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

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## The FOSS Team

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

- Step 1, Calculated
- Step 2, Calculated
- Step 3, Calculated
- Step 4, Calculated
- Step 5, Calculated
- Step 6, Calculated
- Step 7, Calculated
- Step 1 and 7, Actual
- Step 2 and 6, Actual
- Step 3 and 5, Actual
- Step 4, Actual

Root → Tip

Moment (in-lbs)

Span (in)
### ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

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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
**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
2D 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)
Strain, Applied Loads, and 2D Shape
Large-Scale Composite Wings - Mississippi State Univ.

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
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
Strain and 2D Shape Sensing
Predator-B UAS - Flight Testing

- 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: ~ \( \frac{1}{4} \) 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 -56°C for 60 min
- Temperature: -56 < T < 40°C
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
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
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 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”.
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
LH$_2$ 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
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- Max sample rate: 100 sps
- Power: 110 VAC
- User Interface: Ethernet
- Weight: ~20 lbs
- Size: 7 x 12 x 11 in

Continuous grated ¼” spaced sensors

High speed sensor

hyFOSS measurement sensor
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
- Applied Loads
- 2D Shape
- 3D Shape
- Temperature and Cryogenic Liquid Level
- 4DSP LLC
Contact Information

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