Optical feather and foil for shape and dynamic load sensing of critical flight surfaces

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ABSTRACT

Future flight vehicles may comprise complex flight surfaces requiring coordinated in-situ sensing and actuation. Inspired by the complexity of the flight surfaces on the wings and tail of a bird, it is argued that increasing the number of interdependent flight surfaces from just a few, as is normal in an airplane, to many, as in the feathers of a bird, can significantly enlarge the flight envelope. To enable elements of an eco-inspired Dynamic Servo-Elastic (DSE) flight control system, IFOS is developing a multiple functionality-sensing element analogous to a feather, consisting of a very thin tube with optical fiber based strain sensors and algorithms for deducing the shape of the "feather" by measuring strain at multiple points. It is envisaged that the "feather" will act as a unit of sensing and/or actuation for establishing shape, position, static and dynamic loads on flight surfaces and in critical parts. Advanced sensing hardware and software control algorithms will enable the proposed DSE flight control concept. The hardware development involves an array of optical fiber based sensorized needle tubes for attachment to key parts for dynamic flight surface measurement. Once installed the optical fiber sensors, which can be interrogated over a wide frequency range, also allow damage detection and structural health monitoring.

Keywords: Dynamic Servo-Elastic (DSE) flight control, Load Monitoring, Fiber Bragg Gratings (FBGs), Fiber Optic Sensors, Structural Health Monitoring (SHM), Structural State Sensing

1. INTRODUCTION

Inspired by the complexity of the flight surfaces on the wings and tail of a bird, it is argued that, in general, increasing the number of interdependent flight surfaces from just a few, as is normal in an airplane, to many, as in the feathers of a bird, can improve flexibility for fight performance over a broader spectrum of conditions. The sensing system can then withstand a larger perturbation range.

As a building block toward such systems, IFOS is leveraging its development of a slender (18 – 20 gauge) highly flexible needle rod that was sensorized with several fiber Bragg gratings (FBGs) to provide 3-D shape information. Strain measurements from the placement of FBGs were combined with the geometrical boundaries of the needle in an algorithm that yielded very precise shape information. Although this development was in the context of shape sensing on a biopsy needle for MRI assisted surgery, it can flexibly be attached as a sensing element to any flight surface or critical component without adding noticeable weight. This information is scalable, i.e. close proximity of the FBGs can yield precise shape sensing for small parts and longer spacing will yield shape sensing for large parts.

A similar arrangement can be made using a thin plate pad (foil), with a small number of FBGs measuring strain (and temperature). Again simple physics based algorithms will translate the relative strains across the plate to a determination of its shape in 3-D space. Attaching such a sensing building block to any surface will determine its shape and hence deduced position. Information from a series of such sensors along critical flight surfaces and components can be coordinated for flight control. In this paper, however, our focus is on the development of the basic building block and the features it can offer. In particular, because of the broadband nature of the FBG as a strain sensor, both static and dynamic strain information can be obtained, allowing the sensing block to act not only as a shape or position sensor, but also as a predictor of failure by measuring the natural frequencies of the surface in question to hundreds of kHz, and by looking for changes in behavior over time or as a function of flight conditions.

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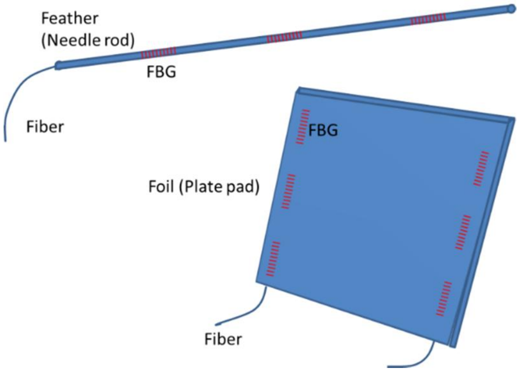

Figure 1. Generalized forms of very small 3D feather (needle rod) and foil (plate pad) assemblies with embedded FBGs

Arrays of FBGs[1] provide multiple electromagnetic-interference-immune harsh-environment-tolerant systems[2]along small diameter optical "nerves" and a basis for multi-point dynamic strain input for SHM. In addition to strain[3], temperature[4] can be measured, as long as appropriate approaches to differentiate these two measurands are used. In addition, with appropriate packaging, derivative measurands such as pressure[5] and acceleration can be obtained. Key to their use as sensors is the interrogation instrumentation discussed in the Sec. 2, following which, in subsequent sections, we discuss (Sec. 3) our vision for usage in a flexible aerostructure control system, (Sec. 4) shape sensing, and (Sec. 5) damage detection, before (Sec. 6) concluding.

2. SENSOR INSTRUMENTATION

IFOS has developed a parallel processing FBG sensor interrogator that allows massive multiplexing of FBG sensors sampled at high rates. Groups of up to approximately16 sensors can be sampled simultaneously on a single fiber from DC up to MHz with the capability of switching between multiple fibers at kHz. This broadband capability allows for smart composite sensing applications ranging from low-frequency load monitoring applications for composite wings[6, 7] to ultra-high frequency acoustic emission (AE) monitoring[8] and Lamb-wave based damage detection[9]. In this paper, we discuss both (a) capturing loading and relatively low frequency dynamic shape sensing phenomena, and (b) higher frequency data for damage detection. A functional schematic of the IFOS system is given in Figure 2. Therein, the PSP, which can be, for example, a lattice of fiber filters[10], diffraction grating, or customized arrayed waveguide grating (AWG)[11], allows for parallel processing of all FBG wavelengths within a given spectral band simultaneously. The DPDE determines the maximum sampling rate.

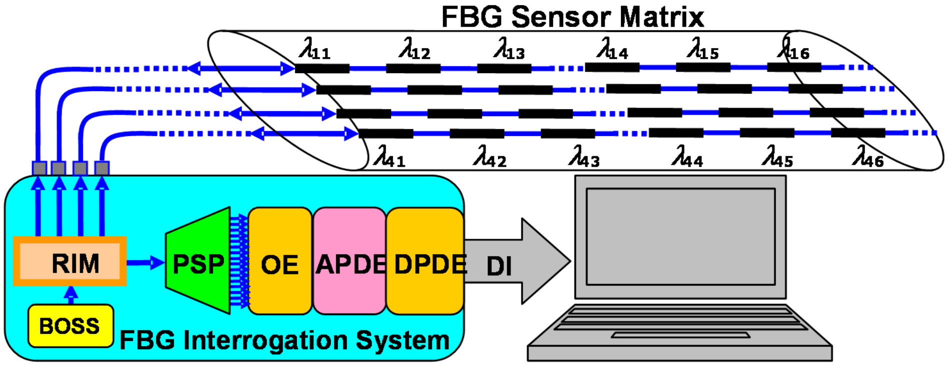

Figure 2. Enabling interrogation instrumentation: The interrogation system comprises a Broadband Optical Source Subsystem (BOSS), Routing and Interface Module (RIM), Photonic Spectral Processing (PSP) subsystem, Opto-Electronic (OE) interface, Analog Post-Detection Electronics (APDE) subsystem, Digital Post-Detection Electronics (DPDE) subsystem and Data Interface (DI).

3. SENSORY-BASED CONTROL ORIENTED SYSTEM FOR FLEXIBLE AEROSTRUCTURES

While not yet as complex as provided by biology as the feathered and morphing wings[12] of a bird, man-made flexible and morphing wings[13-15] are receiving increasing attention, for example, in unmanned air vehicles (UAVs). In addition, the distributed control that has been of interest for aircraft engines[16-20] has potential for application to the total aerostructure.

Figure 3 shows IFOS' conceptual visualization of the distributed sensory-driven control-oriented system for flexible wing control and monitoring applications. The system is based on the use of fiber Bragg gratings (FBGs) as strain dynamic strain sensors. Due to the broadband nature of FBGs, both static and dynamic strain information can be obtained for large numbers of multiplexed sensors, allowing the sensing block to act not only as a shape sensor for the aerodynamic surfaces but also as an input mechanism to permit a rapid response to gust loads or other unpredicted aerodynamic disturbances. These strain measurements can be coupled with FBG pressure sensors to measure pressure distribution over a flexible wing.

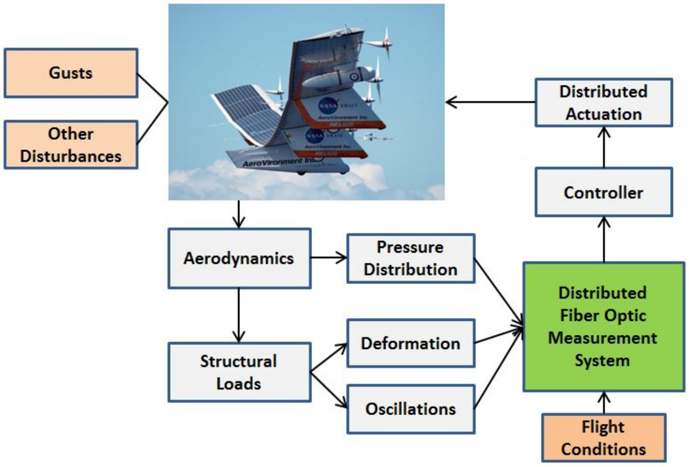

Figure 3. Visualization of the distributed sensory-based control oriented system for flexible wings

Figure 4 visualizes the distributed sensing and actuation architecture for a flexible airframe. This network integrates heterogeneous components – such as fiber optic (FO) sensors, MEMS sensors, and MEMS actuators – in a distributed architecture with a FO network data-bus. One or more networked processors are used for control law computations.

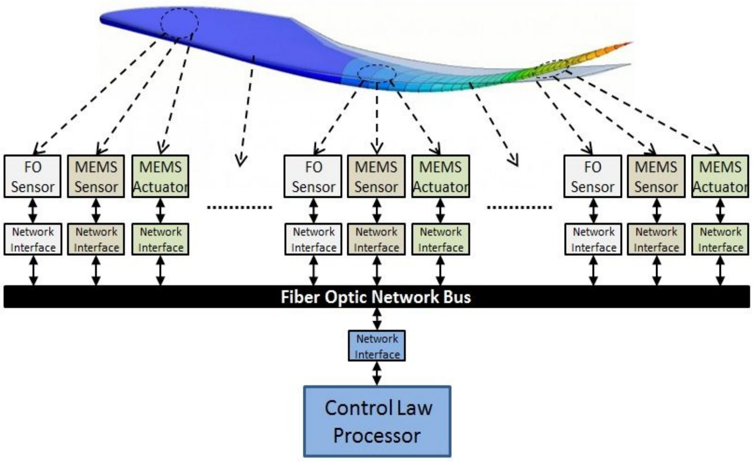

Figure 4: Conceptual schematic of distributed sensing and actuation architecture for flexible airframe application. This is a heterogeneous network of fiber optic (FO) sensors, MEMS sensors, and MEMS actuators connected via a fiber optic network bus.

4. SHAPE SENSING (LOW FREQUENCY)

As a basis for realizing shape sensing input for the aero-control of the previous section, in this section, we discuss shapes sensing for rods (feather quills) and plates (as a basis for flexible wings).

4.1 Feather Quill (Rod) Shape Sensing

IFOS has developed technology for shape sensing of biopsy needles, which allows determination of the tip with respect to the base with sub-millimeter precision[21]. IFOS is adapting the technology to aerospace problems with shape sensing of critical flight surfaces.

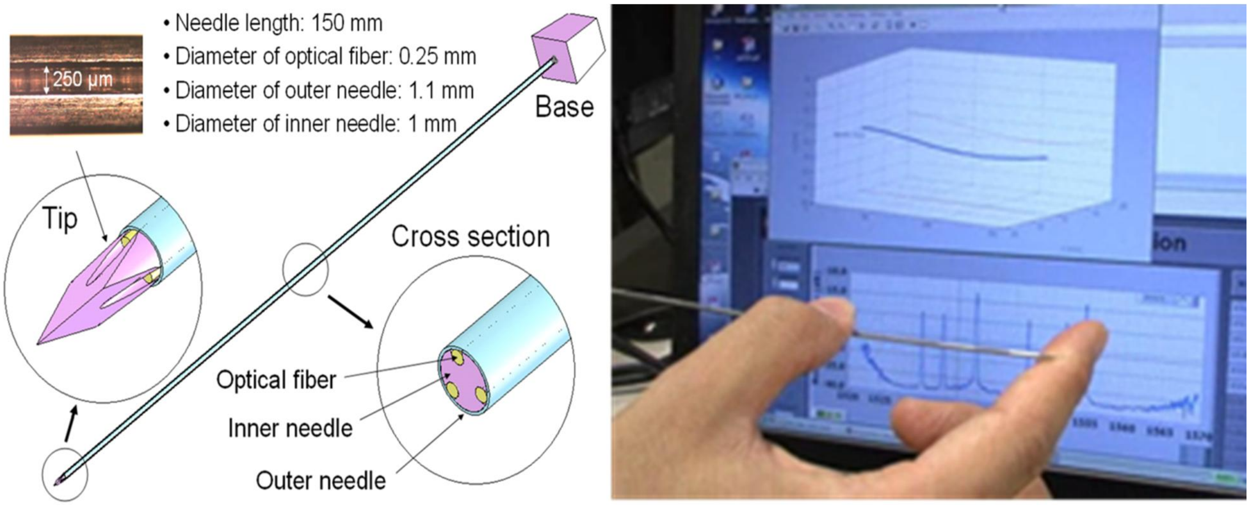

Figure 5. FBG sensors along the length of the needle/feather quill provide 3D shape information

4.2 Plate Shape Sensing

Going beyond the 1D rod (feather quill) structure, IFOS has also been sensorizing plates and panels as shown in the example of Figure 6. Figure 7 shows shape visualization for the plate in four different states as can be determined from the strains measured by each FBG. Figure 8 Figure 8 similar results for a model of a panel like wing – Such results could be extended to UAV wings such as those of HELIOS[22] depicted in Figure 3.

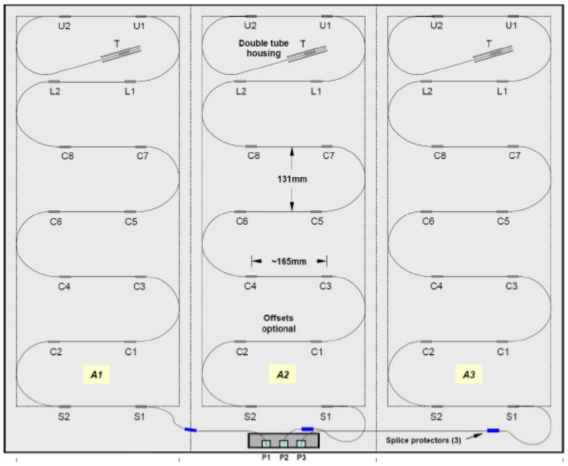

Figure 6. 3’ x 5’ plate with multiple FBG sensor arrays.

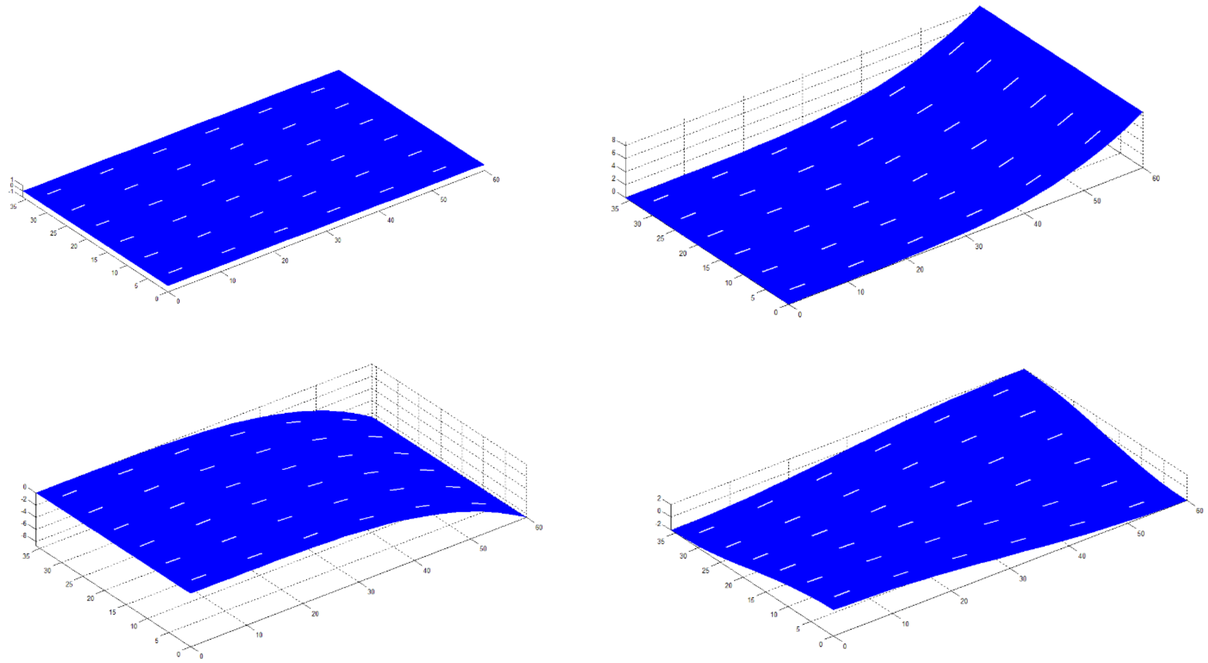

Figure 7. Multiple arrays of FBGs on a 3' x 5' plate provide information of the shape of the plate

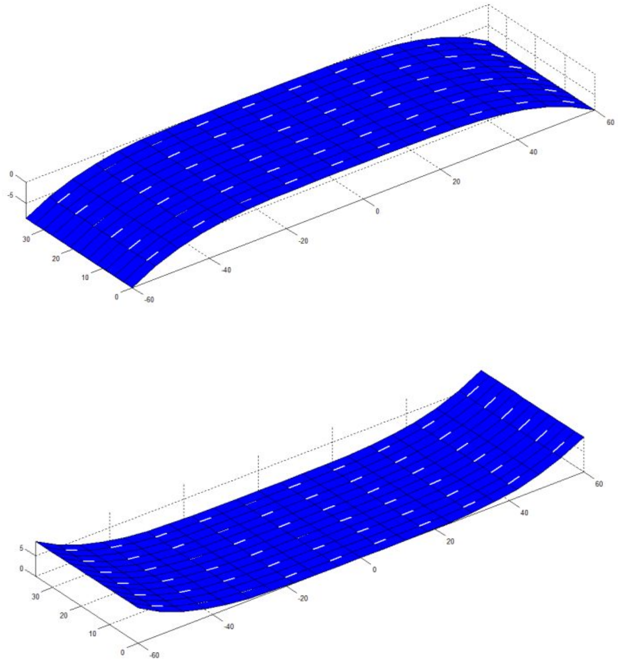

Figure 8. Flexible panel wing shape sensing: FBG arrays distributed over a wing such as that of the HELIOS UAV could provide shape sensing information for better control of the UAV.

5. DAMAGE DETECTION (MID TO HIGH FREQUENCY)

Traditional ultrasonic methods utilize pulsed signals propagating through a material or structure and changing heir characteristics depending on structural condition. This approach works well in a far field of a sensor (typically piezoelectric) and in structures of relatively simple geometry as structural features will results in retransmission of the acoustic pulse. Alternatively, a continuous wave (CW) signal in mid-frequency range may be used to excite structure and obtain its local structural dynamic response. Quite differently to the conventional ultrasonic approach, CW response is sensitive to structural condition in the near-field of a sensor and is applicable to complex structures. Because of relatively high frequencies, from tens to hundreds of kHz, small-scale damage can be resolved and sensitivity is localized because high frequencies attenuate rapidly and may not propagate large distances. Localized sensitivity also enables location of damage as a sensor nearest to damage typically would exhibit more pronounce response in comparison to sensors located further away from damage. It is our opinion that ultrasonic and CW methods complement each other as they address different damage detection distances and structural complexities.

IFOS is working with New Mexico Tech (NMT)[23] to exploit IFOS broadband high frequency dynamic strain measurement capabilities with sampling demonstrated[8] up to 3 MHz for measurements on aluminum wings with optical fiber sensors using a high frequency spectral method analogous to electromechanical impedance (EMI). We refer to Reference [23] in this proceedings volume.

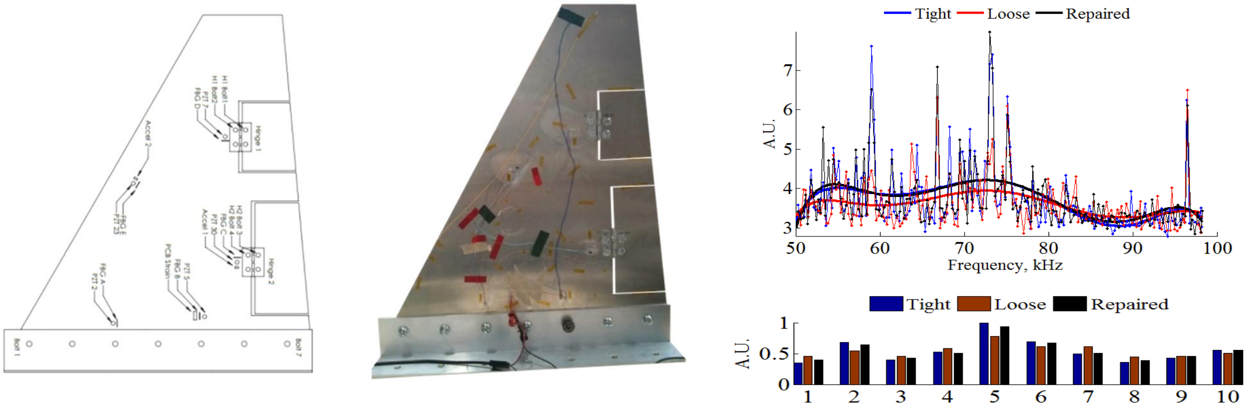

Figure 9. FBG sensing system on a model T38 wing: Polynomial fitting and energy methods are used for cross spectrum damage detection.

To complement the above, IFOS has also performed ultrasonic Lamb wave based damage detection in composite plates and curved shells with 4 surface-attached FBGs sampled at 0.5 MS/s to showcase the identification of delamination[24] – see Figure 10.

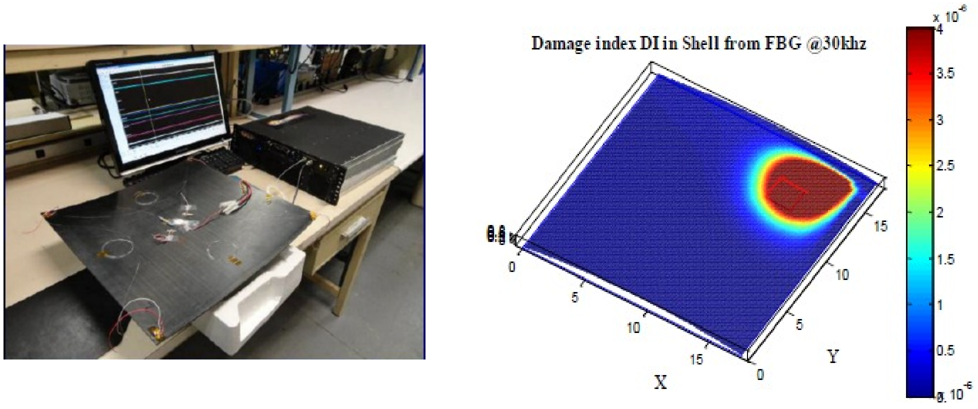

Figure 10. IFOS Lamb wave based delamination identification for a curved composite shell with four FBGs placed at the corners and sampled simultaneously at 0.5 MS/s.

6. CONCLUSIONS

Optical fibers are small-in-diameter, light-in-weight, electromagnetic-interference immune, electrically passive, chemically inert, flexible, and may be surface attached (e.g., to metals) or embedded into different materials such as composites. Together with the appropriate enabling sensor interrogation system sampling from (a) quasi-DC to kHz up to (b) MHz, they can provide (a) load monitoring, dynamic shape and force sensing, and when appropriately packaged, pressure and acceleration input for active control and (b) damage detection and health monitoring capabilities.

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REFERENCES

[1] Hill, K. O. and Meltz, G., “Fiber Bragg Grating Technology Fundamentals and Overview,” J. Lightwave Technol. 15(8), (1997).

[2] Black, R. J. and Moslehi, B., "Advanced end-to-end fiber optic sensing systems for demanding environments (Invited Paper)," Proc. SPIE, 0L.1-9 (2010).

[3] Black, R. J., Zare, D., Oblea, L., Park, Y.-L., Moslehi, B. and Neslen, C., “On the gage factor for optical fiber grating strain gages,” SAMPE'08, 18-22 (2008).

[4] Black, R. J., Costa, J. M., Moslehi, B., Zarnescu, L., Hackney, D. and Peters, K., "Fiber optic temperature profiling for thermal protection heat shields," Proc. SPIE 9062, Paper 41 (2014).

[5] Moslehi, B. and Costa, J. M., “Fiber optic pressure sensor based on differential signaling,” US Patent 8,402,834, (2013).

[6] Costa, J. M., Black, R. J., Moslehi, B., Oblea, L., Patel, R., Sotoudeh, V., Abouzeida, E., Quinones, V., Gowayed, Y., Soobramaney, P. and Flowers, G., "Fiber-optically sensorized composite wing," Proc. SPIE 9062, Paper 41 (2014).

[7] Moslehi, B., Black, R. J. and Faridian, F., "Multifunctional Fiber Bragg Grating Sensing System for Load Monitoring of Composite Wings," Proc. 2011 IEEE Aerospace Conference, Paper 1557 (2011).

[8] Moslehi, B., Black, R. J., Costa, J. M. and Faridian, F., "Highly Scalable Operational Sensor System for Harsh Environment Applications," Proc. SAMPE 2012, Paper 57-2333 - 14 pages (2012).

[9] Black, R. J., Faridian, F., Moslehi, B. and Sotoudeh, V., “Structural Health Monitoring With Fiber Bragg Grating and Piezo Arrays,” NASA Tech Briefs, 26-27 (Oct. 1, 2012).

[10] Moslehi, B., Black, R. J., Toyama, K. and Shaw, H. J., "Multiplexible Fiber-Optic Strain Sensor System with Temperature Compensation Capability," US Patent 6597822 issued 22 July 2003; US Patent 6788835 issued 7 Sept 2004 and US Patent 6895132 issued 17 May 2005 (2003).

[11] Lopatin, C. M., Mahmood, S., Mendoza, E., Moslehi, B., Black, R., Chau, K. and Oblea, L., "Progress in miniaturization of a multichannel optical fiber Bragg grating sensor interrogator," 66193X (2007).

[12] Lentink, D., Müller, U., Stamhuis, E., De Kat, R., Van Gestel, W., Veldhuis, L., Henningsson, P., Hedenström, A., Videler, J. J. and Van Leeuwen, J. L., “How swifts control their glide performance with morphing wings,” Nature 446(7139), 1082-1085 (2007).

[13] Ifju, P. G., Jenkins, D. A., Ettinger, S., Lian, Y., Shyy, W. and Waszak, M. R., “Flexible-wing-based micro air vehicles,” AIAA paper 705(2001-3290), 1-11 (2002).

[14] Pines, S., “Aerodynamic flutter derivatives for a flexible wing with supersonic and subsonic edges,” Journal of the Aeronautical Sciences (Institute of the Aeronautical Sciences) 22(10), (2012).

[15] Perkins, D. A., Reed, J. L. and Havens, E., "Morphing wing structures for loitering air vehicles," 2004-1888.

[16] Behbahani, A., Culley, D. and Smith, B., “Status, vision, and challenges of an intelligent distributed engine control architecture,” Optimization 1, 3891 (2007).

[17] Costa, J. M., Black, R. J., Moslehi, B. and Behbahani, A. R., "Advances in high temperature fiber optic sensors for turbine engine applications," Proc. 58th International Instrumentation Symposium (2012).

[18] M. Pakmehr, N. F., T. Cazenave , E. Feron, A. Behbahani, "Distributed Modular Control Architecture Development for Gas Turbine Engines," Proc. 58th International Instrumentation Symposium (IIS) (2012).

[19] Moslehi, B., Sotoudeh, V., Faridian, F., Costa, J. M., Black, R. J., Behbahani, A., O'Brien, W., Ha, D. S. and Austin, M., "Intelligent and robust sensors using fiber-optic network distributed engine control," Proc. 57th International Instrumentation Symposium, Vol. 488 (2011).

[20] Pakmehr, M., Dhingra, M., Fitzgerald, N., Paduano, J. D., Wolf, M., Feron, E. and Behbahani, A., "Distributed Architectures Integrated with High-Temperature Electronics for Engine Monitoring and Control," Proc. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference (2011).

[21] Park, Y.-L., Elayaperumal, S., Daniel, B., Ryu, S. C., Shin, M., Savall, J., Black, R. J., Moslehi, B. and Cutkosky, M. R., "Real-time estimation of 3-D needle shape and deflection for MRI-guided interventions," Mechatronics, IEEE/ASME Transactions on 15(6), 906-915 (2010).

[22] Noth, A., Siegwart, R. and Engel, W., [Design of solar powered airplanes for continuous flight] ETH, (2008).

[23] Schlavin, J., Zagrai, A., Clemens, R., Black, R. J., Costa, J., Moslehi, B., Patel, R., Sotoudeh, V. and Faridian, F., "Combined electromechanical impedance and fiber optic diagnosis of aerospace structures," Proc. SPIE 9064, Paper 36 - 90640X-90640X-13 (2014).

[24] Sotoudeh, V., Black, R. J., Moslehi, B. and Qiao, P., "Lamb wave-based damage detection of composite shells using high-speed fiber-optic sensing," Proc. SPIE 9062, Paper 42 (2014).