Advanced Fiber Optic-Based Sensing Technology for Unmanned Aircraft Systems

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UAS Payloads Conference
San Diego, CA
11/16/2011
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

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

- \( I_R \) – spectrum of \( i^{th} \) grating
- \( n \) – effective index
- \( L \) – path difference
- \( k \) – wavenumber

Laser tuning
Grating region
Tuning direction

start \( \lambda \) stop

R1 – spectrum of \( i^{th} \) grating

L1 \rightarrow \text{Laser light} \rightarrow \text{Reflector} \rightarrow \text{L2} \rightarrow \text{L3} \rightarrow \text{Loss light}
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

![Graph showing spectral mapping between Wavelength($\lambda$) domain and Length(L) domain with FFT transformation.](image-url)
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

Signal Conditioning and A/D

Perform FFT

Wavelength Domain

Length Domain

Perform Windowing

Perform iFFT

Filtering and Centroid

Centroid to Strain Conversion

Length Domain

Wavelength Domain

1548 to 1552nm
Research and Technology Development Areas

- Algorithm Development

- FBG System Development

- Instrumentation

- Ground Testing / R&D

- Flight Testing
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
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
Real-time Wing Shape Measurement
Theoretical Development

Deflection of a Single Fiber:

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

Typically the first station is at the root:
\[ y_0 = \tan \theta_0 = 0 \]

Slope:

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

[Diagram of FOSS Ground System with Data Server and FOSS units connected to Display PCs]
Research and Technology Development Areas

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

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

Theoretical development
Coupon testing
Analysis and Modeling
Sensor Installation
Embedding / Fabrication
Failure Testing
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
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 given 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