  - active guided wave scans performed with 50 kHz excitation

- 36 impact events monitored passively that triggered active scans
  - 18 impacts randomly distributed on same side of fastener line as nodes
  - 18 impacts randomly distributed on opposite side of fastener line as nodes

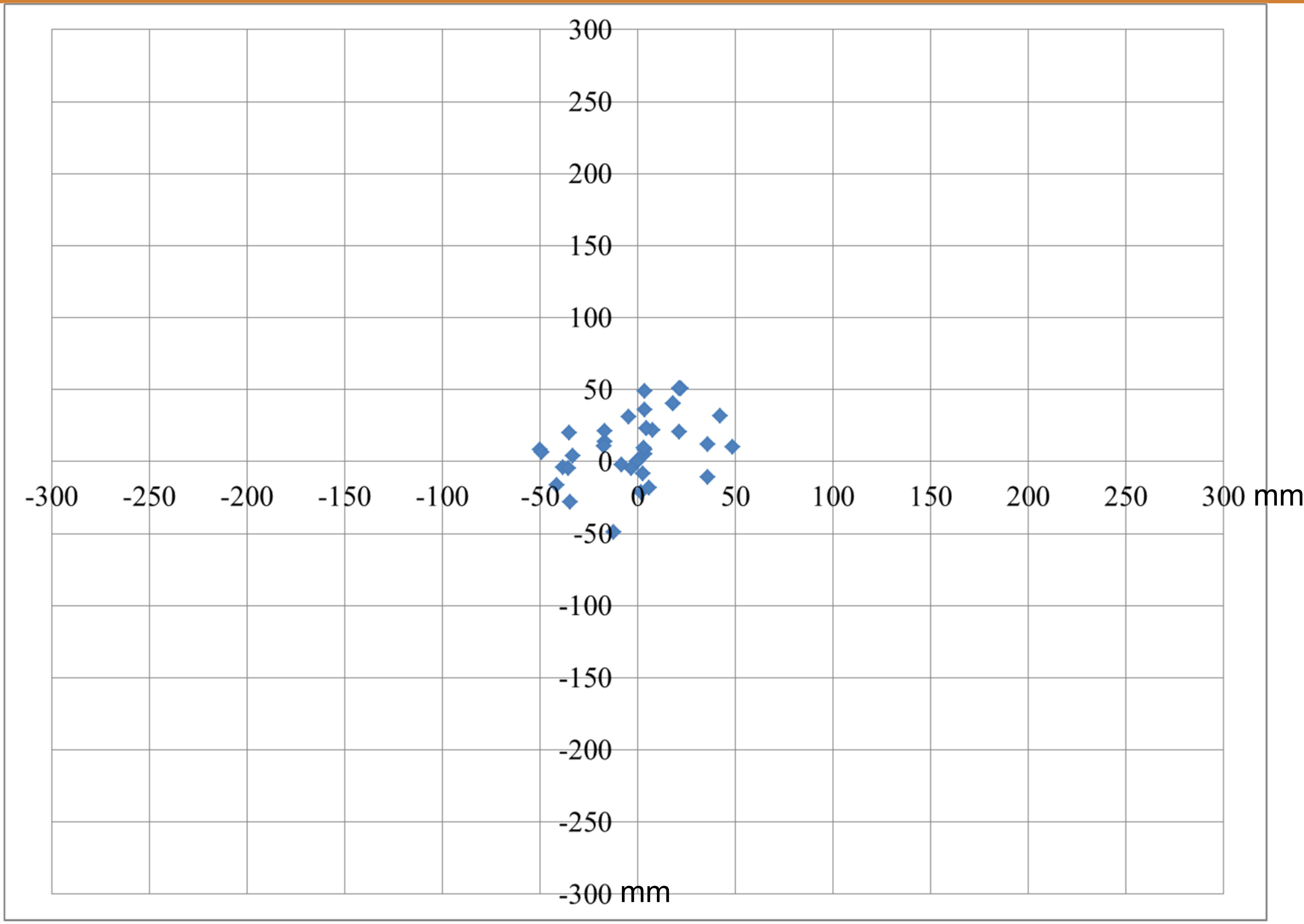
- 42 active scans were triggered manually
  - 6 scans followed the loosening (hand-tight) of a random fastener
  - 36 scans without impact or loosened fastener (false positive check)

Passive Mode Impact Detection Results

- System showed excellent sensitively to impact events
  - 100% detection (36/36) following impact events
  - no false triggers at pre-programmed threshold
  - phase coherent scan produced for each AE result
  - Cartesian coordinates distilled for maximum likelihood centroid of scan

- Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - predictions cluster relatively closely near origin relative to size of plate
  - mean error for AE localization ~ 25 mm
  - no trend observed for results obtained on one side of fastener line vs other

Re-Centered Passive AE Impact Detection Results



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Active Mode Impact Detection Results

- System showed good sensitively to impact damage
  - 100% detection (36/36) of ~0.5 mm deep dents following AE detection
  - no false positives indicated (0/36) following non-impact scans
  - phase coherent scan produced for each AE result
  - Cartesian coordinates distilled for maximum likelihood centroid of scan

- Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - more scattered than AE, but predictions still group relatively close to origin
  - mean error for GW localization ~ 50 mm
  - no trend observed for results obtained on one side of fastener line vs other
  - some error may be accumulated due to each subsequent dent introducing additional scatterers into structure; while subtracted in algorithm, still redistributes ultrasonic energy through structure in inhomogeneous pattern

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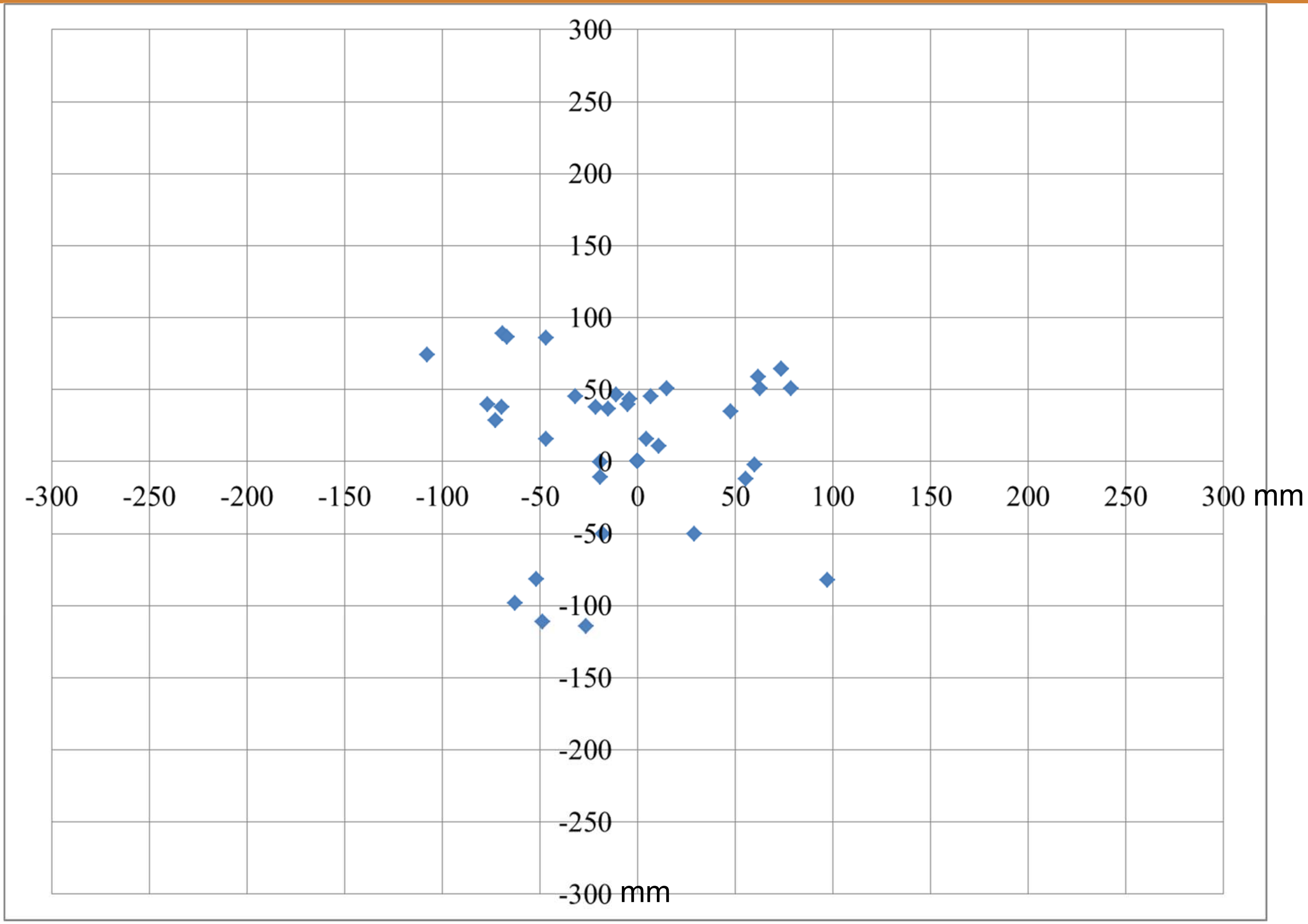
Re-Centered Active GW Impact Detection Results



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Active Mode Fastener Detection Results

- System showed excellent sensitively to loose fastener detection
  - 100% detection (6/6) of hand-tightened fasteners
  - no false positives indicated (0/36) following non-loosened scans
  - phase coherent scan produced for each AE result
  - Cartesian coordinates distilled for maximum likelihood centroid of scan

- Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - more scattered than AE, but predictions still group relatively close to origin
  - mean error for GW localization ~ 5 mm
  - essentially translates to localization within ±1 fastener position

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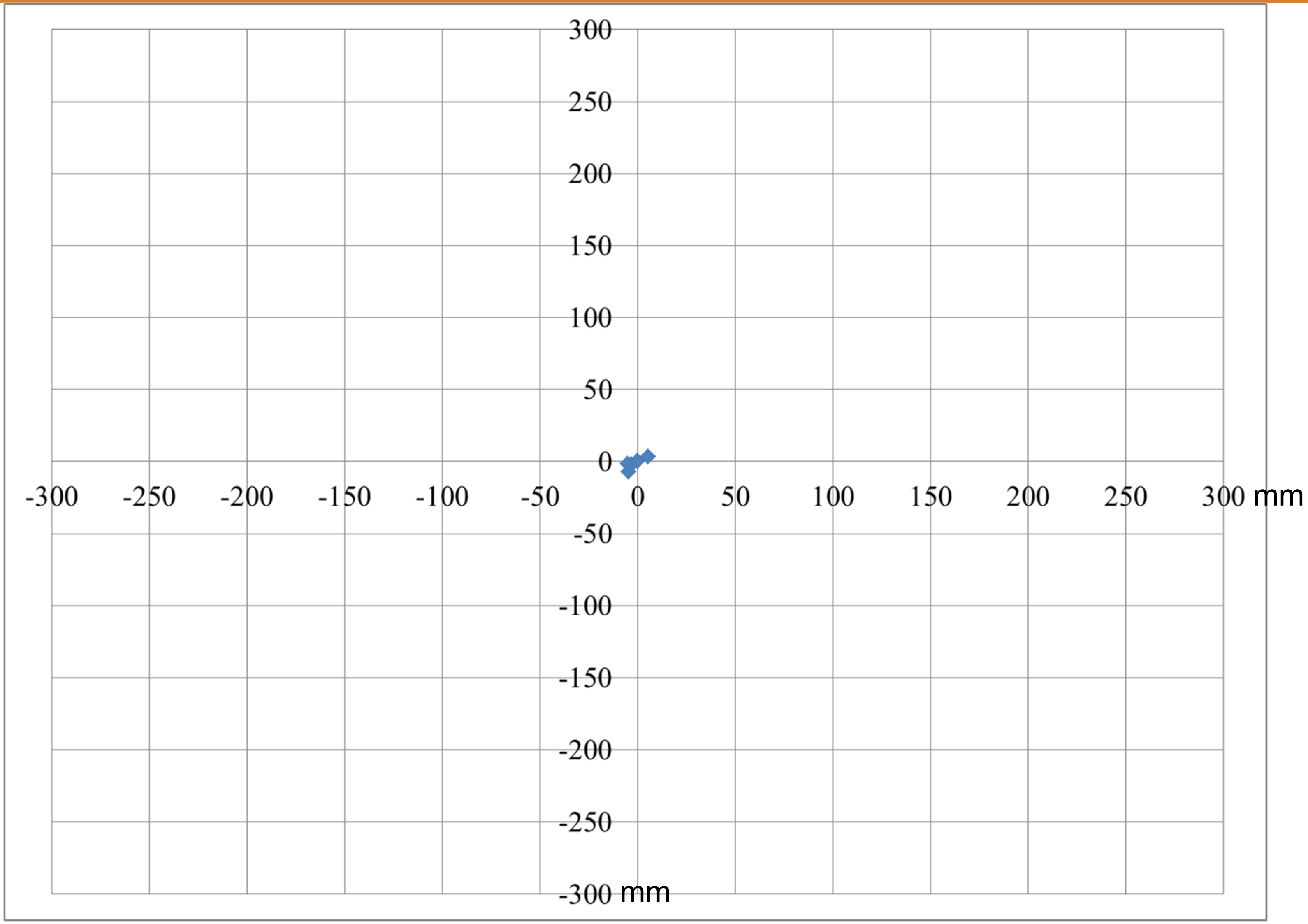
Re-Centered Active GW Fastener Detection Results



Summary

- Paper present results for a controlled experiment investigating the use of an SHM system for hybrid passive/active operation
  - Aluminum plate with row of fasteners instrumented with a single sensor
  - 36 impact events using falling mass, AE + GW detection & localization
  - 36 manually-triggered active scans to check false-positives
  - 6 manually-triggered active scans with loosened fasteners
- Results indicate good sensitivity for both active/passive modes
  - 100% AE-based ~20 J impact detection, 25 mm mean localization error
  - 100% GW-based ~0.5 mm dent detection, 50 mm mean localization error
  - 100% GW-based loose fastener detection, 5 mm mean localization error
  - no false positives for active or passive modes with appropriate thresholds
- Hybrid beamforming approach provides an efficient & accurate means for impact/damage detection, possible to add DC sensors

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Technology & Transition Readiness

Naval Applications

Surface Vessels – TRL 7

- 14 sensors installed on USS Independence
- continuously operating since 2/2012
- monitoring weld-line cracks & temperature

Submarines – TRL 5

- underwater testing
- scaled testing planned

Fixed-Wing Aircraft

Unmanned – TRL 6

- full-span test conducted on Triton wing assembly
- full-span test conducted on Predator wing spar

Manned – TRL 6/7

- C-17 empennage tests
- F-22 lug fatigue tests
- C-130 hot-spot flight test planned for 2014

Rotorcraft

BlackHawk – TRL 6

- 100+ subcomponent impact/damage tests
- ongoing subassembly testing w/SIK
- tail gearbox spin-stand crack-tracking tests

CH-53K – TRL 5

- relevant material tests
- environmental tests

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