NASA Applications of Structural Health Monitoring Technology

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9th International Workshop on Structural Health Monitoring
Stanford University
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NASA Focused Structural Health Monitoring

Key Drivers
- Vehicle-focused
- Real-time, decision-making
- Online processing
- Onboard systems
- Lightweight, Small size, Low power, System solutions

Enabling Technologies
- Advanced Sensing
  - Multi-parameter
  - Sensor arrays
- Advanced Systems and Processing
  - Solid state
  - Rugged
  - High Speed
- Ultra-Efficient Algorithms

Structures
Materials
NDE
SHM
SHM Aerospace Vehicle Applications

NASA Structural Health Monitoring Technology

- Space Shuttle Orbiter
- International Space Station
- Composite Crew Module
- Uninhabited Aerial Vehicles
- Space Vehicles
- Reentry Vehicles
- Vehicle Pressure Systems
- Launch Vehicles
Topics

• Structural Health Monitoring
  – Definition
  – SHM vs NDE

• Agency Overview of SHM Activities
  – Accel & Acoustic-based SHM on STS (Prosser, NESC)
  – Wireless-based SHM on ISS / STS (Studor, JSC)
  – Piezo-based SHM on ISS (Madaras, LaRC)
  – Fiber-optic-based SHM on Aerospace Vehicles (Richards, DFRC)
    • Uninhabited Aerial Vehicles
    • Composite Crew Module
    • Reentry Vehicles
    • Space Vehicles
    • Vehicle Pressure Systems
    • Expendable Launch Vehicles
Space Shuttle Orbiter

Wing Leading Edge Impact Detection System (WLEIDS)
Columbia Accident Investigation
Catastrophic Impact Damage Test on RCC Panel 8

July 7, 2003

Impact on Panel #8: Broken Panel

Acoustic Emission Sensor Data

Peak g's

Air Blast Test Accelerations

AE Sensors

Accelerometers

J1  J2  J3  Triax

Panel 5  Panel 6  Panel 7  Panel 8  Panel 9  Panel 10

22.89  24.18  26.60  32.57  33.00  31.47
24.18  26.60  32.57  33.00  31.47  35.89
18.17  14.39  14.39  20.9  20.9  22.15
50.00  50.00  50.00  50.00  50.00  50.00

Impact on Panel #8: Broken Panel

2.0  2.0  2.0  2.0  2.0  2.0
2.0  2.0  2.0  2.0  2.0  2.0
2.0  2.0  2.0  2.0  2.0  2.0
WLEIDS Operations

- Installed on all Shuttles
- Successfully flown on all flights since Columbia
- Detected small impacts during ascent
  - Small amplitude, nondamaging
  - Likely popcorn foam
- Detected several small MMOD impacts

Sensors and Data Recorder in Wing

WLEIDS probable impact signal
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  – Piezo-based SHM on ISS (Madaras, LaRC)
  – Fiber-optic-based SHM on Aerospace Vehicles (Richards, DFRC)
    • Sensor Development
    • Strain-based Parameter Development
      – Shape, Loads, Liquid Level, Magnetic Field
    • Sensor Attachment / Characterization
    • System Development
    • Ground / Flight Applications
# Space Shuttle / ISS
## Evolution of Micro-WIS Systems

<table>
<thead>
<tr>
<th>System</th>
<th>MicroWIS (SBIR)</th>
<th>Extended Life MicroWIS</th>
<th>MicroSGU / MicroTAU</th>
<th>Wideband MicroTAU</th>
<th>Enhanced WB MicroTAU</th>
<th>Ultra-sonic WIS (new Ph2 SBIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>IVHM</td>
<td>Thermal Models</td>
<td>Cargo Loads Cert Life Extension</td>
<td>MPS Feedline Dynamics</td>
<td>Wing Leading Edge Impacts</td>
<td>ISS Impact/Leak Monitoring</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>1.7” dia. x 0.5”</td>
<td>2.7”x2.2”x1.2”</td>
<td>2.7”x 2.2” x 1.2”</td>
<td>3.0”x 2.5” x 1.5”</td>
<td>3.25”x2.75”x1.5”</td>
<td>3.4” x2.5”x 1.1”</td>
</tr>
<tr>
<td><strong>Sample Rate</strong></td>
<td>Up to 1Hz</td>
<td>Up to 1Hz</td>
<td>Up to 500Hz (3 channels)</td>
<td>Up to 20KHz (3 channels)</td>
<td>Up to 20KHz (3 channels)</td>
<td>Up to 100KHz (10 channels)</td>
</tr>
<tr>
<td><strong>Data Storage</strong></td>
<td>None</td>
<td>2Mbytes</td>
<td>1Mbyte</td>
<td>256Mbytes</td>
<td>256Mbytes</td>
<td>1Gbyte</td>
</tr>
<tr>
<td><strong>Battery Life</strong></td>
<td>9 months</td>
<td>10+ years</td>
<td>2-3 missions</td>
<td>1 mission</td>
<td>1 mission</td>
<td>3 years</td>
</tr>
<tr>
<td><strong>Sensor Types</strong></td>
<td>Temperature (Flight Cert) and Resistive sensors: Strain, Accelerometer, Pressure</td>
<td>Temperature (Flight Cert) and Resistive sensors: Strain, Accelerometer, Pressure</td>
<td>Acceleration &amp; Strain (Flight Cert) or Resistive sensors. Includes Pressure as Trigger Channel.</td>
<td>Accelerometer &amp; Temperature (Flight Cert) or Piezoelectric and Resistive Sensors</td>
<td>Accelerometer &amp; Temperature (Flight Cert) or Piezoelectric and Resistive Sensors</td>
<td>Ultrasonic Microphone and Acoustic Emission</td>
</tr>
</tbody>
</table>
Wireless Instrumentation Systems
Unique Solutions To Real Shuttle Problems

• **Temperature Monitoring**
  - Validation of thermal models for design modifications and operations
  - Micro-WIS (first flown in non-RF configuration)

• **Structural Loads and Dynamics**
  - SSME support strain data needed for certification life predictions
  - Cargo to orbiter trunion dynamics and loads
  - Micro Strain Gauge Unit (Micro-SGU) and Micro Tri-Axial Accelerometer Units (Micro-TAU)

• **SSME Feed-Line Crack Investigation**
  - Main propulsion system flow-liner dynamics
  - Wide-Band Micro-TAU

• **Wing Leading Edge Impact Detection**
  - Sense impact of ascent debris and MMOD on-orbit
  - Enhanced Wide-Band Micro-TAU (EWBMTAU)

• **SRMS On-Orbit Loads**
  - Increases needed to support contingency crew EVA repairs at end of boom
  - Wireless Strain Gauge Instrumentation System (WSGIS) and EWBMTAU
  - Also used for monitoring Shuttle Forward Nose dynamics during roll-out
Current accelerometer count on ISS is 81 (SDMS: 33  EWIS: 30  IWIS: 18).
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    • System Development
    • Ground / Flight Applications
Distributed Impact Detection System Concept

- Original DIDS concept is to detect and locate impacts via a wireless sensors system.

DIDS System Concept

- Module is asleep until event signal threshold is crossed.
- Sensor module can record four signals at 1MHz rate.
- Sensors can record and transmit ~6000 events.
- Batteries can last up to 5 years.
- Laptop computer can control multiple units.

- Current DIDS system concept is to detect leak locations on space vehicles.

MMOD strike example
ISS Ultrasonic Background Noise Test (UBNT) System Overview

- In order to detect leaks, the amplitude of the ultrasonic background noise levels is required.

**System Overview**

- **910Mhz**
- **DIDS**
  - **Sensor Cable**
    - Length: 2 Meters
    - SMA connector
    - Teflon jacket
    - Kynar heat shrink
- **DIDS Power Supply**
  - WLE L91 Battery Pack
  - 2 – Energizer L91 AA batteries
  - 3.0 VDC output (nominal)

**Diagram Illustrates**
- JSL File Server
- OCA/Ground
- Principal Investigator (LaRC)
- Power supply and DIDS sensor units attached to ISS Module pressure wall using velcro.
- AE sensors attached using pre-certified adhesives.

**NOTE:** Diagram illustrates system configuration by ISS Module. No more than 7 DIDS sensor units will be used in any ISS Module.
Crew laptop on ISS

DIDS Wireless Receiver tethered to crew laptop

DIDS Wireless Sensor Units

Note: All Sensor hardware is Internal
Data recorded on Dec. 12, 2012. Twenty-four hour data take.
Photo of Behind the Rack of USLab105 with UBNT Sensors Installed

Installed during Feb, 2013 by Chris Hadfield (shown)
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Fiber Bragg Grating (FBG)
Optical Frequency Domain Reflectometry (OFDR)

FBG-OFDR can dramatically improve structural and system efficiency for space vehicle applications by improving both affordability and capability by …

- Providing >100x the number measurements at 1/100 the total sensor weight
- Providing validated structural design data that enables future launch systems to be lighter and more structurally efficient
- Reducing data system integration time and cost by utilizing a single small system for space / launch vehicles
- Increasing capability of measuring multiple parameters in real time (strain, temperature, liquid level, shape, applied loads, stress, mode shapes, natural frequencies, buckling modes, etc.
- Providing an unprecedented understanding about system/structural performance throughout space craft and mission life cycle
Fiber Optic Sensing System (FOSS)
Operation Overview

Fiber Optic Sensing with Fiber Bragg Gratings
- Multiplex 1000s of sensors onto one “hair-like” optical fiber
- All gratings are written at the same wavelength
- Uses a narrowband wavelength swept laser source to interrogate sensors
- In addition to measuring strain and temperature, these sensors can be used to determine a variety of other engineering parameters

\[ I_R = \sum_i R_i \cos(k2nL_i) \]
\[ k = \frac{2\pi}{\lambda} \quad \frac{\Delta\lambda}{\lambda} \rightarrow \mu\varepsilon \]

- \( R_i \) – spectrum of \( i^{th} \) grating
- \( n \) – effective index
- \( L \) – path difference
- \( k \) – wavenumber
Dryden’s FOSS
Current Capabilities

Current system specifications

- Fiber count: 8
- Max sensing length / fiber: 80 ft
- Max sensors / fiber: 4000
- Total sensors / system: 32,000
- Max sample rate (flight): 100 sps
- Max sample rate (ground): 100 sps
- Power (flight): 28VDC @ 4.5 Amps
- Power (ground): 110 VAC
- User Interface: Ethernet
- Weight (flight, non-optimized): 27 lbs
- Weight (ground, non-optimized): 20 lbs
- Size (flight, non-optimized): 7.5 x 13 x 13 in
- Size (ground, non-optimized): 7 x 12 x 11 in

Environmental qualification specifications for flight system

- Shock: 8g
- Vibration: 1.1 g-peak sinusoidal curve
- Altitude: 60kft at -56C for 60 min
- Temperature: -56 < T < 40C
SHM Aerospace Vehicle Applications

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Uninhabited Aerial Vehicles
Global Observer UAS - Aerovironment

- Proof-load testing of components and large-scale structures
Uninhabited Aerial Vehicles
Global Observer UAS - Aerovironment

- Validate strain predictions along the wingspan
- Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.
- FO Strain distribution measurements are being used to interpret shape using Dryden’s 2D shape algorithm
- A 24-fiber system was designed of which 18, 40ft fibers (~17,200 gratings) were used to instrument both left and right wings
Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.
**UAVs - Global Observer UAS (AV)**

*Flight Testing of Strain and 2D Shape Sensing*

- Validate strain predictions along the left wing in flight using 8, 40ft fibers (~8000 strain sensors)
- An aft fuselage surface fiber was installed to monitor fuselage and tail movement
- Strain distribution were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.
- 8 of the 9 total fibers are attached to the system at any given time
- The system performed well and rendered good results
**Predator-B UAS - Flight Testing**

**Strain and 2D Shape Sensing**

- 18 flights tests conducted; 36 flight-hours logged
- Conducted first flight validation testing April 28, 2008
- Believed to be the first flight validation test of FBG strain and wing shape sensing
- Multiple flight maneuvers performed
- Total of 6 fibers (~3000 strain sensors) installed on left and right wings
- Fiber optic and conventional strain gages show excellent agreement
- FBG system performed well throughout entire flight program

Video clip of flight data superimposed on Ikhana photograph
ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$E_{11}, \text{GPa}$</td>
<td>$5.54 \times 10^1$</td>
<td>$1.19 \times 10^2$</td>
<td>$8.50 \times 10^{-2}$</td>
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<tr>
<td>$E_{22}, \text{GPa}$</td>
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<tr>
<td>$G_{12}, \text{GPa}$</td>
<td>$4.21 \times 10^0$</td>
<td>$4.21 \times 10^0$</td>
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<tr>
<td>$v_{12}$</td>
<td>$3.00 \times 10^{-2}$</td>
<td>$3.10 \times 10^{-1}$</td>
<td>$3.20 \times 10^{-1}$</td>
</tr>
<tr>
<td>$\rho, \text{kg/m}^3$</td>
<td>$1.49 \times 10^3$</td>
<td>$1.52 \times 10^3$</td>
<td>$4.95 \times 10^{-1}$</td>
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</tbody>
</table>
Full-Scale Composite Wings
Strain, Applied Loads, and 2D Shape - Mississippi State

Test Procedure for displacement
• Collect FBG strain data
• Use displacement Eq. and Strain data to calculate deflection

Test procedure for out-of-plane loads
• Determine EI for the wing
• Determine moment acting on wing
• Determine Load applied

<table>
<thead>
<tr>
<th>Applied Load, N</th>
<th>Calculated Load, N</th>
<th>Error, %</th>
<th>Difference, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>-185.5</td>
<td>-178.8</td>
<td>3.60</td>
<td>6.7</td>
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<tr>
<td>-194.4</td>
<td>-210.0</td>
<td>7.98</td>
<td>15.5</td>
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<tr>
<td>-241.5</td>
<td>-252.0</td>
<td>4.35</td>
<td>10.5</td>
</tr>
<tr>
<td>-288.5</td>
<td>-291.5</td>
<td>1.05</td>
<td>3.0</td>
</tr>
<tr>
<td>-333.3</td>
<td>-332.9</td>
<td>0.12</td>
<td>0.4</td>
</tr>
<tr>
<td>-378.1</td>
<td>-381.1</td>
<td>0.80</td>
<td>3.0</td>
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<tr>
<td>-422.9</td>
<td>-435.9</td>
<td>3.07</td>
<td>13.0</td>
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<tr>
<td>-472.2</td>
<td>-486.4</td>
<td>3.01</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Average EI=98728.2-N*m²
SHM Aerospace Vehicle Applications

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- Launch Vehicles
Monitoring of MMOD Impact Damage to TPS
NASA Dryden / CSIRO Australia collaboration

Objective

- Detect & evaluate Micrometeoroid and Orbital Debris (MMOD) impact damage to Thermal Protection Systems (TPS) using embedded acoustic and thermal sensor networks

Principles

- Detect and locate impacts using acoustic emission sensor networks
- Evaluate severity of damage with optical fiber thermal sensor network
- Utilize centralised or self-organising operation with local network architecture on modular tiled structure

Novel aspects

- Development of switched optical fiber sensor network to enhance robustness
- Capable of central control or autonomous self-organising operation.
- Functional damage evaluation – monitor effect on thermal properties.
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SHM Aerospace Vehicle Applications
Vehicle Pressure Systems

Embedded Strain - The Multidisciplinary Challenge

- Fiber Optic Sensors embedded within Composite Overwrapped Pressure Vessels
- Goal is to understand embedded FBG sensor response
  - Requires comprehensive, multi-disciplinary approach

Sensors
- Reliability
- Characterize
- EFPIs

Mechanics
- Strain states
- Strain transfer

Composites
- Lay-ups
- Residual Strains
- Cross-ply Cracks

System
- Quality – Accuracy, precision
- Quantity – Speed, multiplexing
- Software, hardware

Optics
- Wave propagation
- FBG theory
- Optical anisotropy
Vehicle Pressure Systems

Composite Overwrapped Pressure Vessels (COPVs)

Objectives

• Perform real-time in-situ structural monitoring of COPVs with embedded fiber Bragg grating sensor arrays
• Develop analytical and experimental methods to reliably interpret embedded strain sensor measurements
• Develop a robust “early-warning” indicator of COPV catastrophic failure
• Provide finite-element-like experimental strains in real time for:
  – Health Monitoring on International Space Station
  – Model validation to improve future designs

Approach

• Develop and evaluate surface-attachment techniques
• Install surface fiber optic sensors
• Conduct test to 80% of burst pressure
• Overwrap surface FBGs with composite layers
• Install new surface FBGs over “embedded” FBGs
• Conduct burst test
• Develop data analysis and visualization techniques to reliably predict COPV failure

NASA Dryden and WSTF test team
Composite Overwrapped Pressure Vessels
Installation Methods

Installation methods developed

- Transfer pattern to bottle surface
- Mask and fill basecoat paths
- Sand down close to surface layer
- Route and attach FBGs
Embedded Fiber to 5000 psi
Hoop Direction
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NASA Structural Health Monitoring Technology
FOSS Current and Future Work
Flight Demonstration on a Launch Vehicle (KSC-Launch Services)

TPS Health Monitoring
Embedded Strain
Magnetic Field
Applied Loads
Strain
Temperature and Cryogenic Liquid Level
2D Shape
3D Shape
Cryogenic Liquid Level-Sensing

The Challenge

- The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements.
- Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level along with high wire count.

FOSS Approach

- While using a uniquely developed fiber optic structure (CryoFOSS), the transitional phase can be mapped more accurately.
- Using a single continuous grating fiber, a high degree of spatial resolution can be achieved, as low as 1/16”
**LH₂ Testing of CryoFOSS at MSFC**

**Objective**
- Experimentally validate CryoFOSS using Dryden’s FOSS technology

**Test Details**
- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of 20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope with a ruler (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH₂ liquid level sensor (CryoFOSS)

**Results**
- CryoFOSS sensor discerned LH₂ level to ¼” in every case
- Excellent agreement achieved between CryoFOSS, boroscope, and silicon diode Cryotracker

**Bottom line**
- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for ground and in-flight cryogenic fluid management systems
LH$_2$ Liquid Level Results

Combined Results

CryoFOSS compared to Boroscope
Solving the Challenge of Flexible Dynamics

- Improved flight performance
- Stretching tanks?
- Improved launch availability
- The ability to validate structural dynamics?
- Want to drop those expensive body bending sensors?
- FBG sensor technology:
  - Large number of sensors
  - Very small weight penalty
  - Insensitive to EM noise
  - High update rate (1 KHz non-multiplexed)

Opportunities for real time estimation and control created by novel FBG interrogation technology
FOSS Current and Future Work
Flight Demonstration on a Launch Vehicle (KSC-Launch Services)

- TPS Health Monitoring
- Embedded Strain
- Magnetic Field
- Applied Loads
- Strain
- Temperature and Cryogenic Liquid Level
- 2D Shape
- 3D Shape
Anticipated Impact of Fiber Optic based SHM

• Potential to revolutionize aerospace design and performance throughout the vehicle life-cycle
  – Design and development
  – Fabrication
  – Test and Evaluation
  – In-flight operation
  – Off-nominal flight
  – End of life-cycle decisions
Future work: Small UAS Flight System

Current system specifications

- Fiber count: 4
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 1000
- Total sensors / system: 4000
- Max sample rate (flight): 100 sps
- Power (flight): 28VDC @ 2 Amps
- User Interface: Ethernet
- Weight: 5 lbs
- Size: 3 x 5 x 11in

sUAS Research Vehicle

2000 FBG Strain Sensors

sUAS Flight System

sUAS in Flight
Questions?