PZT & CNT based SHM Systems for Impact Detection & Localization

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MD7-Pro Digital SHM System

- Metis Design developed & validated system through SBIR funding
  - AF03-T017 – Intelligent SHM Infrastructure (hardware)
  - AF06-097 – Adaptive Damage Detection (software)
  - USS Independence (N10-T042)
  - Triton UAS (N12-125)
  - Blackhawk (N12-T007, COST-A & others)

- System focus on low mass, low power, expendability, retro-fit
  - novel sensor/algorithm design for large-area coverage
  - distributed intelligence on a digital sensor bus
  - multifunctional capabilities at each node location
MD7-Pro Structural Sonar

- Analog sensor base for impact/damage detection
- Greatly reduces typically required sensor density
- 1 PZT actuator & 6 PZT sensors in small package
- Facilitates both active/passive beamforming
MD7-Pro Acquisition Node

- Digital node for distributed acquisition & local computation (15 g mass)
- Greatly reduces mass of cables & centralized hardware, eliminates EMI
- Facilitates both active (guided wave) & passive (AE) detection methods
- 8 breakout analog & digital channels + built-in triaxial accelerometer & temp
MD7-Pro Acquisition Node + Structural Sonar
MD7-Pro Low Speed Channel Validation

**Strain Gauge Calibration & Validation**

- MD7 Measurement (V) vs. Strain (µε)
- MD7080 vs. MD7081

**Crack Gauge Calibration & Validation**

- MD7 Measurement (V) vs. Number of Fractured Traces
- MD7080 vs. MD7081 vs. Model

**Thermocouple Calibration & Validation**

- MD7 Measurement (V) vs. Temperature (°C)
- MD7080 vs. MD7081

**Thermistor Calibration & Validation**

- MD7 Measurement (kΩ) vs. Temperature (°C)
- MD7080 vs. MD7081
MD7-Pro Accumulation Node

- Digital node for 64 GB data accumulation & global processing (20 g mass)
- Can support up to 100 Acquisition nodes on serial bus
- Hosts complex C++ embedded algorithms w/FPGA & 2 GB RAM
- Gigabit Ethernet + USB access to data, programmable interface

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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
Performance Evaluation

- Single MD7 node detection on 2mm thick Al plate with 20 rivets
  - 36 impact events of ~20 J of energy from falling 1 cm semi-spherical mass
  - half of impact on each side of rivet line

- Hybrid passive/active detection demonstrated
  - 36 passive/active auto-triggered measurement following impact events
  - 6 manually triggered active measurements with a fastener removed
  - 36 manually triggered active measurements without any impact or damage
Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin:

- 100% detection (36/36) following impact events
- No false triggers recorded at pre-set threshold levels
- Mean error for AE localization ~ 25 mm
- Predictions cluster relatively closely near origin relative to size of plate
- No trend observed for results obtained on one side of fastener line vs other
Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin

- 100% detection (36/36) of ~0.5 mm deep dents following AE detection
- no false positives indicated (0/36) following non-impact scans
- mean error for GW localization ~ 50 mm
- more scattered than AE, but predictions still group relatively close to origin
- no trend observed for results obtained on one side of fastener line vs other
Active Mode Fastener Detection Results

- Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - 100% detection (6/6) of hand-tightened fasteners
  - no false positives indicated (0/36) following non-loosened scans
  - mean error for GW localization ~ 5 mm
  - least amount of scatter due to massive local stiffness change
  - essentially translates to localization within ±1 fastener position
Conformal Multi-functional Assemblies

- Conformal assemblies for composite & metallic host structures
  - central carbon nanotube (CNT) layer is core to these properties
  - surrounded by electrically insulating layers (film adhesive and/or GFRP)
  - selective electrodes integrated to steer current flow

- Little impact to physical structure, 100 - 200 µm & 5 - 10 g/m²
  - can be co-cured with composite laminate
  - can be installed over composite or metallic skin in secondary process

- Enable multi-functional capabilities: anti-icing, health monitoring
 Structural Health Monitoring (SHM)

- **SHM improves reliability, safety & readiness @ reduced costs**
  - sensors add weight, power consumption & computational bandwidth
  - cables add weight, complexity, as well as durability & EMI concerns
  - scaling SHM for large-area coverage has presented challenges

- **Advantages of proposed CNT-based SHM methodology**
  - CNT “sensors” can actually improve specific strength/stiffness of structure
  - can use thinner/lighter electrodes such as metal-mesh or direct-write
  - simple to scale over large structure, maintains good local resolution

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In-Space Inspection Workshop 14 of 24
Damage shifts CNT links in affected zone, increases resistivity
- Nearly linear increase in % resistance change with impact energy
- < 1% change in resistance away from impact zone

Surface & sub-surface images produced in post-processing
- 20 joule impact caused ~10-20% resistance change (no visible change)
- 40 joule impact caused ~20-30% resistance change (no visible change)
- 60 joule impact caused ~40-60% resistance change (no visible change)
Detection sensitivity is a strong function of CNT network aspect ratio:

- 2400 mm² CNT w/160 mm² damage yields ~25% in resistance increase.
- Same damage in a 1 m long strip of the same width would yield ~2% change.
- 10 mm² damage would still be over the noise floor.

Simple 2D network resistor model is in good agreement with data.
• Impacts below threshold of 30 J had <0.25% change in resistance
  - impacted surfaces exhibited >1% change in resistance after 30 J impacts
  - majority of specimens showed increase of ~15% after 110 J impacts
  - possible to increase CNT monitoring patch length to 1 m with 0.1% change
• Variability due to impact events, could be observed in “dents” too
Impact Test Acoustic Response (N111-067)

7 J Impact

108 J Impact

7 J Impact Zoomed-In

108 J Impact Zoomed-In
• Resistance is proportional to strain for low displacement
  ➢ load/displacement curves for all specimens are in close agreement
  ➢ tensile-side resistance increases due to CNT network being stretched-out
  ➢ compressive-side resistance decreases due to CNT being pushed together
• Permanent resistance increase after 25 mm deflection (>400 N)
Unloaded Bend Test Results (N111-067)
1m CFRP Submarine Propeller Test Specimen
4-Point Bend Results: Loaded vs Unloaded Results

- Same trends observed in 1 meter specimen as smaller coupons
  - tensile-side resistance increases linearly with enforced displacement
  - compressive-side resistance decreases linearly with enforced displacement

- Permanent resistance increase after 25 mm deflection (>4 kN)
Effect of CNT on Laminate Mechanical Properties

- 4 sets of ASTM tests performed professionally by testing house
- CNT surface layer statistically has no effect on any mechanical stiffness or strength properties in normal operating strain ranges

**Impact ASTM-D256-10**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>33 ft-lbs/in</td>
</tr>
<tr>
<td>CNT on surface</td>
<td>37 ft-lbs/in</td>
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</tbody>
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**Tensile ASTM-D638-10**

**Compressive ASTM-D695-8**
Technical & Business Contact

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