Fiber Optic Sensing in Space Structures: The Experience of the European Space Agency

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ABSTRACT
The applications of fiber optic sensors on board spacecraft and launchers are discussed based on the experience gained by several ESA funded R&D projects along with the experience of preparing the first spaceflight hardware demonstrations.

Keywords: optical fiber sensors, spacecraft sensors, aerospace sensors, launcher sensors, spacecraft health monitoring

1. INTRODUCTION

Spacecraft monitoring is critical for the successful operation of any space mission. A variety of sensors are required to provide critical information about the spacecraft health during fabrication, testing and service lifetime. Space is a very challenging environment for any sensing system as it is characterized by microgravity, vacuum (causing outgasing) presence of radiation (γ rays, protons, electrons, heavy ions) large thermal variations, mechanical vibrations and shock resulting from the launch. The specifications for any sensor to be used in a spacecraft are derived by the type of mission primarily defined by the orbital altitude, the operational lifetime and the location of the sensor in the spacecraft.

Fiber optic sensing systems are considered for space applications due to many advantages that can lead to solutions with the potential to out perform their conventional counterparts. These include: insensitivity to electromagnetic interference, freedom from sparking electrostatic discharge, lightweight and flexible harness that can result in significant mass savings, flexible sensor distribution at remote locations in the structure, efficient multiplexing for high sensor capacity, low power requirements per sensor, high signal to noise ratio for high measurement accuracy, multi-parameter sensing, remote interrogation, potential to embed in composite structures. The European Space Agency (ESA) has been investigating fiber optic sensors for several years and currently the first operational spaceflight demonstrations are under development. In the following text, the main R&D activities of ESA in this field are presented.

2. FIBER OPTIC SENSORS IN SATELLITES

There are many potential applications for fiber optic sensors on satellites, ranging from the mapping of strain and temperature distribution to monitoring the spacecraft attitude. The categorization of the fiber optic sensor applications presented next is made according to the satellite subsystem.

Structure and payload monitoring

Space structures are exposed to a severe environment and structural strength margins are often minimized to meet strict mass budgets therefore making them susceptible to damage due to thermal and mechanical loading. In addition, many space structures have a requirement for high dimensional stability and therefore their rigidity and shape are critical and should be monitored. Fiber Bragg Grating (FBG) sensors represent a promising solution for structural monitoring as they are suitable for multi-parameter sensing, can be multiplexed efficiently and can either be embedded or surface mounted [1]. This makes FBGs suitable for strain and temperature mapping of structures during all phases of operation from fabrication through to in service monitoring. Such mapping is useful for determination of structural deformation, vibration detection and suppression, micrometeorite impact detection and classification, and validation of satellite thermal management systems such as the monitoring of heat pipes [2].

Composite materials are increasingly being employed in spacecraft and ESA continues to investigate the application of embedded and surface mounted FBG strain sensors as a means to monitor such structures. ESA has also been active in

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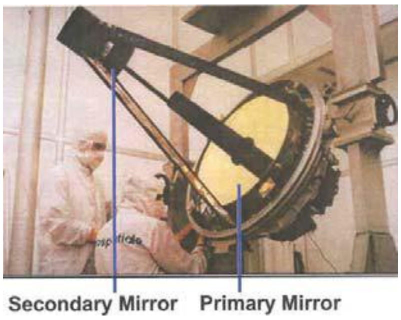
examining the role of **adaptive composite structures** for space applications. Adaptive structures are useful in many applications such as the suppression of frequency modes, isolation of vibration and the compensation for structural deformation mainly due to thermal or gravitational changes experienced in space. The extreme temperature variations in space can cause serious problems for structures that require very high positioning tolerances, for example telescopes and antennas. To compensate for structural deformation the Agency has investigated the use of adaptive structures. Fiber optic sensors are embedded in the structure together with actuating elements to compensate for deformations. As an example, a tripod demonstrator (typical of a telescope structure) with embedded FBG sensors and actuators in one of the 3 legs was developed as illustrated in Figure 1. Although the overall sensor/actuator design and embedding technique has to be optimized, the demonstrator showed that this type of structure can be successfully operated adaptively to counteract environmentally induced deformations.



a.

b.

Fig.1. a. The tripod structure of a typical telescope based on primary and secondary mirror.
b. Breadboard design of a tripod leg, using composite materials with embedded fiber optic sensors and Piezo film actuators visible in the surface (Courtesy of HPS and KAYSER-THREDE)

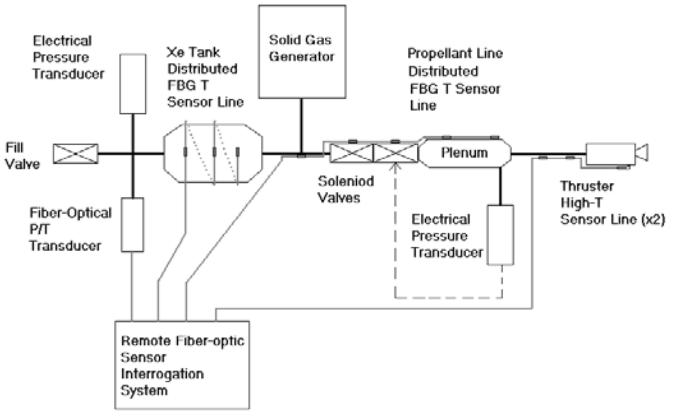
Another example of an adaptive structure is a flywheel support that was actively damped to reduce the coupled vibration. Active vibration suppression can be needed in structures particularly in situations where the accurate pointing of optical payloads over extended measurement periods is required. As is illustrated in Figure 2 a composite support has been instrumented with FBG sensors for static strain measurements and piezoelectric transducers (PZT) patches for vibration suppression. The major challenge of these smart structures continues to be the reliable and robust integration of FBGs into the composite structure and the decoupling of the strain and temperature effects.

Fig. 2 Demonstration of a flywheel mount that is actively vibration damped equipped with embedded fiber optic and PZT sensors. The flywheel would be mounted at the attachment points visible at the top. The cables are fibers or PZT patches. (Courtesy of Carlo Gavazzi Space)

Propulsion subsystem

The propulsion subsystem of a satellite is responsible for providing the critical thrust for maneuvering the spacecraft once in space. Monitoring of this system using a variety of sensors is critical for achieving mission success and determining the remaining fuel for mission management and decommissioning purposes. ESA has investigated the development of a fiber optic sensor system for the propulsion subsystem and a flight demonstration is currently under preparation for PROBA II, scheduled to fly in 2007. PRoject for On-Board Autonomy (PROBA) are a series of ESA small low earth orbit satellites dedicated to demonstrating in spaceflight new technologies that provide advanced onboard functionality. Figure 3a shows PROBA-I that was launched in 2001[3]. The propulsion subsystem selected for PROBA II consists of a hybrid cold gas – solid gas generator propulsion system comprised of a Xe tank, solid gas generator, plenum and thruster. The performance and operational safety of this system requires the monitoring of pressure (0 to 45 bar) and temperature at various locations across the system such as the thrusters (-40°C to 400ºC), the fuel tanks and the connecting fuel pipes (-40°C to 70°C). The fiber optic sensor demonstrator (FSD) on board PROBA II will consist of a single central interrogation unit connected to a fiber optic harness consisting of several output/return lines with serially distributed wavelength multiplexed FBG sensors. The FSD shown in Figure 3b will serve primarily as a back up system to the existing sensors. However, since the fiber optic pressure sensor will have a higher dynamic response and better resolution (10 Hz, 2 mbar) than its electrical counter part, and due to the multiplexing capability of the temperature sensors (with resolution better than 0.1°C), the FSD is expected to provide extra valuable information. In addition, it is planned to have one channel available for monitoring the temperature distribution on the optical sub assembly of the sun sensor payload with no additional cost or burden to the mission. This demonstrates the scalability of the FBG sensor system. The FSD has a targeted weight of 1.3 kg, volume of 1400 cm^3 and a peak power consumption of less than 3.5 W whereas the average power required during an orbit is just 0.4 W. The PROBA II mission provides ESA with experience in all phases of preparing a fiber optic sensor system for a real spaceflight mission (from design to integration and in flight monitoring) and builds confidence in the use of this technology for space applications.

a.



b.

c.

Fig. 3. a. The PROBA-I spacecraft during assembly by VERHAERT.
b. Schematic of the fiber optic sensor demonstrator for the propulsion subsystem of PROBA II, and
c. Schematic of the interrogation unit box with total volume of 1400 cm^3 (Courtesy of MPB)

Attitude and Orbit Control subsystem

Gyroscopes are used for maintaining the attitude and orbital control of the spacecraft and are required for many missions. Traditionally inertial measurement systems have relied on mechanical gyros, however in recent years fiber optic gyroscopes (FOG) are being viewed as an alternative because they are solid state, mechanically robust, lightweight and consume less power. The experimental, short-duration mission, Sloshsat-FLEVO satellite (Figure 4) that uses a 3-axis FOG (± 98°/s) is an example of where FOGs have shown an additional advantage being off-the-self available in a competitive price [4]. This obviously is a special case of a spaceflight where the short duration does not impose any special radiation requirements. Presently, ESA and CNES are jointly funding the development of a family of space qualified FOGs for the European space business. After several steps of prototyping and validations for vibration, shock, thermal vacuum, and radiation, a flight demonstration of a 3-axis gyro will be flown onboard the FBM (French-Brazilian Micro satellite). This FOG is 0.01°/h class over a wide temperature range. In parallel, high-performance gyros are being developed to satisfy the needs of a wide variety of missions and have been base-lined for the Pleiades (earth observation) and Planck (space science) missions. Of the biggest challenges is to address the radiation requirements since FOGs have proved to be particularly vulnerable to radiation [1]. New types of radiate hard fibers (possibly microstructure ones) would have to be examined.

Fig 4. The Sloshsat during assembly at NLR. The fiber optic gyroscope arrangement is visible in the lower right part of the front side of the Sloshshat. Two FOG (by Litton-Litef) perpendicular to each other are seen. A third one in the third axis is not visible.

3. FIBER OPTIC SENSORS IN LAUNCHERS

ESA's launcher program consists of:

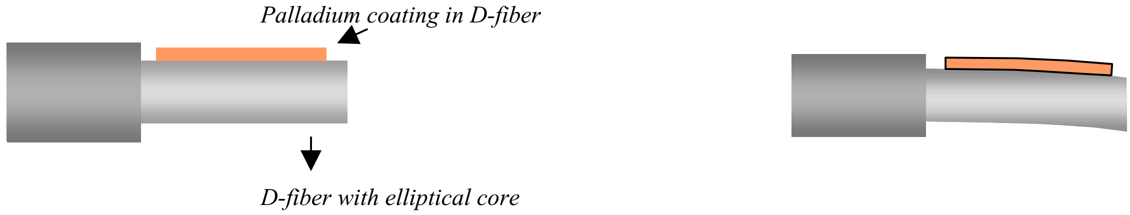
- the Ariane launcher (for payloads up to 10 tons in Geosynchronous Transfer Orbit) currently a major player in space transportation,
- the Vega launcher (for small payloads) currently under development, and
- the Next Generation Launcher (reusable or expendable) currently in its definition phase in the Future Launchers Preparatory Programme

The launcher platform has extensive measurement requirements of engine, fuel tanks and structure (temperature, acceleration, strain, pressure) generally in an environment that is mechanically and thermally harsh. Currently the bulk of the sensors are only applied during design and test phases. Out of thousands of sensors employed during testing of the Ariane launcher only a few are used during flight. It would be desirable to have these sensors available also during the flight, for improved safety and optimization of launch parameters. Clearly this represents an opportunity for the fiber optic sensor market. ESA intends to investigate the applicability of fiber optics as pressure and temperature sensors (in high temperature environments exceeding 1000 ^{o}C) and strain sensors for dynamic measurements.

Reusable Launch Vehicles (RLV) seem to offer the potential for major cost reduction of access to space which is being examined by the FLPP [5,6]. Innovative reusable structural concepts and architectures (to minimize dry mass), advanced materials and manufacturing processes, and refined analytical techniques combined with an efficient Structural Health Monitoring System (SHMS) will provide to the RLV the targeted improved performance at a reduce cost while reducing the operational risk.

Also, engine health monitoring is a key prerequisite to ensure vehicle reusability at affordable cost. The monitoring of a reusable propulsion system requires advanced sensors and measurement systems, capable of sustaining the harsh environment during engine operation. The development of appropriate optical fiber sensors is needed to establish the proper engine health monitoring system. The Thermal Protection System (TPS) and load carrying hot structures will also be instrumented with optical fibers as it is recognized to be among the most important technology challenges for the RLV program. ESA has looked at two distinct applications of fiber optic sensors for RLV health monitoring: the structure of large reusable cryogenic tanks and the inter-tank composite structure.

In the case of the cryogenic tanks a suit of embedded sensors has been investigated for the combined monitoring of strain, temperature and H_2 leakage using FBGs [7]. H_2 leakage detection is based on use of *palladium coated FBGs* as the chemical sensors (Figure 5). The preliminary conclusions are that the FBGs will function as strain gauges (-1000με to + 3000με) over a wide range of temperatures down to cryogenic temperatures of 20K. The temperature sensor also operate down to these temperatures where the fiber needs to be encapsulated in a special glass capillary with a high coefficient of thermal expansion in cryogenic temperatures. However, at cryogenic temperatures the palladium coated FBG H_2 sensors are not practical as they exhibit an inadequate response time below – 30 ^{o}C. One possible solution is to locally heat the sensors. Also, the fact that the sensor is based on a cantilever design means that a dedicated fiber is required for each sensor not allowing multiplexing of H_2 sensors which is a significant disadvantage for an application that requires extensive monitoring.



a. No Hydrogen is present

b. Presence of Hydrogen causes elongation and bending of the palladium coating, elongation of the fiber core and hence a detectable shift at the Bragg wavelength

Figure 5. Palladium coated fiber optic Hydrogen sensor on a D-shaped cantilever structure (Courtesy of KAYSER-THREDE)

With respect to the inter-tank structure ESA has investigated the use of FBGs for strain and temperature measurement as part of the SHMS [8]. Figure 6 shows a reduced scale demonstrator of an RLV inter-tank Carbon Fiber-Reinforced Plastics structure with embedded and surface mounted FBGs to measure both static and dynamic strain. Further tests on the structure will investigate the effects of hot and cold temperatures, high strains, combined thermal and mechanical loads and high cycle mechanical loading for the determination of the durability and health of the structure.

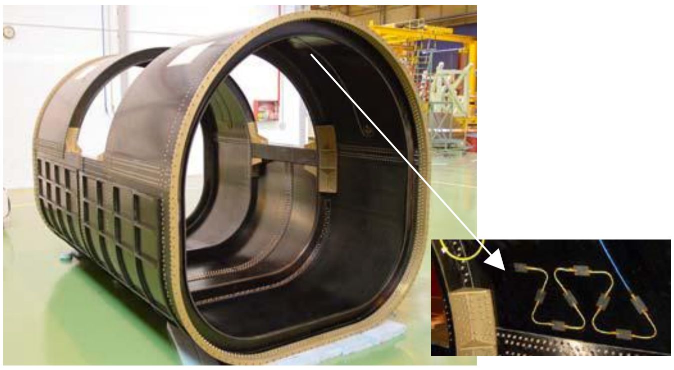


Figure 6. Embedded and surface mounted (inset) fiber optic in a composite inter-tank demonstrator structure (3m long 2m diameter) resembling part of a future reusable launcher (courtesy EADS, CASA and CONTRAVES SPACE). The SHMS for the full-scale inter-tank structure is expected to require 95 strain and 33 temperature sensors, with FBGs being the preferred sensing technology. Tests with the SHMS had a sensitivity of 1με and a range of 3500με sampled at 50 Hz allowing dynamic strain to be monitored

4. FIBER OPTIC SENSORS IN ATMOSPHERIC ENTRY VEHICLES

The re-entry of a spacecraft through any atmosphere at hypersonic speed is one of the most difficult phases of a space mission with the spacecraft being exposed to extreme friction. Understanding better the implications of the aerothermodynamic phenomena in the spacecraft health is therefore critical as some missions depend on this knowledge and hence extensive flight testing and validation is required. **EXPERT,** shown in Figure 8a, is a 1.6 m long, 1.1 m diameter test, 330 kg vehicle that will be employed to test various structural parameters under the stress induced to the spacecraft by the aerothermodynamic phenomena during its re-entry to the earth's atmosphere in hypersonic speeds [9]. Several test flights are foreseen to be launched by the Volna-7 launcher taking-off from Murmansk (Russia). EXPERT will be released in space and following a ballistic trajectory will land in Kamchatka peninsula after traveling several minutes in space. The capsule will be exposed to extreme friction-induced temperatures and mechanical strains. FBGs are proposed to be used in the interior of the Nose Cone Thermal Protection System-TPS as shown in Figure 8c. Currently ESA has an open call for ideas for technologies for the EXPERT vehicle. The developments for the EXPERT test vehicle will also be applied to applications in future **planetary atmospheric probes**. The recent successful landing of the Huygens probe in Titan, 1.2 billion km away from the Earth Ground Stations and the failure of the Beagle lander in Mars demonstrate that in such challenging missions it is critically important to have a good understanding of the health of the planetary probe through all stages of the atmospheric entry.

a. *b.* *c.*

Fig 8: a. A mock up of Expert
b. EXPERT's ballistic trajectory in space and re-entry flight
c. Points of interest for instrumentation with the fiber optic sensor in the Nose Cone TPS of Expert and example of a possible fiber sensor layout

5. FIBER OPTIC SENSORS ON BOARD THE INTERNATIONAL SPACE STATION

Extensive experiments take place continuously in the International Space Station – ISS typically in the field of Life and Physical Sciences. Furnaces are used in many fundamental material science experiments on board the ISS. The inadequate performance of the temperature sensors used to monitor the heating elements largely limit the performance and lifetime of such furnaces. ESA has investigated the problem through a study targeting to provide accurate, long-term drift-free temperature measurement at elevated temperatures in the region 1800^{o}C to 2000°C. The initial survey revealed that at these elevated temperatures *Sapphire fibers* (encapsulated in tantalum sheaths) offered the best solution using radiometry techniques. Experimental verification however was much more difficult as the construction of the furnace mandated the use of bent optical fibers with a bending radius of <50 mm. The bending of the fibers resulted in brittle failures at temperatures around 1200°C, well below the target temperatures due to stresses in the fiber. Furnace temperature measurements up to 1500°C were successfully demonstrated using straight fibers. The material performance of sapphire fibers and their high temperature buffers at temperatures above 1800°C still remains unknown and hence the applicability of such sensors requires further investigation.

Fig.7. A photograph of the tantalum sheaths of two temperature sensors mounted in the test cartridge. Each sheath has an encapsulated sapphire fiber optic sensor. (Courtesy of NPL)

6. FIBER OPTIC SENSORS IN GROUND TESTING OF SPACE STRUCTURES

During ground qualification of any space structure extensive tests take place. The introduction of fiber optic sensors can be seen as two fold. First, they can be considered as specialized sensors, particularly in cases where the environment is very harsh such as extremely high temperatures. ESA has in its technology development plan the development of pressure and thermal flux sensors able to operate in environments that reach temperatures up to 2000 ^{o}C, for example in the engine nozzle. Another application is the use of FBGs for measuring the impact of high frequency acoustic noise in the antenna reflectors. In this application the interrogation unit is called to operate in sampling rates of some KHz which is not usually required in other applications [1].

Looking at this from another point of view, during qualification testing a large number of sensors are temporarily integrated in the spacecraft. Removing them is a delicate and time consuming process in order to avoid inducing any damage to spacecraft components. By using a light weight, low power consumption, dedicated fiber optic sensing network that is permanently integrated in the spacecraft, the sensors could be used for both the ground qualification and for the spacecraft monitoring during the mission. This approach would reduce the number of ground operations and facilitate the handling of the spacecraft. It allows also the direct correlation between the measured ground test results and the actual performance and spacecraft status in space.

7. FIBER OPTIC SENSORS IN SOLAR SAILS

The applicability of fiber optic sensor technologies is also considered in the frame of the study of Solar Sails as propulsion system for spacecraft. Solar sails are extremely thin structures of extremely large (for spacecraft standards) area that can reach thousands of m^2 [10]. It is for example deployed around central booms in the 4 directions around the payload as shown in Figure 9. The *average* surface mass density of solar sails has to be as low as possible up to the limit that it maintains its mechanical integrity. It must be as low as 10 g/m^2 or even less for long interplanetary or interstellar travel. Understanding the dynamics of strains induced in the sail and the attitude of the booms is very important especially during the first spaceflight demonstrations in order to evaluate its behavior, assess the mechanical limits and possibly re-examine the design. A fiber optic sensor arrangement would monitor the stain induced in the solar sail structure mainly and the deformations of the booms with the interrogation unit placed in the payload. Given the extremely low weight of the solar sail any design of a fiber optic sensor arrangement must keep the mass to an absolute minimum.

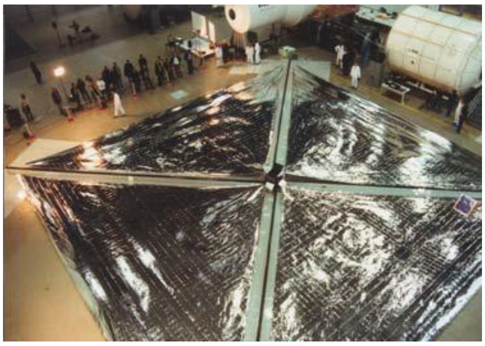


Fig. 9 A ground model of a solar sail deployment demonstrator fully deployed in DLR (lack of gravity was artificially created by means of lifting He Balloons)

8. CONCLUSIONS

In space, the adoption of fiber optic sensors over existing technologies is justified on the basis either of improved performance (when used individually) or on their capacity for a higher degree of multiplexing, though it has still to be demonstrated that this results in simplified integration. In specific missions with no strict radiation requirements the fact that they are off-the-self available at competitive prices gives a definite advantage. Several issues still remain largely unanswered, such as the most appropriate mounting or embedding techniques for fiber optic sensors in environments that can be both mechanically and thermally extreme. Also, the impact of microgravity in the sensor operation must be taken into account to avoid measurement errors [11]. The measurement of pressure and temperature at elevated temperatures above 1000 °C, the sensing of H_2 leakage, and the determination of fuel in microgravity conditions remain open challenges. The future reusable transportation vehicle has demanding health monitoring requirements and represents a very challenging field open to fiber optic sensor technologies. The benefits of introducing a dedicated spacecraft sensing subsystem using a hybrid combination of fiber optic sensors integrated with other technologies is still to be validated. If this technology is to be adopted it is decisively important that spacecraft manufacturers get more experience in integrating fiber optic sensor system into the space structures and gain the necessary confidence and comfort in its use. The applications of fiber optic sensors investigated or considered by ESA are summarized below:

Satellite Subsystem	**Sensor**
Structure and payload	Temperature, Static and Dynamic Strain
Propulsion	Temperature, Pressure, Valve Status, Remaining Liquid Propellant (microgravity)
Attitude Control	Rotation, Acceleration
Launcher subsystem	
Propulsion	Temperature, Pressure, Acceleration, Leak detection, Valve Status
Structure	Temperature, Strain, Acceleration, Leak detection
Atmospheric entry vehicles	
Thermal Protection System	High Temperature
ISS	
Experiments	High Temperature (up to 2000°C)
Ground testing	
Rocket nozzle	Pressure. Thermal Flux (High Temperature),
Antennas Reflectors	Strain (Dynamic in High Frequency)
Solar Sails	Strain, Temperature

Table: Fiber optic sensors applications for space structures

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