FIBER OPTICS SENSING SYSTEM (FOSS) AT NASA ARMSTRONG FLIGHT RESEARCH CENTER (AFRC): SUMMARY AND RECENT DEPLOYMENTS

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OUTLINE

• Motivation
• Traditional Strain Gauge vs Fiber Optics Sensors
• Technology overview of Fiber Optics Sensors
• FOSS technology review
• Development of FOSS at NASA
• Capabilities of FOSS
• Recent NASA projects involving FOSS
SENSORS IN A HUMAN BODY

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>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Optic Sensors</td>
<td>Pain, temp, pressure sensors</td>
</tr>
<tr>
<td>Piezo’s, SMAs</td>
<td>Muscles</td>
</tr>
<tr>
<td>IVHM, Smart Systems</td>
<td>Brain</td>
</tr>
</tbody>
</table>
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HOW TRADITIONAL STRAIN GAUGE WORKS

- Invented by Edward E. Simmons and Arthur C. Ruge in 1938
- As the object is deformed, the foil is deformed, causing its electrical resistance to change

\[
\text{Strain } (\varepsilon) = \frac{\Delta R}{\rho \cdot R_G}
\]

- \(\Delta R\) = change in resistance due to strain change
- \(R_G\) = Initial resistance of gauge
- \(\rho\) = gauge factor
### Pros/Cons of Resistive Strain Gauge

#### Advantage
- Industry Proven
- High sample rate available (kHz to MHz) for dynamic response

#### Disadvantage
- Each gauge has unique gauge factor
- No Multiplexing available
- Susceptible to EMI (Electromagnetic Interference)
- Lead Wire Resistance effect
- Installation time
- Temperature Compensation
- 1 A/D card to interrogate 1 sensor → bulky

**NI 9235, NI 9236**

±29.4 mV/V, Quarter-Bridge Strain Gage, 10 kS/s/ch, 8 Ch Mod
WHY FIBER OPTIC SENSORS?
One Of These Things (is Not Like The Others)

(Heavy)

(Fiber for 628 FOSS sensors)

(Big)

(Light, small, easy)

(Hard)
PROS/CONS OF FIBER OPTICS SENSORS

• Advantage
  – No unique gauge factor
  – Multiplexing available
  – Not Susceptible to EMI
  – No Lead Wire Resistance effect
  – Installation time
  – 1 A/D channel can interrogate hundreds of sensors

• Disadvantage
  – New technology
  – Temperature Compensation also required
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FIBER SENSOR – FIBER BRAGG GRATING (FBG)

- Fiber Reflector that reflects a particular wavelength and transmit all others
- Bragg Wavelength: $\lambda_B = 2n_e \Lambda$
HOW DO FBG SENSORS WORK?

• Like an accordion → change in Bragg Wavelength

\[ \lambda_1 \rightarrow \lambda_1 + \Delta \lambda \rightarrow \lambda_1 - \Delta \lambda \]

Wavelength (\( \lambda \))
FBG FABRICATION (DRAW TOWER GRATING)
HOW IS STRAIN/TEMPERATURE CALCULATED?

• Similar to Strain Gauge

• Strain ($\varepsilon$) = \(\frac{\Delta \lambda_B}{\rho \cdot \lambda_B}\)
  - $\Delta \lambda_B$ = change in Bragg wavelength due to environmental change
  - $\lambda_B$ = Initial Bragg wavelength of FBG
  - $\rho$ = strain-optics coefficient
**Typical FBG Sensing via Wavelength Division Multiplexing (WDM)**

- **Excitation Source (light source)**
  - LED
  - Laser
- **Fiber Sensors (FBG)**
- **Photodetector (A/D)**
- **Detection Scheme (Optical Spectrum Analyzer)**
**PRO/CON OF WDM**

- **Advantage**
  - Sensors can be ~km away from interrogator
  - Relative Simple Measurement
  - Commercially Available
  - High Sampling Speed Available (~MHz)

- **Disadvantage**
  - Location of each sensor matters
  - Each sensors has to have unique wavelength
  - Only ~10 sensor can occupied 1 data channel
    - **Aliasing effect**
      - When 2 sensors intersects one another
NASA’s Unique FBG Interrogation Technique: OFDR

• Optical Frequency Domain Reflectometry (OFDR):
  – Based on laser interferometry
    • Single Longitudinal mode laser needed
  – Involves signal processing
    • Fourier Transform/inverse Fourier Transform
  – Use weak reflectivity FBG
    • Typical WDM FBG’s R=80%
    • Typical OFDR FBG’s R=0.05%
  – So why use OFDR for sensing instead?
    • Many advantages that WDM can’t match
**ADVANTAGE OF OFDR OVER WDM**

- High Spatial Density over WDM-based sensing
  - Up to 1000 FBGs can be multiplexed onto single fiber
  - FEM type of data can be achieved through real-time testing

- Cost per sensor length is reduce vs WDM-based sensors
  - $60/meter of draw tower made FBG (1/2” per FBG) vs $200 per WDM FBG

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*NASA Composite Crew Module Testing (2011)*
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FOSS GRATING MODULATION MULTIPLEXING METHOD (OPTICAL FREQUENCY DOMAIN REFLECTOMETRY)

- All FBGs are written at the same wavelength ($\lambda_B$), instead of each having a unique wavelength (WDM)
  - Multiplexing of hundreds of sensor is possible.
- A narrowband wavelength tunable laser source is used to interrogate sensors.
- Each FBG sensor is only ½ inch long

\[ I_R = \sum_i R_i \cos(k2n_0L_i) \quad k = \frac{2\pi}{\lambda} \]

- $R_i$ – spectrum of $i^{th}$ grating
- $n_0$ – effective index
- $L$ – path difference
- $k$ – wavenumber

![Diagram of FBG sensor setup](image-url)
**PROCESSING PROCEDURE (COMPLETE PICTURE)**

1. **Tuning Laser**
   - 1548nm
   - 1552nm

2. **Signal Conditioner and A/D**
   - S/C
   - A/D

3. **Perform FFT**
   - Wavelength Domain
   - Length Domain

4. **Perform iFFT**
   - Wavelength Domain
   - Length Domain

5. **Filtering and Centroid**

6. **Centroid to Strain Conversion**
Layman’s Term: Tuning your Favorite Radio Station!

Radio receives ALL frequencies

Multiple frequencies are broadcasted on airwave

Radio tuner accepts ONE frequency
Radio Analogy to Optical Frequency Domain Reflectometry

Laser light

Photo-detector (Receive ALL sensor signal)

Sensor Frequency ID
(Broadcast Tower)
Determined via location of sensor

97.3 97.7 98.1

FFT/iFFT to “dial in” to particular sensor information
(Radio Tuner)

Wavelength (\(\lambda\))
OFDR IN ACTION (FFT)

Wavelength Domain ($k$)

Spatial Domain ($x$)

FBG-FBG interaction

FBG from close up
SUMMARY - FOSS IN BRIEF

• FOSS utilizes OFDR technique
  – Requirement for OFDR
    • Physics
      – Fast narrow-linewidth swept laser
      – Low reflectivity FBGs with identical Bragg wavelength
      – Optical network generating interferometry
      – Robust analog photo-detector
    • Electronics
      – Fast A/D acquisition card
      – Fast algorithm to perform FFT/iFFT (or similar) operation
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**BACKGROUND HISTORY**

- NASA AFRC (then Dryden)’s Aerostructures Branch 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 collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft
  - Focused on validating vendor’s FO VHM system
    - Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
  - Contractor’s system limited to *1 sample every 30 seconds*
- Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight
BACKGROUND OF TECHNOLOGY FOR FLIGHT MONITORING

Fiber Bragg Grating (FBG) sensors in optical fibers have been used for several years to determine the temperature, pressure, and strain to which a structure is subjected.

This invention uses FBG sensor data and allows end users to continuously monitor strain distribution as well as determine many other engineering parameters (i.e. stress, buckling, shape, loads, etc.).


The technology was developed for monitoring the wing displacement of unmanned aerial vehicles (UAV) to proactively prevent crashes.

Helios Mishap Report – lessons learned
- Measurement of wing dihedral in real-time should be accomplished with a visual display of results available to the test crew during flight
- Procedure to control wing dihedral in flight is necessary for the Helios class of vehicle
AFRC’S ROLE IN FIBER SENSING TECHNOLOGY

• Technology is first pioneered/patented at NASA Langley Research Center (LaRC) during the late 90’s:
  – Laboratory-based system
  – One sample being taken every 30 seconds (one channel).

• AFRC miniaturized and developed an “one-box system” for aerospace application
  – Compact system for flight or ground test
  – Patented improved sampling rate to 100 samples per second (multiple channels)

Parker; US Patent 8,700,358
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AFRC’s FOSS CAPABILITIES

System specifications (2014)

- Fiber count: 8
- Max sensing length / fiber: 40 ft
- Max sensors / fiber: 2000
- Total sensors / system: 16000
- Max sample rate (flight): 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

Aircrafts supported: Ikhana, Global Observer, G-III
cFOSS v1.0 SYSTEM SPECIFICATIONS

• Specifications:
  • Fiber count: 4
  • Max Fiber length: 40 ft
  • Max # sensors/system: 8,000
  • Max Sample rate: 100 Hz
  • Power: 50W @ 28Vdc
  • Weight(w/o enclosure): ~6lbs
  • Size (w/o enclosure): 3.5 x 5.7 x 12 in
  • Vibration and Shock: NASA Curve A (DCP-O-018)

• Applications:
  – UAVs

![cFOSS v1.0](image1)

![cFOSS v2.0 onboard X-56](image2)

![cFOSS v1.0 onboard APV-3](image3)
STRUCTURAL ALGORITHMS USING FOSS

• **Structural Shape**
  – Real-time wing shape measurement using fiber optics sensors
    • (Ko, Richards; Patent 7,715,994)

• **Externally applied loads**
  – Real-time applied loads on complex structures using fiber optic sensors
    (Richards, Ko; Patent 7,520,176)

*Win-tip deflection measurement of AFRC’s Predator B via FOSS*
COMBINED TEMPERATURE AND STRAIN SENSING

• Three fiber-optic channels measuring both strain and temperature:

  • Red fiber bonded and will measure strain and determine shape

  • Yellow fiber is both bonded and unbonded through polyimide tubes

  • Blue fiber is run in Polyimide tubes to decouple from substrate, measuring temperature only

Fiber sensors move freely in polyimide tubing to decouple temperature with respect to strain

TPS Heat Shield strain / temp loading with FOSS
Cryogenic Liquid Level-Sensing Using cryoFOSS

• 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

• FOSS Approach
  – While using anemometry methods the transitional phase can be mapped better
  – **Using a single continuous grating fiber high spatial resolution can be achieved**
  – In conjunction with the continuous grating fiber, Dryden’s adaptive spatial density algorithm can resolve even higher spatial resolution targeting in the region where the actual level is located

• Applications:
  – Launch vehicles
  – Satellites
  – Civil Structures
  – Ground Testing
  – COPV bottles
CRYOFOSS DEPLOYED AS LH₂ LIQUID LEVEL SENSOR

Objective

– Experimentally validate Dryden-developed LH₂ liquid level sensor (cryo-FOSS) using Dryden’s fiber optic strain system (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 (validating standard)
  • Cyrotracker (ribbon of 1-in spaced silicon diodes)
  • MSFC Silicon diode rake
  • Fiber optic LH₂ liquid level sensor

Results

– **Cryo-FOSS sensor discerned LH₂ level to approx. ¼” in every case**
– Excellent agreement achieved between cryo-FOSS, boroscope, and silicon diode cryotracker

Bottom line

– Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for the ground- and in-flight cryogenic fluid management of launch vehicles in the future

*Parker Jr et al, USP 9074921*
HYBRID FIBER OPTIC SENSING SYSTEM (hyFOSS)

- hyFOSS is a combination of two existing technologies both based on fiber Bragg gratings
  - Wavelength Division Multiplexing (WDM) allows for high speed (kHz) acquisition speed but low number of gratings per fiber
  - Optical Frequency Domain Reflectometry (OFDR) allows for high spatial resolution (1000s of grating) but inherently low sample rates (<100Hz)
- Combining both technologies coupled on to the same fiber
  - high spatial resolution (lower sample rates) along the entire length of the fiber using OFDR
  - high sample rates at strategic points along the fiber using WDM

Example hyFOSS fiber layout

Parker Jr et al, USP 9664506
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
3-CORE SHAPE MEASUREMENT

- From collaboration with NASA LaRC, shape sensing using fiber strain sensors has been realized.
- Initial research focuses upon 3-core fiber.
- This specialty fiber can be replaced with 3 conventional fibers superposition from one another at 120 degrees.
- From knowing the strain value of each fiber, the 3-dimensional position of the fiber can be correctly rendered in real-time.

*Chan et al, USP 8970845*
3D SHAPE SENSING
3D Shape Sensing on Wearable
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COMPOSITE SHELL BUCKLING KNOCKDOWN FACTOR (2016)

• Sponsor: NESC
• FOSS technology:
  – Strain monitoring
• Benefit to the project:
  – FOSS is being used to obtain experimental validation of knockdown factor margins
  – The ability to reduce margins and maintain safety could lead to significant weight savings
SBKF TEST
SBKF - RESULTS

(Top) FOSS measured max bending strain ($\varepsilon_b$) distribution across SBKF article is consistent with DIC speckle-graph (Bottom) results

*Pena et al, AIAA 2018*
FOSS on X56 (2017-CURRENT)

• X56:
  – Testbed for designing aircraft with highly flexible, lightweight wings.
  – Less structurally-rigid wings could be critical to future long-range, fuel-efficient airliners.

• FOSS on board to measure strain
  – 2D shape sensing to measure wing-deflection
  – Measure flutter modes if exists
X56 FOSS Data – Wing Tip Displacement

- Bending moment (resistive gages)
- Scaled wing tip displacement (FOSS)
SUMMARY

• NASA AFRC has successfully develop fiber optics strain sensors (FOSS) technology from laboratory to real-world application

• Commercialization of technology is on-going via NASA Technology transfer
  – Aerospace Sector
  – Energy Sector
  – Biomedical Sector
THANK YOU - FOSS TEAM AT AFRC

- Dr Lance Richards
  - Aircraft structures, strain measurement research
- Allen Parker
  - System Design and Development, Data Processing & Visualization
- Anthony Piazza
  - Sensor Characterization, Application & Interpretation
- Dr Patrick Chan; hon.chan@nasa.gov
  - Optics Development, Laser Research and Development
- Phil Hamory
  - Advanced System Algorithm Development
- Frank Pena
  - Mechanical Design & Development, Structural Simulation and Testing
- Paul Bean
  - Software/ Hardware development
- Ryan Warner
  - Real-time operating system implementation
- Shideh Nadari
  - Computer Processing, software development
DETERMINATION OF WING DEFLECTION

- Deflection Transfer Functions formulated by integrating the curvature equation for deformed beam elastic curve
  - Structure divided into analysis domains
  - Strain described by a linear function in each domain
  - Curvature equation integrated to yield slope and deflection equations
- No calibration test required

Deflection of a Fiber:
\[ y_i = \frac{(\Delta l)_i^2}{6c_{i-1}} \left[ 3 - \frac{c_i}{c_{i-1}} \right] \varepsilon_{i-1} + \varepsilon_i \]  
+ \( y_{i-1} + (\Delta l)_i \tan \theta_{i-1} \)

Slope:
\[ \tan \theta_i = \frac{(\Delta l)_i}{2c_{i-1}} \left[ 2 - \frac{c_i}{c_{i-1}} \right] \varepsilon_{i-1} + \varepsilon_i \]  
+ \( \tan \theta_{i-1} \)

Distance to neutral axis:
\[ c_{top} = \frac{\varepsilon_{top}}{\varepsilon_{bottom} - \varepsilon_{top}} h \]
LOAD TRANSFER FUNCTION PROCESS

• Load Transfer Functions used to calculate bending moment at each analysis station
  – Cross-sectional properties term calculated by applying known load
    • $EI/c$ term backed out at each evaluation station
  – With properties term known, strain is directly related to bending moment

\[
\frac{M}{\epsilon} = \frac{EI}{c}
\]

Calculate moment at each station

Operational Loads

Measure Strains

Calibration Load

Known Moments

Measure Strains

Properties at each station
**Instrumentation**
- 2880 FBG strain sensors (1920 recorded at one time)
- 1440 FBG sensors per wing
- User-selectable number of FBG sensors for real-time wing shape sensing
- 16 strain gages for FBG sensor validation
- 8 thermocouples for strain sensor error corrections
FLIGHT TEST VALIDATION - IKHANA

Photogram Targets
- Left Wing
  - Optical Fiber 1
  - Optical Fiber 2
  - Optical Fiber 3
- Right Wing
  - Optical Fiber 4
  - Optical Fiber 5
  - Optical Fiber 6

Strain Gage
- LH Wing
  - Optical Fiber 1
  - Optical Fiber 2
  - Optical Fiber 3
- RH Wing
  - Optical Fiber 4
  - Optical Fiber 5
  - Optical Fiber 6
FLIGHT TEST VALIDATION - IKHANA

- 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 2D wing shape sensing
- Multiple flight maneuvers performed
- Two fiber configurations
- Fiber optic and conventional strain gages show excellent agreement
- FBG system performed well throughout entire flight – no issues
Four fibers were installed around the module’s three windows and one hatch. Real-time 3D strain distributions were collected as the module underwent 200% DLL pressurization testing. Measured strains compared and matched well to predicted model results. Project Conclusion:

- “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.”
hyFOSS Multiplexer Diagram

1550nm Tunable light source from FOSS fiber 1

1310nm Broadband light source

3-port Circulator

Wavelength division multiplexer

This multiplexer combines both forward propagating light sources while separating reflect light from sensor into their respective components.

1550nm

WDM Analyzer

WDM Analyzer: 70nm bandwidth @ 1310nm

Continuous grating ¼" spaced sensors

Parker Jr et al, USP 9664506

1310/1550nm

Narrowband Reflector box

NBR: ~80nm bandwidth @ 1550nm. Chirped grating with 50% reflectivity, only reflect at 1550nm while passing all 1310nm light.

Standard optical patch cable

Continuous grating fiber providing ¼" spatial resolution combined with multiple WDM sensors throughout.

High speed WDM sensor

hyFOSS measurement sensor

Continuous grating fiber providing ¼" spatial resolution combined with multiple WDM sensors throughout.
CRYOTE 3

- Sponsor: LSP (KSC)
- FOSS technology:
  - Strain sensing, Temperature sensing, Liquid Level sensing
- Benefit to the project:
  - CRYOTE 3 being used as a test bed to further develop the Liquid Level sensing capability of FOSS
  - FOSS Temperature and strain sensing capabilities are helping to provide high fidelity data in the transition from liquid to gas state in cryogenic tanks
  - Data being used to validate models for the liquid level boundary region