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
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)
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
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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  – 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” x 2.2” x 1.2”</td>
<td>2.7” x 2.2” x 1.2”</td>
<td>3.0” x 2.5” x 1.5”</td>
<td>3.25” x 2.75” x 1.5”</td>
<td>3.4” x 2.5” 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>
</tr>
<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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    • 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
Crew laptop on ISS
Server
DIDS Wireless
Sensor Units
tethered to crew laptop

Note: All Sensor hardware is Internal
ISS Ultrasonic Background Noise Test (UBNT) System Overview

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

**System is on orbit in the ISS awaiting astronaut time for installation**
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
SHM Aerospace Vehicle Applications

NASA Structural Health Monitoring Technology

Launch Vehicles

Space Shuttle

International Space Station

Composite Crew Module

Vehicle Pressure Systems

Reentry Vehicles

Space Vehicles

UAVs
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

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

R\textsubscript{i} – spectrum of \textit{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
• 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.”

![Composite Crew Module](image)

### Inner Hatch FBG Strains, Max Pressure

-2000 0 2000 4000

- FBG  Predicted

Microstrain (μin/in)

24
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

Video clip of flight data superimposed on Ikhana photograph
# Full-Scale Composite Wings

Strain, Applied Loads, and 2D Shape - Mississippi State

## Engineering Properties of Composite Materials

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Woven fabric</th>
<th>Unidirectional fabric</th>
<th>Foam core DIAB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toray-T700G</td>
<td>Toray-T700S</td>
<td>Divinycell HT 50</td>
</tr>
<tr>
<td>$E_{11}$, GPa</td>
<td>$5.54 \times 10^1$</td>
<td>$1.19 \times 10^2$</td>
<td>$8.50 \times 10^{-2}$</td>
</tr>
<tr>
<td>$E_{22}$, GPa</td>
<td>$5.54 \times 10^1$</td>
<td>$9.31 \times 10^0$</td>
<td>--</td>
</tr>
<tr>
<td>$G_{12}$, GPa</td>
<td>$4.21 \times 10^0$</td>
<td>$4.21 \times 10^0$</td>
<td>--</td>
</tr>
<tr>
<td>$\nu_{12}$</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>$\rho$, 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>
</tbody>
</table>
Full-Scale Composite Wings
Strain, Applied Loads, and 2D Shape - Mississippi State

MEASURED AND CALCULATED WING TIP DEFLECTIONS

<table>
<thead>
<tr>
<th>F, N</th>
<th>Measured δ L, m</th>
<th>Calculated δ L, m</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1373</td>
<td>-0.184</td>
<td>-0.178</td>
<td>3.02</td>
</tr>
<tr>
<td>1592</td>
<td>-0.209</td>
<td>-0.205</td>
<td>2.29</td>
</tr>
<tr>
<td>1837</td>
<td>-0.241</td>
<td>-0.231</td>
<td>4.08</td>
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<tr>
<td>2036</td>
<td>-0.265</td>
<td>-0.257</td>
<td>3.23</td>
</tr>
<tr>
<td>2269</td>
<td>-0.295</td>
<td>-0.284</td>
<td>3.75</td>
</tr>
</tbody>
</table>

OUT-OF-PLANE APPLIED LOAD

<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>
</tr>
<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>
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<tr>
<td>-333.3</td>
<td>-332.9</td>
<td>0.12</td>
<td>0.4</td>
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<tr>
<td>-378.1</td>
<td>-381.1</td>
<td>0.80</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>

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

Average EI=98728.2-N*m²
Next Generation Structural Health Monitoring on Reentry Vehicles

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

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

Strain (με)

TT (sec)

F1eG161
F1eG174
F1eG187
F1eG201

F1eG343
F1eG356
F1eG369
F1eG382

0°
90°
180°
270°

H_5
H_7
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”.

1st Gen CryoFOSS Test Results

Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)

Cryogenic Rake w/ silicon diodes & FOSS fiber

Liquid level

CryoFOSS Fiber

Silicon Diode
**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
LH₂ Liquid Level Results

Combined Results

CryoFOSS compared to Boroscope
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