

# A Review of Fiber Optic Technology for Turbine Engine Instrumentation Channel: Control, PHM, and Test Cell Applications

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The next generation of gas turbine engines will potentially have Full Authority Digital Engine Control (FADEC) Systems that consists of wired, wireless, and fiber optics technologies. This paper focuses on the fiber optics technologies for engine applications. Optical fiber sensors have the potential to deliver new and effective measurement in many applications aided by the following properties: (a) immunity to and non-generation of electromagnetic interference (EMI), (b) electrical passivity and thus safety in explosive environments, (c) transmission of sensed information over long distances and through difficult to access regions, (d) very small diameter size allowing integration into smart materials, (d) high durability in many environments, (e) minimal mass, particularly important in aerospace applications, (f) geometric flexibility coupled with capability for multiple functionality, enabling "non-line-of-sight" measurements and contributing to ease of installation compared with alternative approaches. For practical application a fiber optic sensing system needs to include: sensors, fiber optic link, interrogator (comprising photonics, electronics and firmware/software), data interpretation and decision-aid algorithms/software. Fiber optics for diagnostics and troubleshooting are used in varying capacities to test, measure, analyze, transmit, distribute, and/or simulate an optical signal with which procedures and processes associated with maintenance, problem solving, and calibration of equipment and/or networks can be performed. With all the scientific and engineering advancements in the field of fiber optic sensing, the maturity of this technology is high enough and well beyond the experimental lab environment. With its rather low cost, fiber optics sensing technology is a proper option for turbine engine industry.

## I. Introduction

THE next generation of gas turbine engines will potentially have Full Authority Digital Engine Control (FADEC) systems that consists of wired, wireless, and fiber optics technologies. There is currently much activity in wired and wireless systems; this paper will only focus on the fiber optics technologies. The proposed use of photonics and fiber optics for engine FADEC is not new. In the 1990's several efforts were devoted to use fiber optics, but, at that time, they were not enough to promote vast industrial application of this technology. On the other hand, there have been many recent developments in this technology that make its application much more attractive.

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Optical fiber sensors have the potential to deliver new and effective measurement in many applications aided by the following properties[1][2]: (a) immunity to and non-generation of electromagnetic interference (EMI), (b) electrical passivity and thus safety in explosive environments, (c) transmission of sensed information over long distances and through difficult to access regions, (d) very small diameter size allowing integration into smart materials, (d) high durability in many environments, (e) minimal mass, particularly important in aerospace applications, (f) geometric flexibility coupled with capability for multiple functionality, enabling "non-line-of-sight" measurements and contributing to ease of installation compared with alternative approaches.

Fiber optic technology would not even be considered if it did not offer distinct advantages over traditional copper media. From controls perspective, the major capability improvements of fiber optics are higher data bus communication (via a 50 Mbps fiber optic bus, or higher data rates using Fibre Channel standards), EMI immunity, higher reliability for use in harsh engine environment, and extended range of sensors. Fiber optics for sensing applications are used to communicate with a sensor device, or use a fiber as the sensor itself, to conduct continuous monitoring of physical engine parameters. The FAA is concerned about EMI threats, and with the engine complexity, the engine manufacturers are concerned about engine weight. The future FADEC systems have to be more compatible; since, they most probably will use fiber optic sensing for control, prognostics and testing. Major breakthroughs have been made recently by the communication industries that can be transitioned to the turbine engine controls and prognostics and health management (PHM) systems. This paper will discuss possible implementation of photonics propulsion control systems.

Fiber optics for diagnostics and troubleshooting are used in varying capacities to test, measure, analyze, transmit, distribute, and/or simulate an optical signal with which procedures and processes associated with maintenance, problem solving, and calibration of equipment and/or networks can be performed.

One of the most challenging turbine-engine sensor requirements is measuring the gas temperature as it exits the combustor and enters the turbine. The durability and performance limit of engine temperature sensors are some of the issues arising from the increase in engine temperatures. Thermocouples are commonly used for engine temperature sensing, but their lifetime is significantly decreased in the high temperature environments. As a result, these sensors have been moved downstream to a cooler operating condition. The turbine inlet temperature is then estimated using an empirically derived relationship with resulting inaccuracies.

The optical probes are inserted directly into combustors and provide direct image information on the combustion processes and on local heating of the combustor. Similar probes have also been used as a conduit for fiber-optic instrumentation to permit application of nonintrusive line-of-sight optical diagnostics in regions that are not accessible to conventional line-of-sight instrumentation. In such applications emissions / absorption measurements have been obtained at a "point" using line-of-sight diagnostic techniques that usually integrate the result over the entire line of sight of the instrument. IFOS' designs are capable of non-line-of-sight measurements at multiple points in harsh environments on a single strand of optical fiber.

IFOS, in collaboration with Pratt & Whitney (P&W), has performed on-engine testing, at the Virginia Tech's propulsion lab, to extend these techniques to include spectrally resolved measurements [3][4] in addition to developing networking approaches [5]-[8]. Once the sensors and optical-based FADEC has been selected, fiber optic harnesses and connectors have to be designed. The optical harnesses today carry several signals at several wavelengths of light, and have to be designed to operate in the same thermal and vibration environment as the sensor and the engine. Data multiplexing and fiber redundancy has to be considered to reduce weight while improve sensor redundancy.

With all the scientific and engineering advancements in the field of fiber optic sensing, the maturity of this technology is high enough and well beyond the experimental lab environment. With its rather low cost, fiber optics sensing technology is a proper option for certain applications in aerospace industry; and it is nearly ready for transitioning. IFOS, in collaboration with gas turbine engine manufacturers, is capable of moving fiber optic sensing technology towards transition into diverse engine platforms. In this paper a brief review of fiber optic technology for gas turbine engine control, PHM and test cell applications is presented.

## **II. Fiber Optics for Engine Control Applications**

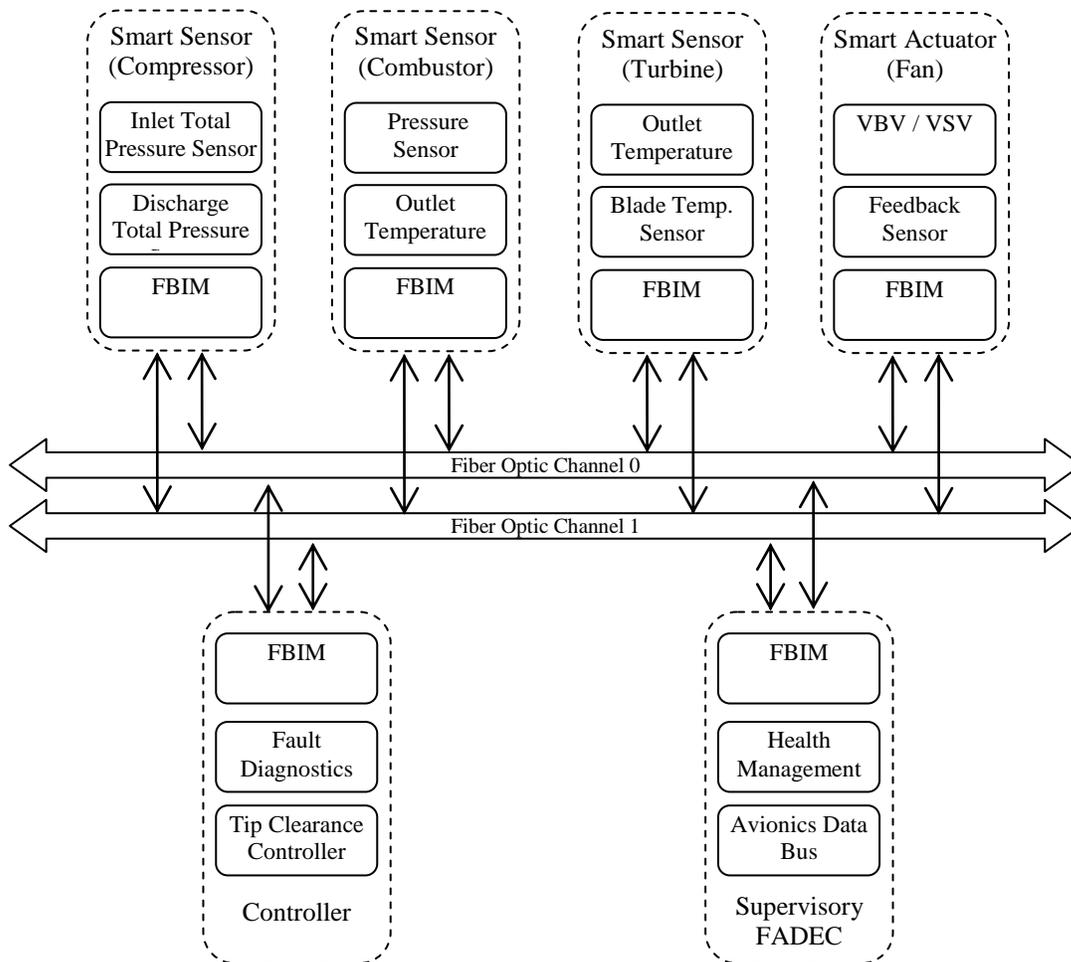
Transition from legacy centralized control architectures to fully distributed engine control architectures can be achieved in a step by step manner by considering intermediate architectures. Partially distributed architectures are more feasible for small turbo-shaft engines, where there are not much significant wire harness weight savings. Also,

for larger aircraft engines, it is easier to implement such architectures using legacy sensors and then move towards a fully distributed architecture [1]-[11]. A brief review of fiber optic application in turbine engine control systems is given below.

### A. Fiber Optic based Engine Control Network

Figure 1 shows an example of engine distributed control with two optical communication channels. Smart Sensors or Smart Actuators, which each consists of a Fiber Bus Interface Module (FBIM), a TTP/C Module and a Sensor/Actuator Module, are connected to each of the fiber optic channels. The sensor module shown in Figure 1 can consist of only one sensor or an array of sensors. The function of sensor module is to collect the information from array of sensors, perform I/O conditioning and if required, can also perform other functions like health management and diagnostics. TTP/C module then encodes the data using the time triggered protocol. FBIM consist of optical interface that supports, adds/drops, broadcasts and passes optical signals on a bi-directional ring bus with automatic protection. There can be a global supervisory controller, which oversees the control action as well as a group of local controllers, for example, inlet fan controller, compressor controller, etc.

The bandwidth of optical fiber network can be further increased by use of Wavelength-Division Multiplexing (WDM), which uses lasers having different wavelengths to transmit the data on a single optical fiber. This technique can be further divided into Coarse WDM or Dense WDM depending on the channel spacing. References [12]-[15], [16], [17] provide an overview of the developments of WDM for use in aerospace applications. WDM based fiber optic network which can work at a temperature range of -55 °C to +125 °C is discussed in [18]. The use of Optical Ring Network based on CWDM (CORIN) or based on DWDM (DORIN) for aircraft engine control is discussed in [5].



**Figure 1. D<sup>2</sup>FADEC Architecture [20].**

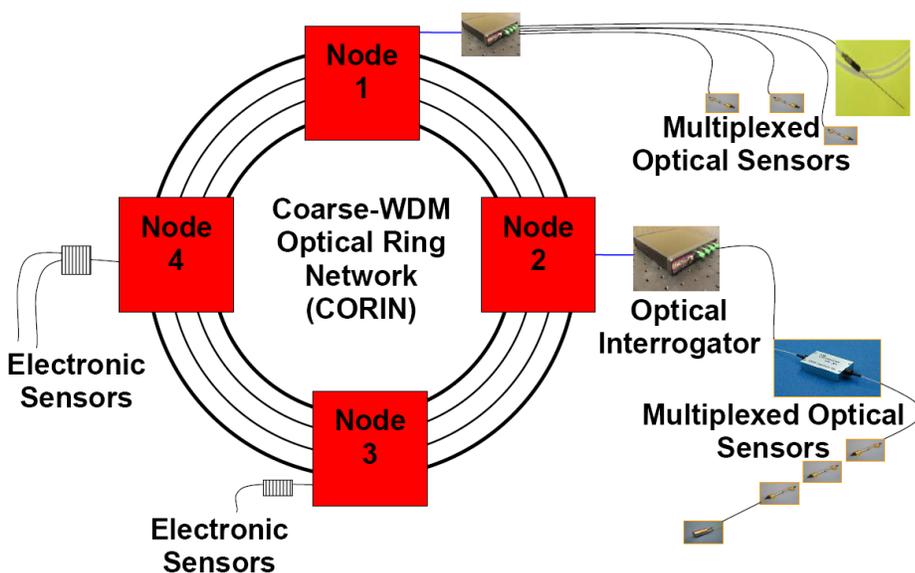
**B. Coarse Optical Ring Network (CORIN) for Turbine Engines**

The Full-Authority Digital Engine Control (FADEC) centralized architecture has been the norm in aeroengine control systems. In centralized systems, changes are costly and complex. Additionally, requirements for increased performance, wider operability, and reduced life-cycle costs necessitate innovative solutions to replace traditional systems. To address this need, IFOS has developed a distributed fiber-optic backbone network architecture suitable for critical aero-engine performance monitoring. Based on resilient high-reliability and self-healing telecom-class network models, IFOS's distributed fiber-optic Wavelength-Division Multiplexing (WDM) backbone architecture adopts a Coarse Optical Ring Network (CORIN) [5]-[8], [19] with standardized optical network interfaces. Recent advances in WDM have yielded major capacity increases and reliability improvements overcoming electronic bottlenecks with optical networks.

Distributed control architectures involve engine-mounted “smart” sensors that communicate with the propulsion system controller through high-speed data buses. These "smart" sensors will provide self-reliance for calibration and testing and will only transmit necessary processed data. Use of these smart sensors would eliminate the need for point-to-point wiring of sensors over extended distances from the engine controller thus greatly reducing engine harness weight [35]. The use of smart sensors for jet-engine control is currently limited by the availability of mature high-temperature electronic components that can withstand the engine operating environment. As technology advances, smart sensors will appear in many different engine applications. One of the most challenging areas of turbine-engine sensing is the measurement of the gas temperature exiting the combustor and entering the turbine. The durability and performance limit of engine temperature sensors is an issue for an increased engine temperature.

Therefore, thermocouples are commonly used for engine temperature sensing, but their lifetime is significantly decreased in a high-temperature environment. Consequently, many of these sensors have been moved downstream to a cooler area. Turbine inlet temperature is then estimated using an empirically derived relationship with resulting inaccuracies. Our research aims to address the deficiencies in current sensor technology. The objective of our work is to make available robust intelligent sensor technology, which can operate in an environment with temperatures >1200°F and vibrations >500 g rms. We plan to extend the operating temperature of the sensors to >2000°F.

The IFOS distributed architecture integrates electrical sensors, probes and actuators with future optical sensing systems in a fault-tolerant architecture. This design provides significant size and weight reduction, major reliability gains, operational, maintenance and economic benefits, resulting in enhanced performance and reduced life cycle costs for next-generation avionics. A 4-node (2 optical, 2 electronic) CORIN system combining multiplexed fiber-optic sensors with electronic sensors is shown in with thermocouple-based temperature sensors.



**Figure 2. Four-node CORIN [3].**

A version of this CORIN system for the case of fiber-optic temperature and strain sensors combined with electrical (thermocouple) sensors was tested at Virginia Tech on a Pratt & Whitney PT6 engine. The test results demonstrated excellent performance of the communications protocols managing information from disparate sensor nodes on the optical ring, thus forming the basis for a Distributed Control System (DCS) architecture. IFOS and Pratt & Whitney plan to transition the technology to government platforms.

*1. Some Experimental Results*

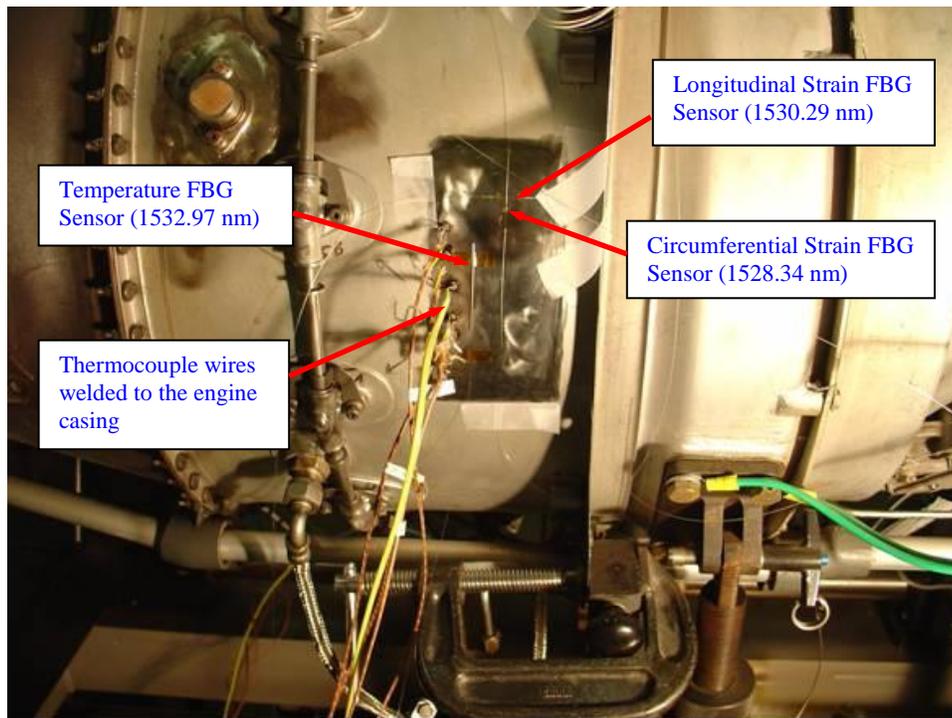
The group of engine casing sensors is shown in Figure 3. Data analysis results for the temperature sensors are shown in Figure 5, and those for the strain sensors are shown in Figure 5 and Figure 6. Observations are documented within the following paragraphs in this section.

Temperature sensors

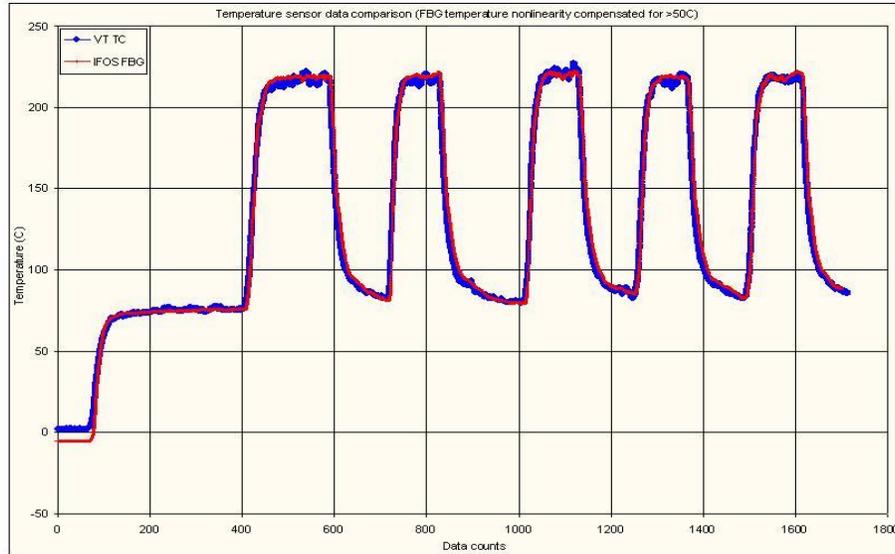
The first evaluation is a comparison between FBG and TC temperature sensors. A nonlinear calibration curve, generated with a coarse set of actual FBG readings vs. temperature, was thus applied and updated results are shown in Figure 5. It seems the engine casing temperature was approximately 75°C at idle and 220°C at maximum throttle. The FBG temperature readings are now comparable to the TC readings. Much finer calibration data for both types of sensors would improve correlation and measurement accuracies.

Strain sensors

With the FBG temperature sensor response available, temperature compensated strain sensor data can be evaluated for both longitudinal and circumferential mounting cases. Figure 5(a) shows the longitudinal strain. Figure 5(b) shows the magnified first cycle data section in Figure 5(a). The longitudinal FBG strain sensor readings correlate with engine throttle levels. The strain pattern repeats during the cycle test.

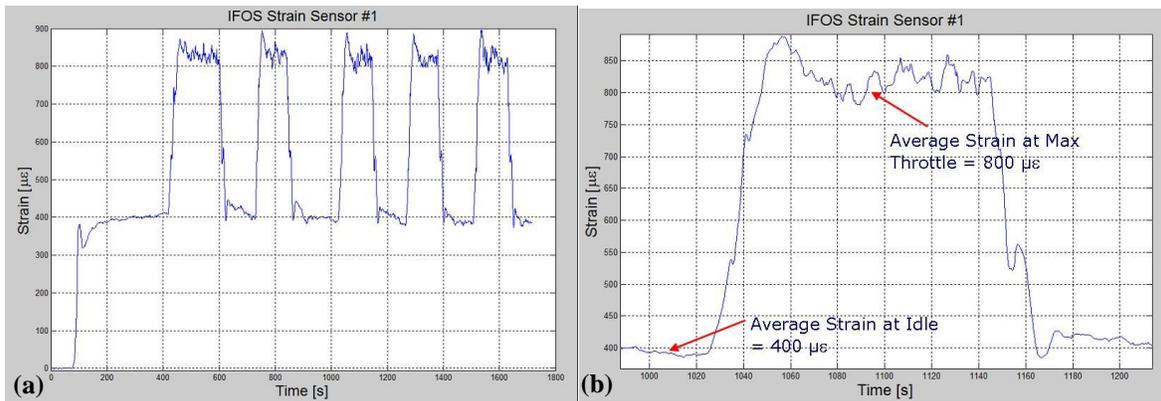


**Figure 3. Electrical and fiber optic sensors on the PT6 engine casing [3].**

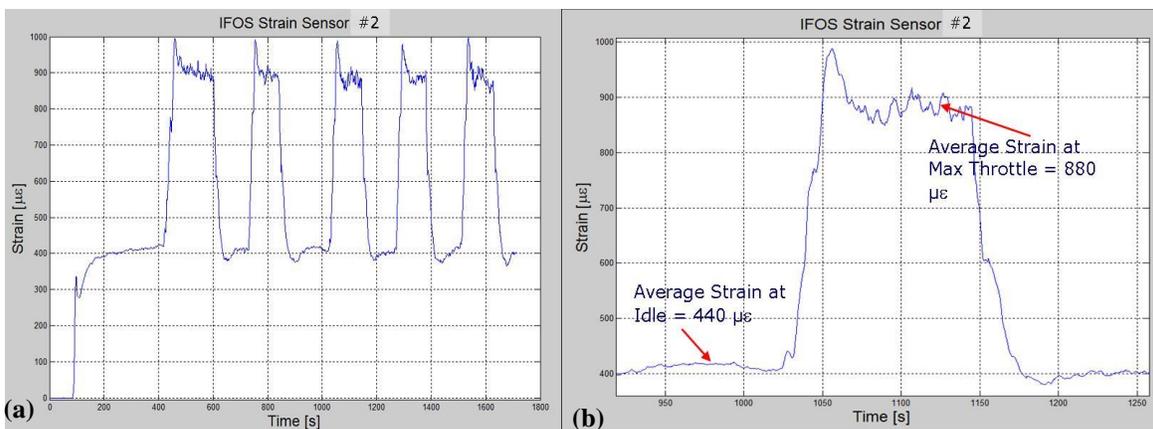


**Figure 4. Cycle test – FBG (nonlinear calibration curve) vs. TC temperature readings [3]**

Figure 6(a) shows the circumferential strain. Figure 6(b) shows the magnified first cycle data section of Figure 6(a). The circumferential FBG strain sensor readings also correlate with engine throttle levels, and the strain pattern also repeats during the cycle test. The circumferential strain levels were observed to be approximately 10% higher than longitudinal strains.



**Figure 5. (a) Longitudinal casing strain (temperature compensated) with (b) zoom of first cycle [3].**

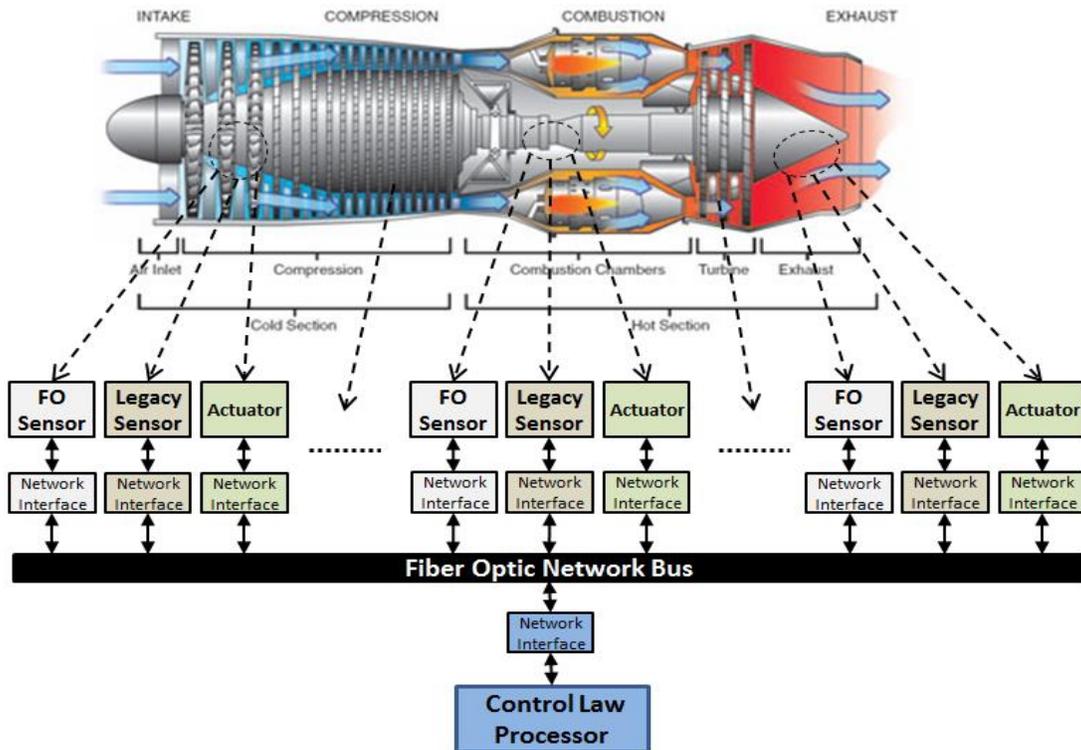


**Figure 6. (a) Circumferential casing strain (temperature compensated) with (b) zoom of first cycle [3].**

### C. Fly-by-Light Systems

Fly-by-light (FBL) control systems have been investigated previously by various researchers [22]-[29]. FBL control systems are different from their fly-by-wire (FBW) counterparts in that they use fiber optic links instead of wires to transmit data from the flight control computers to the actuator controller. Fiber optic systems are capable of transmitting multiple channels of bidirectional information with lighter hardware, are intrinsically immune to electromagnetic interference, and possess a broader transmission spectrum. The FBL system transmits a redundant signal, which requires a second wire bundle in a traditional FBW system [30]. Despite the fact that fiber optics technology has extensive applications in communications, it has not yet seen significant applications in civil aviation due to integration, validation, reliability, and cost factors. Several of the latest fighter aircraft, including the Eurofighter Typhoon, uses a fiber optic control link, and Gulfstream recently flight-tested a FBL-version of the G650 [30]. The German DLR operates the first fly-by-light research helicopter.

Figure 7 visualizes a conceptual schematic of a distributed optical control architecture for gas turbine engine systems. This engine control architecture is interconnecting various fiber optic and legacy sensors along with different engine actuators and control processors. This network can be designed to integrate heterogeneous components – such as fiber optic (FO) sensors, legacy sensors, and actuators – in a distributed architecture with a fiber optic network bus as its data-bus. One or multiple processor can be used for control law computations.



**Figure 7. Conceptual schematic of distributed optical control architecture for gas turbine engine application. This is a heterogeneous network of fiber optic (FO) sensors, legacy sensors, actuators, and control law processor/s connected via a fiber optic network bus.**

The optical network control system (ONCS) is a spatially distributed system in which the communication between fiber optic sensors, legacy sensors, actuators, and control processors occur through a shared optical communication network, as shown in Figure 8. In ONCS bandwidth, packet dropout and network induced delays usually are not critical issues [31], [6], [8], for proper operation of the control system, but depending on the overall ONCS configuration, effects of jitter, noise, etc. on the stability of the whole system should be studied.

For gas turbine engine applications, high temperature conditions affect the communication in the networked architecture [32], [33], and there is a need to understand the effects of the high temperature on the communication system within ONCS framework. In the distributed engine control some of the electronics employed as smart nodes

(sensors and actuators), should be placed in high temperature positions, and hence the processing in those elements will be affected by high temperature [34].

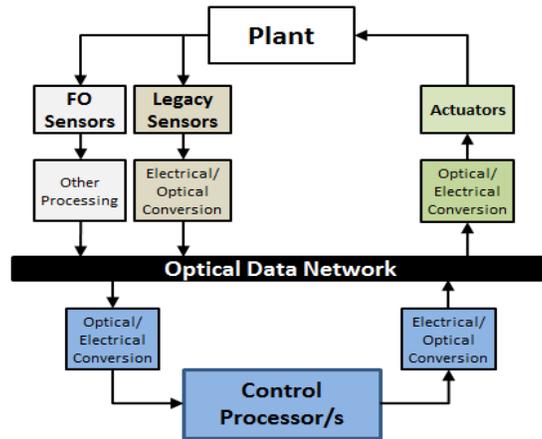


Figure 8. Schematic of a simple optical networked control system architecture

### III. Fiber Optics for Engine PHM Applications

In this section a brief review of the fiber optic technology for engine PHM applications is presented. This section is mostly adapted from [1].

#### A. End-to-End Fiber Optic Sensing Systems

For practical application a fiber optic sensing system needs to include: sensors, fiber optic link, interrogator (comprising photonics, electronics and firmware/software that converts, for example voltages to measurands such as strains, temperatures or pressures), data interpretation and decision-aid algorithms/software (Figure 9). Two examples of end-to-end sensors systems are: fiber Bragg grating (FBG) sensor and Raman-based distributed temperature sensor (DTS) systems; FBG sensor system is reviewed in the next section.

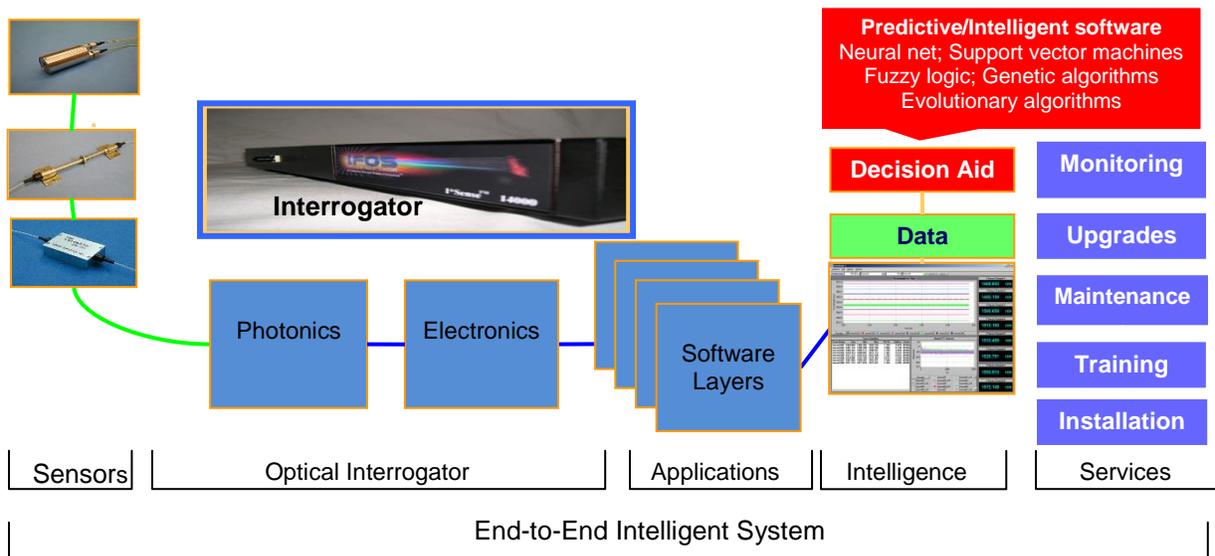
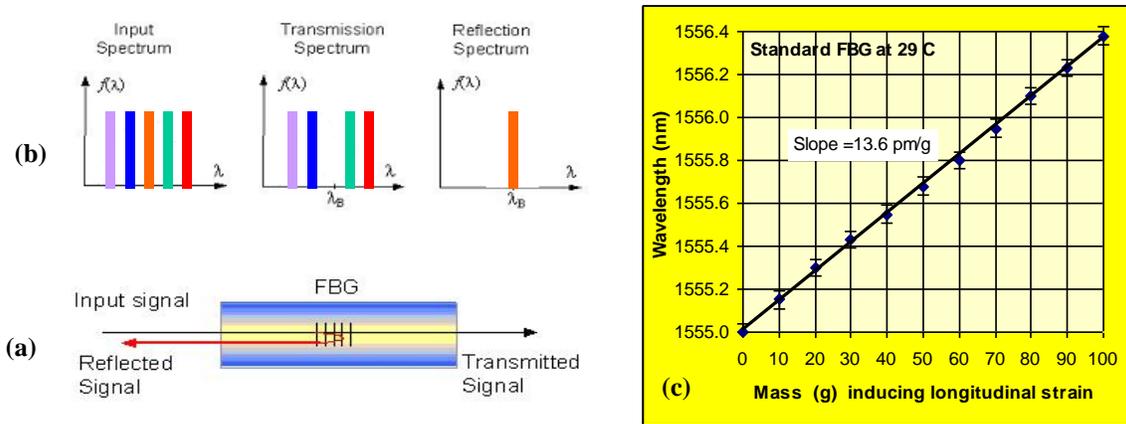


Figure 9. IFOS's end-to-end intelligent fiber optic sensor system [1].

#### 1. Fiber Bragg Grating Sensor (FBG) Systems

The writing of FBGs [36] into select regions along an optical fiber provides a means of creating discrete high-sensitivity, high-resolution sensing sections along the fiber. Furthermore, FBGs are highly multiplexable: many FBGs can be written into a single optical fiber to provide multipoint sensing along that fiber; then, one or more fibers can be integrated as a “nerve(s)” providing “feeling” for “smart” structures. Given these properties, FBG sensing systems are being deployed in a wide variety of applications for structural health monitoring (SHM [36]-[39]) for the measurement of parameters such as strain, temperature, fracture, vibration or simultaneously sensing multiple parameters ([38]-[65]) with diverse applications including, for example, aerospace and robotics [75], nuclear reactors, wind turbines [40], concrete structures [43], bridges [38]-[39], MRI compatible medical devices as well as oil & gas and geothermal wells. FBGs have been established as a particularly important sensor component for static and dynamic strain measurements in smart structures. This is chiefly due to their precision, resolution and reliability, tolerance of extreme conditions and immunity to RF electromagnetic interference. In many applications, arrays of FBG sensors along a single fiber at multiple locations are required to collect data samples at high speed with micro-strain resolution. However, traditional approaches to processing the optical signals either lack in sampling rate speed or are cost-prohibitive as the number of optical sensors increases. On the other hand, recent advances in interrogation technology are opening up the possibility of supporting a large number of FBG sensors (on the order of a hundred per fiber) at high speed (hundreds of kHz to MHz).



**Figure 10. (a) Fiber Bragg grating (FBG) consists of length of the fiber core (typically several mm) where the refractive index varies periodically with the grating pitch,  $\Lambda$ , about a mean refractive index of the core,  $n$ . (b) Given a broadband input spectrum the FBG removes a narrow wavelength band from the transmission spectrum. This wavelength band appears in the reflection spectrum and is centered on a wavelength characteristic of the FBG and known as the Bragg wavelength  $\lambda_B = 2\Lambda n$ . (c) The reflected wavelength is linearly proportional to strain  $\epsilon$  on the grating providing the basis for strain sensing – In particular, the fractional change in wavelength is related to the strain by  $\delta\lambda_B/\lambda_B \approx 0.78\epsilon$  for a silica fiber. In the graph the strain is induced by hanging on the fiber weights whose mass is given in grams – We refer to [66] for detailed relationships between wavelength change, wavelength and weight for a range of optical fibers [1].**

As shown schematically in Figure 10, a fiber Bragg grating operates by acting as wavelength selective filter that reflects a narrow band of wavelengths centered on the grating’s characteristic wavelength referred to as the Bragg wavelength,  $\lambda_B$ . The Bragg wavelength is related to the grating pitch,  $\Lambda$ , and the mean refractive index of the core,  $n$ , by  $\lambda_B = 2\Lambda n$ . Both the fiber refractive index and the grating pitch vary when strain is applied to the FBG and/or the temperature is changed. Wavelength change measurement then provides a basis for strain and temperature sensing. For example, high-resolution strain sensing operation can be achieved by precise measurement of the wavelength.

A key element in any FBG sensing system is the optical interrogator. Interrogators can be constructed to measure the wavelength change with sub-picometer resolution, thus allowing sub-microstrain resolution strain sensing. A general schematic for parallel processing interrogator system to measure the wavelengths reflected by the grating sensors as a basis for determining strain as shown below in Figure 11. Therein we show a schematic of an FBG interrogation system supporting multiple grating sensors on multiple optical fibers capable of reaching hard-to-access regions via bending paths with immunity to electromagnetic interference and possibly over several kilometers. The interrogator

sends out light along each fiber to each grating and analyzes the reflected spectra to determine changes in the Bragg wavelength of each grating.

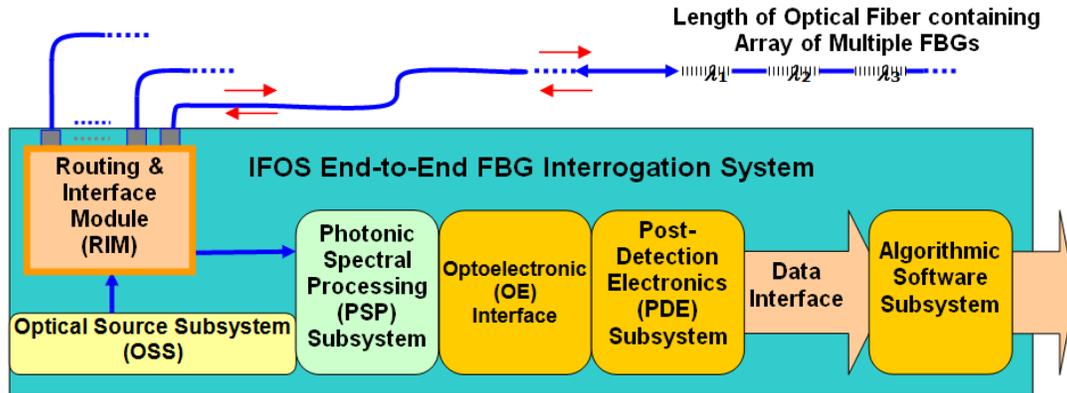


Figure 11. IFOS parallel processing FBG interrogation supporting multiple FBG arrays [1].

### B. Extreme-Temperature Environments

Given appropriate coatings and/or packaging, optical fiber sensors fare relatively well in both cryogenic [71] and elevated temperature [54] environments including those encountered in aerospace, nuclear reactor, geothermal [73] and thermal protections system (TPS) [1], [52]-[54], [76] applications.

Figure 12 shows an example setup for temperature monitoring with an FBG array in a TPS tile subjected to heat from one side as may be the case for a re-entry vehicle. Figure 13 shows that, as one side of the tile was subjected to up to 540°C heat, all FBG sensors survived and tracked temperature at different depths through the TPS tile cross-section.

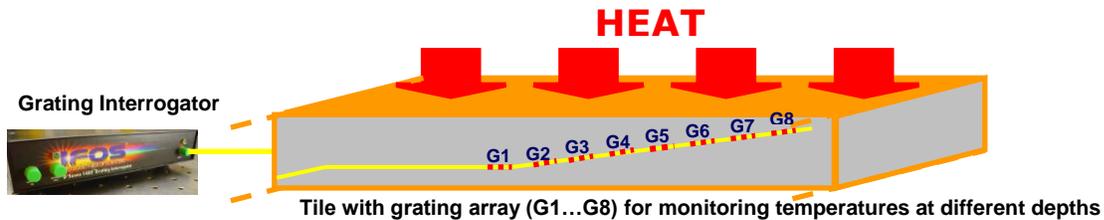


Figure 12. Setup for measurement of temperature profiles in TPS tiles using an array of FBGs [1].

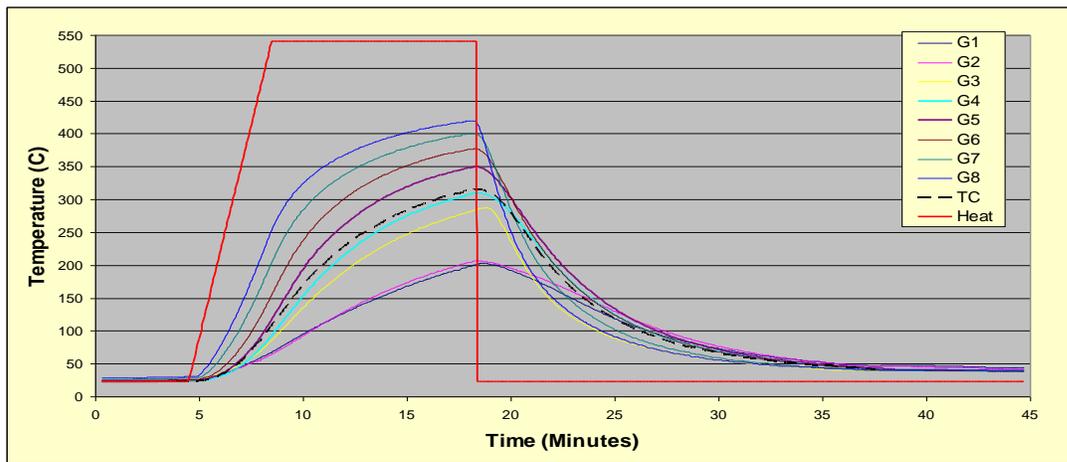


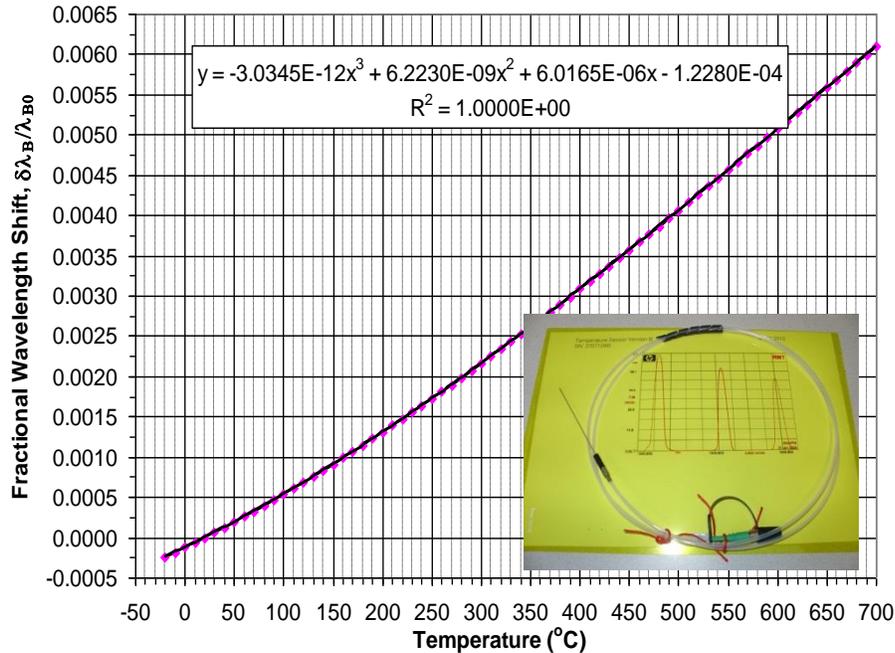
Figure 13. Temperature profile tracking at different depths in TPS with FBG array (G1...G8) and thermocouple (TC) near G4 [1].

## IV. Fiber Optics for Engine Test Cell Applications

A review of fiber optic for gas turbine engine test cell applications is given below. This section is mostly adapted from [4] and [76].

### A. Temperature Sensor Probes and Calibration

A fiber temperature sensing probe was developed including three high temperature fiber Bragg gratings (FBGs) on a single optical fiber with each FBG separated by 20 mm (center-to-center). While the resonant (Bragg) wavelength reflected by FBGs typically varies on the order of 10 pm per degree C, the temperature dependence is in general slightly nonlinear and depends on the FBG writing process. Thus, characterization of the response is particularly important in obtaining accurate FBG-based temperature sensors. The FBGs were calibrated against a type K thermocouple to obtain the temperature dependence of the fractional wavelength shift, i.e., the Bragg wavelength change  $\delta\lambda_B$  divided by the initial Bragg wavelength  $\lambda_{B0}$ , as shown in Figure 14.

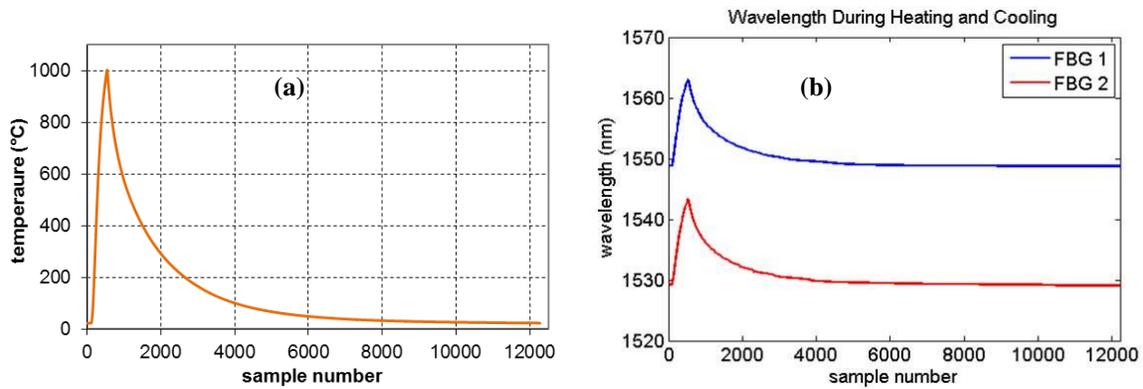


**Figure 14. Nonlinear temperature dependence of the 3 FBGs used for probe shown in the inset - a polynomial fit for the dependence is given where y corresponds to the fractional wavelength shift relative to the wavelength at 20 $^\circ\text{C}$  and x is the temperature in  $^\circ\text{C}$  and the  $R^2$  value for the fit is 1 [4]**

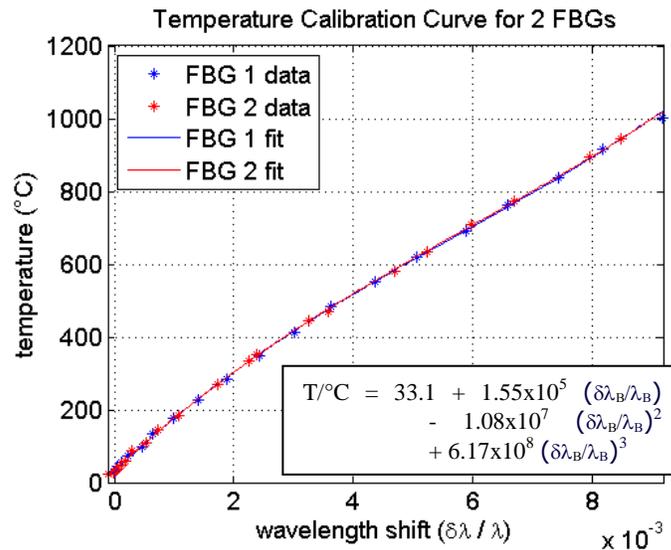
#### 1. Calibration of High-Temperature FBG Array to 1000 $^\circ\text{C}$

The objective was to demonstrate survivability of a grating array (fabricated for measuring differential temperatures) at elevated temperature. We also wanted to show survivability when subjected to tensile loading during and after high-temperature treatment as some tensile loading may occur during a heat-shield operation, and degradation of strength would not be desirable in such circumstances. A Type II grating array in a high-temperature optical fiber was taken to nearly 1000 $^\circ\text{C}$  over a period of 85 minutes, and subjected to approximately 6.8 kpsi of tensile force (applied by hanging 0.6 kg to the end of the fiber) without breaking.

The thermocouple response and FBG wavelength shift as a function of time are plotted in Figure 15. We observe a similar time response in both data sets, as expected.



**Figure 15. (a) Thermocouple temperature vs time. (b) FBG wavelength vs time (2 seconds per sample) [76].**



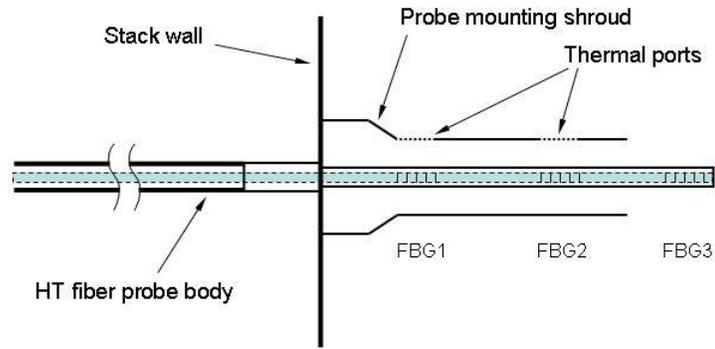
**Figure 16. Calibration curve for high-temperature FBGs deduced from the results in Figure 15 [76].**

The calibration obtained from this test is plotted in Figure 16. A third order polynomial given in Figure 16 was used to fit the FBG temperature response in the temperature range up to 1000°C.

While at 990°C, we subjected the FBG array to 6.78 kpsi tensile stress (46.7 MPa) by hanging 600 grams on the end of the fiber. Following cooling, we subjected the FBG array to 18.1 kpsi tensile stress by suspending 1.6 kg on the end of the fiber without any signs of breakage.

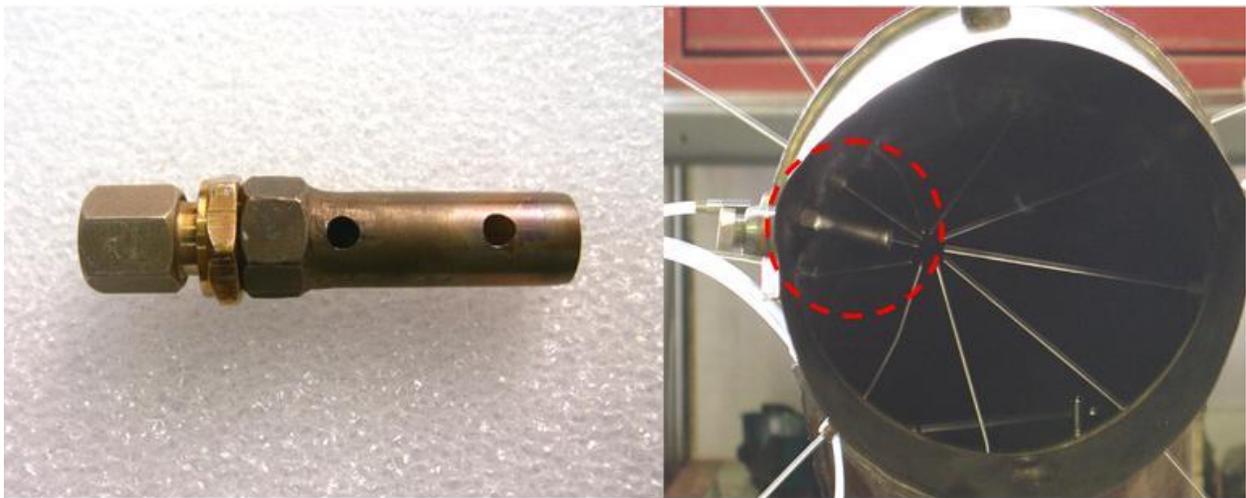
### B. Exhaust Stack High Temperature FBG Sensor Array Mounting

The objective was to evaluate reliability and repeatability of the high temperature probe in the exhaust stack. Results for the high temperature (HT) FBG sensor probes in previous engine test showed incongruent responses, which apparently was due to the probe mounting shroud shielding two of the sensors in the array from sensing exhaust flow directly. To resolve this, careful probe measurements were made and the shroud was correspondingly modified to port exhaust gases such that all three FBG sensors can experience the exhaust flow, as shown in Figure 17.



**Figure 17. High temperature FBG probe mount modifications executed to improve response [4].**

The completed probe mounting in the exhaust stack is shown in Figure 18.



**Figure 18. Mechanical modifications to probe mounting shroud (left) to allow porting of exhaust gases to otherwise shielded FBG sensors, and mounting of the probe unit (right) such that the thermal ports on the shroud face the exhaust gas flow (ports are hidden from this view angle) [4].**

### C. Jet Engine Temperature Cycling & Exhaust Stack Measurements

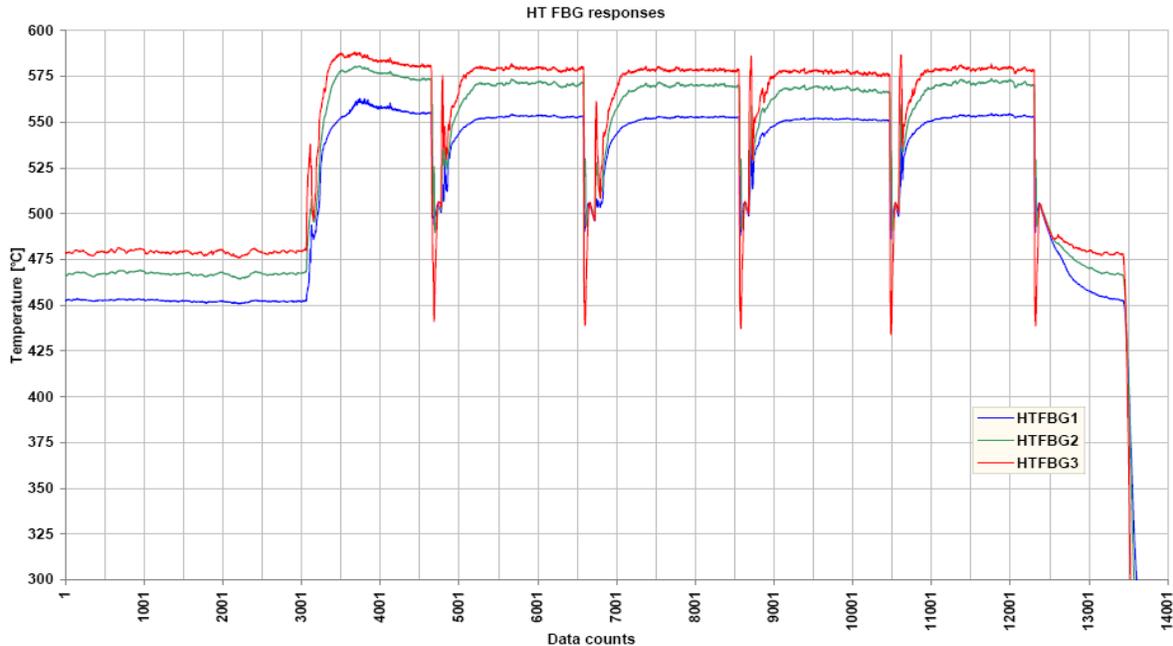
Successive temperature measurements were made for a series of five tests plans. As an illustrative example, Table 1 shows the fifth test plan. This plan was devised to simulate an urgent touch-and-go flight pattern. As can be seen from Figure 19, a fast throttle snap down towards Engine Power (EP) = 55~60% is possible with this PT6 engine, as well as the ability to maintain fairly consistent EP = 100% operation levels after each snap. Figure 19 definitively shows the superior transient response capability of high temperature FBG arrays for jet engine performance monitoring.

With all test plans completed and documented, they clearly showed that the exhaust gas is indeed hotter towards the center of the flow pattern. Furthermore the exhaust stack data patterns correlate with those of the engine casing RTD.

**Table 1. Test plan for jet engine temperature measurements [4].**

	<b>Test Plan: Idle snap + maximum power dwell – 4 (snap) cycles</b>	<b>Total Elapsed Time (Mins, Secs)</b>
1.	Idle for 5 minutes	05'00"
2.	Fast ramp to max and hold for 3 minutes	08'00"
3.	Fast ramp down to idle, count 5, fast ramp up to max	08'30"
4.	Fast ramp to max and hold to 3 minutes from ramp	11'30"
5.	Fast ramp down to idle, count 5, fast ramp up to max	12'00"

	<b>Test Plan: Idle snap + maximum power dwell – 4 (snap) cycles</b>	<b>Total Elapsed Time (Mins, Secs)</b>
6.	Fast ramp to max and hold to 3 minutes from ramp	15'00"
7.	Fast ramp down to idle, count 5, fast ramp up to max	15'30
8.	Fast ramp to max and hold to 3 minutes from ramp	18'30"
9.	Fast ramp down to idle, count 5, fast ramp up to max	19'00"
10.	Fast ramp to max and hold to 3 minutes from ramp	22'00"
11.	Fast ramp down to idle and hold for 3 minutes from ramp	25'00"



**Figure 19. High temperature FBG response for the test plan in Table 1 [4].**

## V. Conclusion

Optical fibers are small-in-diameter, light-in-weight, electromagnetic-interference immune, electrically passive, chemically inert, flexible, embeddable into different materials, and distributed-sensing enabling, and can be temperature and radiation tolerant. With appropriate processing and/or packaging, they can be very robust and well suited to demanding environments. In this paper, we reviewed FBG sensor systems as examples of complete end-to-end fiber optic sensor systems that IFOS has developed comprising not only (1) packaged sensors and mechanisms for integration with demanding environments, but (2) ruggedized sensor interrogators, and (3) intelligent decision aid algorithms and software systems.

Accuracies achievable with optical sensors are comparable or better than those obtained with legacy systems used in jet engine FADECs. Tests support a high degree of reliability and repeatability for the optical sensors. Optical sensor response times are faster than those of legacy thermocouples and are generally believed to have much lower noise levels during high engine throttles. The external materials and mounting methods used for the optical probe were the same as for an equivalent legacy probe. Further cost reductions in instrumentation system complexity and installation labor are expected due to the simplicity and elegance of the optical networking solution. Weight reduction and fan efficiency improvements of engine system are expected due to the use of very low weight, low power fiber optic cables replacing complex and power hungry wire harnesses. Given the sensitivity of turbo fan efficiencies to minute temperature variations across the fan and circumferentially around the fan, the optical system will lend itself well for a new level of control and efficiency.

The performance of distributed engine control systems is strongly dependent on the performance of the communication network. Coarse WDM Optical Ring Network (CORIN) and Dense WDM Optical Ring Network (DORIN) are two candidate communication networks appropriate for engine data network. We also discussed partially distributed architecture for distributed engine control based on CORIN. A conceptual schematic of a distributed optical control architecture for gas turbine engine application is also reviewed.

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