Fiber Optic Sensing System (FOSS) Technology

A New Sensor Paradigm for Comprehensive Structural Monitoring and Model Validation throughout the Vehicle Life-Cycle

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NASA Armstrong Flight Research Center
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# The FOSS Team

<table>
<thead>
<tr>
<th>Team member</th>
<th>Field</th>
<th>Contributions to FOSS</th>
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</thead>
<tbody>
<tr>
<td>Patrick Chan</td>
<td>Optics Engineer</td>
<td>Optics Development, laser research and development</td>
</tr>
<tr>
<td>Philip Hamory</td>
<td>Electrical Engineer</td>
<td>Advanced System Algorithm Development</td>
</tr>
<tr>
<td>Francisco Pena</td>
<td>Structures Engineer</td>
<td>Structural Test and Analysis</td>
</tr>
<tr>
<td>Allen Parker</td>
<td>Electrical Engineer</td>
<td>Systems design &amp; development, data processing and visualization</td>
</tr>
<tr>
<td>Anthony Piazza</td>
<td>Instrumentation Specialist</td>
<td>Sensor characterization, application, &amp; interpretation</td>
</tr>
<tr>
<td>Lance Richards</td>
<td>Structures Engineer</td>
<td>Aircraft structures, strain measurement research</td>
</tr>
</tbody>
</table>
AFRC Structures Test and Analysis

Structural Test and Analysis Products

- **Experimental methods**
  - Structural testing from coupon, subcomponent, component, qual-unit, flight component, full vehicle (for aircraft of all Mach no’s, launch vehicles, spacecraft applications)
  - Ground testing (structural labs, wind tunnels, cryogenic labs)
  - Flight testing
  - Mechanical: Load frames, custom designed test setups, load introduction hardware, restraints, Thermal: high & low temperature (radiant quartz lamps and cryogenic cooling, resp)
  - Aero

- **Structural measurement methods**
  - Strain (stress), temperature, displacement, load, heat flux, discrete, full-field
  - Strain gage technology, fiber optic sensors, load cells, LVDTs, potentiometers, TCs, digital image correlation, thermal imaging, Interferometry, Moire,
  - Experimental Stress Analysis, measurement uncertainty (temperature compensation methods)
  - Correlation of experimental / analytical results
  - Collaborate with analysts to correlate experimental results with analytical predictions

- **Analytical, computational, empirical**
  - Pre-test, pre-flight predictions
  - Validated structural analysis from coupon, subcomponent, component, qual-unit, flight component, full vehicle (for aircraft of all Mach no’s, launch vehicles, spacecraft applications)
  - Collaborate with experimentalists to correlate real-time structural monitoring (comparison of structural performance vs analytical predictions)
  - Post-test, post flight, correlation of analytical/experimental results
    - Tuning of B/Cs, mat props, loads (mech/thermal, i.e applying measured data to analysis models)
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
SHM
Materials
NDE
Background and Inspiration
Biological Inspiration of Fiber Optic Smart Structures

One Square-Inch of Human Skin

- Four yards of nerve fibers
- 600 pain sensors
- 1300 nerve cells
- 9000 nerve endings
- 36 heat sensors
- 75 pressure sensors
- 100 sweat glands
- 3 million cells
- 3 yards of blood vessels

<table>
<thead>
<tr>
<th>Smart Structure</th>
<th>Human Body</th>
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<td>Fiber Optic Sensors</td>
<td>Pain, temp, pressure sensors</td>
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<tr>
<td>Piezo’s, SMAs</td>
<td>Muscles</td>
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<tr>
<td>IVHM, Smart Systems</td>
<td>Brain</td>
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</tbody>
</table>

Courtesy: Airbus
Why Fiber Optic Sensors?
One Of These Things (is Not Like The Others)
Fiber Optic Sensing with Fiber Bragg Gratings

- Immune to electromagnetic / radio-frequency interference and radiation
- Lightweight fiber-optic sensing approach having the potential of embedment into structures
- Multiplex 100s of sensors onto one optical fiber
- Fiber gratings are written at the same wavelength
- Uses a narrowband wavelength tunable laser source to interrogate sensors
- Typically easier to install than conventional strain sensors
- In addition to measuring strain and temperature these sensors can be used to determine shape

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

- \( R_i \) – spectrum of \( i \)th grating
- \( n \) – effective index
- \( L \) – path difference
- \( k \) – wavenumber

Diagram:
- Laser light
- Reflective light (\( I_R \))
- Grating region
- Loss light
How it Works: FBG OFDR Overview

Tunable Laser

1548 to 1552nm

Perform FFT

Perform Windowing

Signal Conditioning and A/D

S/C

A/D

Perform iFFT

Filtering and Centroid

Wavelength Domain

Length Domain

Centroid to Strain Conversion

Length Domain

Wavelength Domain
Armstrong’s FOSS Technology
Current Capabilities

Current system specifications

- Fiber count: 16
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 32000
- 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
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, temp., accel, 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
FOSS Advantages to Conventional Strain Measurements

- Unrivaled spatial density of sensors for full-field measurements
- Measurements immune to EMI, RFI and radiation
- Lightweight sensors
  - Typical installation is 0.1 - 1% the weight of conventional gage installations (based on past trade studies)
  - 1000’s of sensors on a single fiber (up to 80 feet per fiber)
  - No copper wires
- With uniquely developed algorithms, these sensors can determine deformed shape and loads at points along the fiber for real-time feedback
- Great in high strain and fatigue environments
- Small fiber diameter
  - Approximately the diameter of a human hair
  - Unobtrusive installation
  - Fibers can be bonded externally or applied as a ‘Smart Layer’ top ply
- Single calibration value for an entire lot of fiber
- Wide temperature range
  - Cryogenic up to 500°F
  - Very linear thermal compensation

Wire for 21 strain gage measurements
Fiber for 628 FOSS sensors

Fiber optic strain sensors
Fiber optic temperature sensors
Strain gage
Fiber optic strain sensors

Strain sensor comparison
FOSS Sensor Technology Comparison

- Stresses
- Operational Loads
- Strains
- Fatigue Life
- Crack Growth
- Natural Frequencies and Mode Shapes
- Pressure
- Buckling Modes and Shapes
- 2-D Shape
- Operational Loads

FOSS
Fiber Optic Sensing Applications

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

Fiber Optic Sensing System (FOSS) Core Technology
Strain Sensing Applications
Composite Overwrapped Pressure Vessel (COPV)
Sensor Mapping – Surface Mounted Fiber

530 Surface strain measurements
COPV Stiffness / Pressure Monitoring, Individual Sensor

\[ \frac{\varepsilon_i}{P} = \left( \frac{D}{n_i t} \right) \cdot \left( \frac{1}{E_i} \right) \]

Fiber line #8, FBG #97, Micro-strain & Pressure (psi) Vs. Time

Fiber line #8, FBG #97, Micro-strain Vs. Pressure (psi)

COPV Stiffness / Pressure Monitoring

- Expands previous studies performed by the Armstrong NNWG on the structural health monitoring techniques
  - Implementation of real-time finite-element-like fringe plots
  - Further studies into stiffness/pressure monitoring as SHM parameter

Simulated Shield MMOD Testing with Fiber Optic Sensors

Utilize Fiber Optic Sensors on a simulated MMOD shield structure to monitor the response to hypervelocity impacts.

Use Fiber Optic Sensors to determine:
1. If an impact occurred
2. When did the event occur
3. Where did the impact occur
4. Quantify Damage

Fiber Optic Routing and Location of Sensors (as seen from back of plate)

A NASA New Technology Report (NTR) has been filed for the MMOD detection method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Fiber Optic Sensing System Subject Matter Experts for more information.
**MMOD Impact Detection (Target 1)**

**Target 1**
- Projectile Diameter: 0.99mm
- Projectile mass: 0.0014g
- Projectile Velocity: 7,100 m/s

Use Fiber Optic Sensors to determine:
1. If an impact occurred
2. When did the event occur
3. Where did the impact occur
4. Quantify Damage

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**Target 2**
- Projectile Diameter: 0.49mm
- Projectile mass: 0.00017g
- Projectile Velocity: 6,980 m/s

Use Fiber Optic Sensors to determine:
1. If an impact occurred
2. When did the event occur
3. Where did the impact occur
4. Quantify Damage

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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.”
In-Flight Strain Sensing
Small Scaled UAV

- Four Fibers were installed on the aircraft wings on top and bottom of the Left and Right wing
- 2000 time strain measurements were collected at 20Hz during flight
**Current Project:**

**NESC Shell Buckling Knockdown Factor (SBKF)**

<table>
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<tr>
<th>0°</th>
<th>45°</th>
<th>90°</th>
<th>135°</th>
<th>180°</th>
</tr>
</thead>
</table>

- 8 ft

- In 35 feet
Current Project:
Shell Buckling Knockdown Factor (SBKF)

- FOSS Install goals
- Fibers installed on OML and IML surface
- Each fiber near 40 foot long
- FOSS rosette near each bolt interface plus a second rosette halfway between two bolts
- Nearly continuous axial measurements every 45° from top to bottom
- Five nearly continuous hoop measurements around the circumference of the cylinder
- No interference with existing conventional strain gage locations
Current Project:
Shell Buckling Knockdown Factor (SBKF)

- Rosettes are installed in critically loaded areas
- Principle strain orientation and magnitude can be determined
- Distributed strain measurements could be used to verify proper load introduction into the test article
Shape Sensing Applications
Two Strain-Based Deflection Methods

2D Shape Sensing Method
- Uses structural strains to get deflection in one direction
- Fibers on top and bottom surface of a structure (e.g. wing)

3D Shape Sensing Method
- Uses strains on a cylindrical structure to get 3D deflections
- 3 fibers 120 apart on a structure or a lumen
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.
3D Shape Sensing
Prototype Quiet Spike Testing

- Fibers are installed on the prototype of 35ft quiet spike at Gulfstream in Savannah GA.

- Performed tests to determine benefits of deploying FOSS on Low Boom Experimental Vehicle.

- Installed a total of 5 fibers measuring strain at ½” increments (2,570 strain sensors).

- Deflection shape of the Quiet Spike evaluated through the 3D shape algorithm.
Laser measured deflection (solid) vs. calculated deflection based on 3D shape algorithm (dotted)
• Real-time algorithms enable vertical deflection and twist to be obtained from distributed strain measurements
• LabVIEW user interface allows the user to visualize an estimate of the full filed deformation
• A digital inclinometer is used to verify twist estimates

A NASA New Technology Report (NTR) has been filed for the Twist Sensing Method described in this technical presentation and is therefore patent protected. Those interested in using the method should contact the NASA Technology Transfer Program Office at NASA Armstrong Flight Research Center for more information.
Load Sensing
Loads Calibration with conventional strain gage technology

Loads calibrations on A/C wings with conventional strain gages have been successfully performed for over 50 years

- Skopinsky and Aiken Loads Calibration Method allows engineers to obtain:
  - Lift or Shear Force
  - Bending Moment
  - Pitching Moment or Torque

Typical Conventional Loads Calibration requires:

- Dozens of metallic strain gages
  - One sensor per channel
  - Installed on interior load bearing structure of wing
  - Wing skins need to be removed
  - Installation time of approx. 4 to 8 hours per sensor
  - Finite point measurements

- Removal of ground-test-specific instrumentation prior to flight
  - Bulky sensor size restricts the use in high lift regions

- 16 channels of load actuators
  - Application of an array of mechanical loads to determine bending and torsional stiffness properties

- Limited Span-wise load sensing capabilities
Investigations of Fiber Optic Sensing System (FOSS) for Distributed Load Calibration Methodology

Technical Challenge:
- Future projects require a method for monitoring the load distribution within aerospace structures
- Instrumentation weight and installation time of conventional strain gages limit the ability to monitor and control distributed loads within aerospace structures

Current State-of-the-Art:
- Fiber optic strain sensing (FOSS) technology is transitioning to an airworthy alternative to conventional strain gages and will change the approach to aircraft loads calibrations
- FOSS will open up new opportunities to monitor and facilitate control of future launch vehicles

Potential Applications:
- Improved understanding of distributed aerodynamic loading
- Optimized process for aircraft structural loads calibrations for monitoring and controlling flexible, high aspect ratio wings and rocket bodies
- A detailed understanding of the span-wise load distribution will be required for optimizing the aerodynamic performance of future aerospace structures
Aircraft Vehicle Load Control

- **cFOSS 1.0 sUAS Flight system specifications (Convection)**
  - 4 Fiber system
  - Total sensors: 4000
  - Sample rate (max) 100 sps
  - Weight 5 lbs
  - Size 3 x 5 x 11in

- **Autonomously Piloted Vehicle 3 (APV3)**
  - Span: 12 ft
  - Max Takeoff Weight: 55 lbs
  - 22 control surfaces per wing
  - 2,000 fiber optic strain sensors on wings (top and bottom surfaces)
APV3 Segmented Control Surfaces

- Segmented Control Surfaces (SCS) can be utilized to redistribute load in-board to reduce loads during high-g maneuvers.
- FOSS strain and/or deflection measurements could be used with a flight controller to provide load alleviation control.
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Operational Load Estimation Method
Trusses and Moment Frames

Moment Frame Test Article with FOSS
Real-time display of FOSS data
Solar Array and truss structure
Operational Load Estimation Method
Truss and Moment Frames

Cantilever Moment Diagram
Frame Moment Diagram
Measured Moment Diagram on Column (Showing Semi-Frame Behavior)
Operational Load Estimation Method
Truss and Moment Frames

Preliminary OLEM Test Results on Moment Frame Test Article

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<th>Test (#)</th>
<th>Actual Force (lbf)</th>
<th>Estimated Force (lbf)</th>
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<th>Calculated Location (in)</th>
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HyFOSS: What The Technology Does

- Hybrid fiber optic sensing system (HyFOSS) is a combination of two existing technologies both based on fiber Bragg gratings.
  - Technology #1: Wavelength Division Multiplexing (WDM) allows for high speed (kHz) acquisition speed but low number of gratings per fiber.
  - Technology #2: Optical Frequency Domain Reflectometry (OFDR) allows for high spatial resolution (1000s of grating) but inherently low sample rates (<100Hz).
- To combine the best of both technologies coupled on to the same fiber allows for high spatial resolution (lower sample rates) along the entire length of the fiber using OFDR as well as high sample rates at strategic points along the fiber using WDM.

Example hyFOSS fiber layout

- High speed WDM sensor
- OFDR ¼” Spatial Resolution
HyFOSS, Frequency Sweep Vibration Testing

Experimental setup
- Cantilever test article with discontinuous section properties.
- A Finite Element Model has been created to determine strain gage locations.
- Aluminum wing plate structure is excited by an electrodynamic shaker.
- 7 Accelerometers are mounted to the structure to monitor structure mode shapes.
- OFDR and WDM sensors (3) are bonded to the plate.
- Test article is 36 inches long and 12 inches wide.
HyFOSS Sensor Installation

- 100 Hz (OFDR)
- 5,000 Hz (WDM)
HyFOSS test – Fiber Optics & Accelerometer
Frequency Sweep 475 Hz to 525 Hz

High Speed Fiber Optics (5 kHz)

Accelerometers (8 kHz)
Finite Element Output & 100 Hz Fiber Optic Sensors

6.0 lbf

Span (in)
microstrain

Graph showing strain distribution across a span of the structure.
Dedicated High Speed Testing, Impact Test

36 High Speed Fiber Optic Sensors

1 lb.
Impact test, Strain Data time history

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Impact test, Accelerometer vs. High Speed Fiber Optics (5 modes) Test

\[ x = A_1 \cdot \sin(\omega_{n1} t + \phi_1) + A_2 \cdot \sin(\omega_{n2} t + \phi_2) \ldots \]
\[ \dot{x} = \omega_{n1} \cdot A_1 \cdot \cos(\omega_{n1} t + \phi_1) + \omega_{n2} \cdot A_2 \cdot \cos(\omega_{n2} t + \phi_2) \ldots \]
\[ \ddot{x} = -\omega_{n1}^2 \cdot A_1 \cdot \sin(\omega_{n1} t + \phi_1) - \omega_{n2}^2 \cdot A_2 \cdot \sin(\omega_{n2} t + \phi_2) \ldots \]

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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
Concluding Remarks

- **FOSS Benefits**
  - Provides >100x the number measurements at 1/100 the total sensor weight
  - Increases capability of measuring multiple parameters in real time (strain, temp., accel, liquid level, shape, applied loads, stress, mode shapes, natural frequencies, buckling modes, etc.)
  - Provides comprehensive datasets to validate loads / dynamics models

- **For most full-scale structural dynamics applications, FOSS sample rates (16,000 sensors at 100sps) are sufficient**

- **A single hybrid interrogation scheme that gleans the benefits of two different FBG sensing technologies, WDM and OFDR, has been developed and demonstrated**
  - OFDR acquires higher density FOSS measurements (16,000) and lower speed (100Hz)
  - WDM acquires FOSS measurements at higher speed (35kHz) and lower density (~80/fiber)

- **FOSS has the potential to “break the rules” for DFI; it can be used throughout loads/dynamics modeling effort (from ground to flight) by providing an unprecedented understanding about system/structural performance of LV/SC throughout the vehicle life cycle**
Extra Slides
Fiber Bragg Gratings (FBGs)

\[ \lambda_B = 2n_0 \Lambda \]
OFDR
WDM

Broad light Source

Detector

50:50

Sensing arm

Mirror

Compression | Tension

λ

Interference (Linear Scale) [Counts]

Wavelength (nm)

1516-1608
1520-1608
1524-1608
1528-1608
1532-1608
1536-1608
1540-1608
1544-1608
1548-1608
1552-1608
1556-1608
1560-1608
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