NASA Applications of Structural Health Monitoring Technology

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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
SHM Aerospace Vehicle Applications

NASA Structural Health Monitoring Technology

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

SHM Aerospace Vehicle Applications
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)

[Diagram of Space Shuttle Orbiter with wing leading edge and sensor units]
Wing Leading Edge Impact Detection System (WLEIDS) Development

- Columbia accident investigation testing
  - Recovery of DFI sensor data on MADS focused impact testing on RCC
- Additional impact testing
  - Ascent impacts
  - MMOD impacts
- Vehicle testing
- System development and implementation
- Flight results
Columbia Accident Investigation

Catastrophic Impact Damage Test on RCC Panel 8

July 7, 2003

Acoustic Emission Sensor Data

Impact on Panel #8: Broken Panel

Air Blast Test Accelerations

Acoustic Emission Sensor Data

Peak g's
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
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  - **Wireless-based SHM on ISS / STS (Studor, JSC)**
  - 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>Purpose</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>Dimensions</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>
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<tr>
<td>Sample Rate</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>
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<tr>
<td>Data Storage</td>
<td>None</td>
<td>2Mbytes</td>
<td>1Mbyte</td>
<td>256Mbytes</td>
<td>256Mbytes</td>
<td>1Gbyte</td>
</tr>
<tr>
<td>Battery Life</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>Sensor Types</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>
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<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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    - Sensor Attachment / Characterization
    - System Development
    - Ground / Flight Applications
• 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.
**ISS Ultrasonic Background Noise Test (UBNT)**

**System Overview**

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

**Digital Wave - Piezoelectric AE Sensor**
- Model B-225.5
- Frequency bandwidth: 50kHz - 400kHz
- Temperature range: -50°C to +100°C
- Dimensions: 0.625” diameter. x 0.8” H
- Connector type: Microdot

**Sensor Cable**
- Length: 2 Meters

**Antenna/Data 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)

**DIDS Receiver**
- Connected to SSC via USB

**JSL File Server**

**OCA/Ground**

**Principal Investigator (LaRC)**

System is on orbit in the ISS awaiting astronaut time for installation

NOTE: Diagram illustrates system configuration by ISS Module. No more than 7 DIDS sensor units will be used in any ISS Module.
Example of installation behind ISS equipment ramp

(Fit Check in B9 US Lab Mockup)

- DIDS unit installed in open rack in mockup
- UBNT Extended Antenna in ISS hallway
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    • Expendable Launch Vehicles
Fiber Optic Sensing System (FOSS)  
Background

• Dryden initiated fiber-optic instrumentation development effort in the mid-90’s
  – Dryden effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique

• Dryden focused on developing system suitable for flight applications
  – Previous system was limited due to laser technology
  – System limited to 1 sample every 90 seconds

• Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight

• Partnering with Kennedy Space Center, Launch Services Program, Dryden has developed a comprehensive portfolio of intellectual property that is now ready to be commercialized by the private sector.
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

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

- \( I_R \) – 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: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate (flight): 100 sps
- Max sample rate (ground): 60 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
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
Composite Crew Module
NASA NESC - Strain Sensing

• Four fibers were installed around the module’s three windows and one hatch

• 3300 real-time strain measurements were collected at 30Hz as the module underwent 200% DLL pressurization testing

• Measured strains were compared and matched well to predicted model results

• Project concluded:
  • “Fiber optics real-time monitoring of test results against analytical predictions was essential in the success of the full-scale test program.”
  • “In areas of high strain gradients these techniques were invaluable.”
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
Uninhabited Aerial Vehicles
Global Observer UAS - Aerovironment

- Proof-load testing of components and large-scale structures
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 give 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

[Image: Video clip of flight data superimposed on Ikhana photograph]
**ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.**

<table>
<thead>
<tr>
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<tr>
<td>$E_{11}$, GPa</td>
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<tr>
<td>$\nu_{12}$</td>
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<td>$3.20 \times 10^{-1}$</td>
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<tr>
<td>$\rho$, 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>
</tr>
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</table>
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
Personal Observations

- The Shuttle never returned in the same condition as when it launched.
- Flight operations always reveals the unexpected and make known the unknowns.
- NASA's SHM fiber optic sensors are much lighter than conventional strain gage sensors.
- FOSS-OFDR provides massive amounts of quantitative structural performance information in real time and for post test analysis.
- This quantitative information can overcome some of the unknown unknowns that may allow you to fly another day.
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.
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
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
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

- Strain (με) vs. TT (sec)
- H_5 and H_7
- 0°, 90°, 180°, 270°
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

National Aeronautics and Space Administration
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 coarse 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)
  - Cryotracker (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
Magnetic Field Sensing
NASA Dryden / UCLA collaboration

Objective
- To utilize the same magnetically sensitive particles that birds use, for example, to sense Earth’s magnetic field for migratory purposes

Application
- Installing distributed magnetic sensors on a structure could help with navigation
- Identifying disturbances in Earth’s magnetic field could indicate the presence of another vehicle or a missile

Approach
- Fabricate new fiber optic sensor with greater sensitivity to magnetic field (H)
- Apply magnetic field to sensors
- Measure wavelength shifts ($\Delta \lambda_B$)
- Behavior of $\lambda_B$ should follow magnetization behavior of modified sensor

Results
- Experimental results corroborate the theory
- Currently developing new methods for increasing sensitivity of detecting magnetic fields