NASA Armstrong Flight Research Center (AFRC)
Fiber Optic Sensing System (FOSS) Technology

Lance Richards, Allen. R. Parker, Jr., Anthony Piazza,
Patrick Chan, Phil Hamory, and Frank Pena

NASA Armstrong Flight Research Center
Edwards, CA

Information Updated
November, 2014
# The FOSS Team

<table>
<thead>
<tr>
<th>Team member</th>
<th>Background/ experience</th>
<th>Contributions to Fiber Optics Team</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>Phil Hamory</td>
<td>Electrical Engineer</td>
<td>Advanced System Algorithm Development</td>
</tr>
<tr>
<td>Allen Parker</td>
<td>Electrical Engineer</td>
<td>Systems design &amp; development, data processing and visualization</td>
</tr>
<tr>
<td>Frank Pena</td>
<td>Structures Engineer</td>
<td>Mechanical design &amp; development, Structural Simulation and Testing</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</td>
</tr>
</tbody>
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Background

- AFRC initiated fiber-optic instrumentation development effort in the mid-90’s
  - AFRC effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique
- AFRC focused on developing system suitable for flight applications
  - Previous system was limited due to laser technology
  - System limited to 1 sample every 90 seconds
- AFRC initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight
- As a result, AFRC has developed a comprehensive portfolio of intellectual property that is now ready to be commercialized by the private sector.
Fiber Optic Sensor Advantages

- Advantages of FO sensors over conventional technology
  - Light weight
    - Increased payloads
    - Increased range
  - Serial multiplexibility
    - Full-field strain mapping
    - Reduced bundle sizes
    - Reduced time to install/troubleshoot
  - Small size (about the size of human hair)
  - Embeddable
    - Damage detection
    - Internal health assessment
  - Compatibility with telecom
  - No sparking, no ground loops
  - Chemically inert
  - No EMI or EMP
  - Wide application potential
Installation Advantages and Limitations

Installation Advantages

- Greatly reduced installation time compared to conventional strain gages
  - 2 man days for 40’ fiber (2000 strain sensors for a continuous surface run)
  - Multiple sensors installed simultaneously
  - Same surface preparation and adhesives as conventional strain gages
  - Minimal time spent working on vehicle
  - All connectors can be added prior to installation, away from part
  - No soldering, no clamping pressure required

- Can be installed on aerodynamic surfaces with little to no impact on performance

Installation Limitations

- Optical fiber more fragile than conventional strain gages

- Some measurement locations not practical due to fiber minimum bend radius

- Not practical if only interested in spot measurements

![Diagram showing installation process]
Strain Sensing – Ground System

Current Capabilities

Current system specifications

- Sensor Range: +/- 12,000 micro Strain
- Resolution: 2 micro Strain
- Accuracy: 5%
- Fiber count: 8
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate: 100 sps
- Power: 110 VAC
- User Interface: Ethernet
- Weight: ~20 lbs
- Size: 7 x 12 x 11 in
Strain Sensing – Flight System

Current Capabilities

Current system specifications

- Sensor Range: +/- 12,000 micro Strain
- Resolution: 2 micro Strain
- Accuracy: 5%
- Fiber count: 8
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate: 100 sps
- Power: 28VDC @ 4.5 Amps
- User Interface: Ethernet
- Weight: ~30 lbs
- Size: 7.5 x 13 x 13 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
Strain and Applied Loads
Aluminum Flat Plate Validation Testing

Applied Loads Results

Swept Plate - Uniform A Load Case - Mid Fiber

Moment (in-lbs)

Root → Tip

Span (in)
### Strain and Applied Loads

**Large-Scale Composite Wings - Mississippi State Univ**

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**ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.**

<table>
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<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>
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<td>$E_{22}$, GPa</td>
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<td>$\rho$, kg/m$^3$</td>
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<td>$4.95 \times 10^{-1}$</td>
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Strain Sensing
Composite Crew Module

• 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.”
Temperature Sensing
Current Capabilities

Current system specifications

- Sensor Range: -425 deg F to 550 deg F
- Resolution: 1 deg F
- Accuracy: 5%
- Fiber count: 8
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate: 100 sps
- Power: 110 VAC
- User Interface: Ethernet
- Weight: ~20 lbs
- Size: 7 x 12 x 11 in
Temperature Conversion

Test Notes
Eleven FO FBG’s, decoupled from substrate in polyimide tubes, were averaged to generate coefficient to convert strain to Fahrenheit.
2D Shape Sensing
Current Capabilities

Current system specifications
- Max sensing length / fiber: 40 ft
- Resolution: ~ ¼ in.
- Accuracy: 2%
- Max sensing fibers: 8
- Max sensors / fiber: 1000
- Total sensors / system: 8000
- Max sample rate: 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

Requires knowledge of the structures centroid
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)
MEASURED AND CALCULATED WING TIP DEFLECTIONS

<table>
<thead>
<tr>
<th>F, N</th>
<th>Measured δ₁, m</th>
<th>Calculated δ₁, m</th>
<th>Error, %</th>
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<tbody>
<tr>
<td>1373</td>
<td>-0.184</td>
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<td>1592</td>
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<td>2269</td>
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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>
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<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>
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<tr>
<td>-241.5</td>
<td>-252.0</td>
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<td>10.5</td>
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<tr>
<td>-288.5</td>
<td>-291.5</td>
<td>1.05</td>
<td>3.0</td>
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<td>-333.3</td>
<td>-332.9</td>
<td>0.12</td>
<td>0.4</td>
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<td>-378.1</td>
<td>-381.1</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
Strain and 2D Shape Sensing
Global Observer UAS

- 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 AFRC’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
Strain and 2D Shape Sensing
Global Observer UAS

- 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.
Strain and 2D Shape Sensing
Global Observer UAS - Flight Testing

- 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
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
3D Shape Sensing
Current Capabilities

Current system specifications

- Max sensing length / fiber: 40 ft
- Resolution: ~ ¼ in.
- Accuracy: 5%
- Max sensing fibers: 8
- Max sensors / fiber: 1000
- Total sensors / system: 8000
- Max sample rate: 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
3D Strain-Based Deflection Methods

3D Shape Sensing Method
• Uses strains on a cylindrical structure to get 3D deflections
• 3 fibers 120 deg apart on a structure or a lumen
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 determined 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
3D Shape Sensing

Quiet Spike Testing Results – lateral deflection

Laser measured deflection (solid) vs. calculated deflection based on 3D shape algorithm (dotted)
Liquid Level & Cryogenic Liquid Level Sensing
Current Capabilities

Current system specifications
• Max sensing length / fiber: 40 ft
• Resolution: ~¼ in.
• Accuracy: ~¼ in.
• Max sensing fibers: 8
• Max sensors / fiber: 2000
• Total sensors / system: 16000
• Max sample rate: 0.5 Hz
• Power: 110 VAC
• User Interface: Ethernet
• Weight: ~20 lbs
• Size: 7 x 12 x 11 in
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”.
**LH$_2$ Testing of CryoFOSS at MSFC**

**Objective**
- Experimentally validate CryoFOSS using AFRC’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 LH$_2$ liquid level sensor (CryoFOSS)

**Results**
- CryoFOSS sensor discerned LH$_2$ level to $\frac{1}{4}$” 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
hyFOSS
Current Capabilities

Current system specifications

- Sensor Range: +/- 12,000 micro Strain
- Resolution: 2 micro Strain
- Accuracy: 5%
- Fiber count: 8
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate: 100 sps
- Power: 110 VAC
- User Interface: Ethernet
- Weight: ~20 lbs
- Size: 7 x 12 x 11 in
Experimental setup

- 7 Accelerometers are mounted to the structure to monitor structure mode shapes
- OFDR and WDM sensors (3) are bonded to the plate
HyFOSS Sensor Installation

- 100 Hz (OFDR)
- 5,000 Hz (WDM)
HyFOSS Plate – WDM & Accelerometer
Frequency Sweep 475 Hz to 525 Hz
Evaluation & Licensing Opportunities

TPS Health Monitoring

Magnetic Field

Embedded Strain

Strain

Applied Loads

2D Shape

3D Shape

Temperature and Cryogenic Liquid Level

4DSP LLC
Contact Information

Technology Transfer Office
Armstrong Flight Research Center
P.O. Box 273 M/S 1100
Edwards, CA 93523-0273

General Office Inquiries:
Phone: (661) 276-3368

Technology or Licensing Inquiries:
Phone: (661) 276-5743

Email: DFRC-TTO@mail.nasa.gov
Fax: (661) 276-3001