Advanced Fiber Optic-Based Sensing Technology for Unmanned Aircraft Systems

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Fiber Optic Sensing for UAS Applications
Advantages over Conventional Measurements

- Unrivaled density of sensors for spatially distributed 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 out-of-plane displacement and load at points along the fiber
- 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 (cryo – 550F)
Fiber Optic Sensing for UAS Applications

Anticipated Impact

- Potential to revolutionize UAV design and performance throughout the life-cycle
  - Design and development
  - Production
  - Test and Evaluation
  - In-flight operation
  - Off-nominal flight
  - End of life-cycle decisions

Source: COTS Journal

defenseindustrydaily.com
Fiber Optic System Operation Overview

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 use 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

Laser tuning
Grating region
Tuning direction
start \( \lambda \) stop

Laser light
Reflector
\( \Lambda \)
Loss light

Reflected light \((I_R)\)
L1
L2
L3
Fiber Optic System Operation Overview

- Fourier transforms (both forward and inverse) are used to discriminate between gratings
- The Fourier transform separates the $I_R$ waveform into sinusoids of different frequency which sum to the original waveform

<table>
<thead>
<tr>
<th></th>
<th>FFT</th>
<th>iFFT</th>
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<tbody>
<tr>
<td>Traditional</td>
<td>Time(T) $&gt;$ Frequency(F)</td>
<td>Frequency(F) $&gt;$ Time(T)</td>
</tr>
<tr>
<td>Optical</td>
<td>Wavelength($\lambda$) $&gt;$ Length(L)</td>
<td>Length(L) $&gt;$ Wavelength($\lambda$)</td>
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Spectral Mapping

![Wavelength($\lambda$) domain](image1.png)

![Length(L) domain](image2.png)

FFT
Fiber Optic System Operation Overview

- By bandpass filtering around a specific frequency (grating location) within the length domain and performing an iFFT, the spectrum of each grating can be independently measured and strain inferred (FM radio).

- Using a centroid function the center wavelength can be resolved.
- The wavelength change is proportional to the induced strain:

\[
\frac{\Delta \lambda}{\lambda} = K \varepsilon
\]

\(K \) – proportionality constant (0.7-0.8)
Interrogation Process

Tunable Laser

1548 to 1552nm

Signal Conditioning and A/D

Perform FFT

Wavelength Domain

Length Domain

Perform Windowing

Perform iFFT

Filtering and Centroid

Centroid to Strain Conversion

Wavelength Domain

Length Domain

National Aeronautics and Space Administration
Research and Technology Development Areas

- Algorithm Development
- FBG System Development
- Instrumentation
- Ground Testing / R&D
- Flight Testing

\[ y_n = \frac{\Delta l^2}{6c} \left\{ (3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1} (n-i)\varepsilon_i + \varepsilon_n \right\} \]
Research and Technology Development Areas

- Algorithm Development
  - *Real-time wing shape measurement using fiber optics sensors*
    (Ko, Richards; Patent 7,715,994)
  - *Real-time applied loads on complex structures using fiber optic sensors*
    (Richards, Ko; Patent 7,520,176)
  - *Data processing algorithms*
    (Parker, US Patent Pending)

- FBG System Development
- Instrumentation
- Ground Testing / R&D
- Flight Testing

\[ y_n = \frac{\Delta l^2}{6c} \left\{ (3n - 1)\varepsilon_0 + 6\sum_{i=1}^{n-1} (n-i)\varepsilon_i + \varepsilon_n \right\} \]
Real-time Wing Shape Measurement
Motivation – Helios UAV

Helios wing dihedral on takeoff

In-flight breakup

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
Deflection of a Single Fiber:

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

Typically the first station is at the root:

\[ y_0 = \tan \theta_0 = 0 \]

Slope:

\[ \tan \theta_i = \frac{(\Delta l)^2_i}{2c_{i-1}} \left[ 2 - \frac{c_i}{c_{i-1}} \right] \varepsilon_{i-1} + \varepsilon_i \] + \tan \theta_{i-1}
Real-time Wing Shape Measurement
Global Observer – Algorithm Validation Testing

- Strain gages
  - Validate the FBGs
  - Not used for shape prediction, used for structural evaluation

- Photogrammetry
  - Provided validation information for wing shape prediction
  - Measures actual displacement vectors at target points
  - 10 photogrammetry images taken per load condition
Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.
Real-Time Externally-Applied Loads Approach

- Bending moment calculated at each analysis station
- Cross-sectional properties calculated by applying known load
  - $EI/c$ term backed out at each evaluation station
- With properties known, strain can be directly related to bending moment

$$\frac{M}{\varepsilon} = \left(\frac{EI}{c}\right)$$

Get properties at each station

$\left(\frac{EI}{c}\right) \cdot \varepsilon = M$

Calculate moment at each station
Cross-sectional properties calculated using *Uniform* load calibration

### Uniform Load Case

\[ M = \left( \frac{EI}{c} \right)_{UniformA} \cdot \varepsilon_{UniformB} \]

### Single Point Load Case

\[ M = \left( \frac{EI}{c} \right)_{UniformA} \cdot \varepsilon_{SinglePt} \]
Wing Shape and Externally-Applied Loads

Results

- Deflection calculations are accurate (within ~5%)
  - Different test articles
  - Different load cases
  - Different load magnitudes
- Load results will be improved
  - Least-squares method
- Developing methods to further use FOSS measurements
  - Angle-of-twist
  - Improved deflection and load
  - Torque
Research and Technology Development Areas

- Algorithm Development
- FBG System Development
- Instrumentation
- Ground Testing / R&D
- Flight Testing
**NASA Technology FOSS Systems (4DSP)**

**Technical Highlights**
- 4DSP has licensed NASA technology to commercially develop FOSS systems
  - [http://www.4dsp.com/RTS150.php](http://www.4dsp.com/RTS150.php)
- Single laser greatly reduces cost per sensor
- High fiber count systems
  - Modular design with 8 channels per card
  - Expandable
  - Up to 32 fibers possible
  - Up to sensing 80 feet per fiber
- 11” x 7” x 12”
- 100 Hz max sample rate
- Lightweight system for multitude of sensors
  - Approximately 25 lbs

**Cost**
- 8 fiber system approx $100K
  - Up to 16,000 sensors
- 32 fiber system approx $150K
  - Up to 64,000 sensors
- System can be flight-certified (+$30K)
  - Low power requirements (<10 Amps at 28 Volts DC)

**Applications**
- Transport Aircraft, Ships, Civil Structures
Compact FOSS (cFOSS) System
In Development

- **Lightweight, ruggedized system**
  - Packaged within a 6” cube
- **Targeted specifications:**
  - Fiber count: 8
  - Max Fiber length: 80 ft
  - Max # sensors/system: 15,360
  - Max Sample rate: 100 Hz
  - Power: 50W @ 28Vdc
  - Weight: <10 lbs
  - Size: 5 x 6 x 6 in
  - Vibration and Shock: NASA Curve B
  - Altitude: 65kFt
- **Applications:**
  - Fighter aircraft
  - UAVs
  - Launch vehicles
  - Spacecraft
- **Target system cost:** $50K
- **Availability:** End of 2012
Large Scale FOSS (LsFOSS) Technology

- **Technical Highlights**
  - Single laser greatly reduces cost per sensor
  - High fiber count systems
    - Up to 16 fibers monitored simultaneously/system
    - Each fiber can be up to 40ft long
    - Each fiber at 40ft long can have up to 2000 measurements (total of 32,000 /system)
    - Up to 8 systems can be networked together yielding approx. 1 mile of sensing distance (1/4” spacing, 256,000 measurements)
  - 11” x 7” x 12”
  - 100 Hz max sample rate
  - Lightweight system for multitude of sensors
    - Approximately 25 lbs

- **Applications:**
  - Transport Aircraft
  - Ships
  - Civil Structures
  - Ground Testing
  - Structures Laboratory
Research and Technology Development Areas

- Algorithm Development
- FBG System Development
- Instrumentation
- Ground Testing / R&D
- Flight Testing
Installation Advantages

- Greatly reduced installation time compared to conventional strain gages
  - 2 man-days for 40’ fiber (1000 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
  - Circular cross-section eliminates possibility of trapping air between sensor and part (eliminates repeat installations)
- Can be installed with little or no impact to OML

Installation Challenges

- Optical fiber more fragile than strain gages
- Some measurement locations not practical due to fiber minimum bend radius
- Not practical if only interested in spot measurements
Research and Technology Development Areas

- Algorithm Development
- FBG System Development
- Instrumentation
- Ground R&D
- Flight Testing
Embedment of Fiber Optic Sensors within Composites

Biological Inspiration of FOSS

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

One square-inch of human skin

Embedment of Fiber Optic Sensors within Composites
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

Courtesy: M Emmons, GP Carman, UCLA
Embedment of Fiber Optic Sensors within Composite Overwrapped Pressure Vessels (COPVs)

The Goal: Characterize measurement response of fiber Bragg sensors embedded in COPVs
- Determine overall sensor accuracy as a function of its orientation relative to the layered materials in the structure
- Use finite element techniques to understand the thermal/mechanical loads present in the fiber optic, lenticular resin rich region, and the adjacent composite material as well as issues related to ingress/egress.
- Experimentally evaluate the accuracy and long term durability of the embedded sensor / host material system when subjected to quasi-static thermal mechanical loading

The Approach: Evaluate accuracy and long term durability of a fiber optic sensors embedded within COPVs
- Analytical modeling of the fiber optic sensor
- Epoxy composite fabrication
- Quasi-static testing of coupons
- Long term fatigue testing
- Testing of representative aerospace
AeroVironment’s Global Observer
Wing Loads Tests at NASA Dryden

- 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 single fiber shape algorithm
- A 24-fiber system was designed of which 18 fiber 40ft (~17,200 gratings) fibers were used to instrument this wing
Research and Technology Development Areas

- Algorithm Development
- FBG System Development
- Instrumentation
- Ground Testing / R&D
- Flight Testing
Flight Test Results
Predator-B

• Flight validation 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
  – Two fiber configurations
  – Fiber optic and conventional strain gages show excellent agreement
  – FBG system performed well throughout entire flight – no issues

Video clip of flight data superimposed on Ikhana photograph
AeroVironment’s Global Observer
Flight Testing

- Validate strain predictions along the left wing using 8, 40ft fibers
- 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
Concluding Remarks

Fiber Optic Wing Shape Sensing toward UAS applications involves five major areas

- **Algorithm development**
  - Real-time wing shape and applied loads algorithms using fiber optics sensors were in good agreement with conventional measurements

- **FBG system development**
  - Current Flight Systems in Operation: 4 and 8 Fiber Systems
    - Flown on Ikhana and Global Observer, resp.
  - Future Systems underdevelopment:
    - 64 Fiber ‘Large-Vehicle’ System
    - 4 Fiber ‘Compact’ System

- **Instrumentation**
  - Installation Advantages
    - Greatly reduced installation time compared to conventional strain gages
  - Installation Challenges
    - Optical fiber more fragile than strain gages

- **Ground Testing / R&D**
  - A 24-fiber system was used on Global Observer; 18 fiber 40ft (~17,200 gratings) fibers were to measure strain and wing shape in real-time

- **Flight Testing**
  - Predator-B; Ikhana
    - Real time fiber Bragg strain measurements successfully acquired and validated in flight (4/28/2008)
    - Real-time fiber optic wing shape sensing successfully demonstrated in flight
  - Global Observer