Use of transversely loaded fiber optic grating strain sensors for aerospace applications

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ABSTRACT

Most fiber grating sensor technology that has been developed to support strain sensing involves the measurement of axial strain. Fiber grating sensors are however capable of monitoring transverse as well as axial strain. This paper reviews a series of applications of this technology that are of particular interest to aerospace applications.

Keywords: multi-parameter, smart structures, multi-axis, pressure, corrosion

1. INTRODUCTION

By writing a fiber grating into polarization maintaining optical fiber two effective fiber gratings are established along each polarization axis. Because the two axes vary in index of refraction the effective fiber gratings are split spectrally. For typical commercially available polarization preserving optical fiber the spectral split is about 0.3 to 0.4 nm at 1300 nm. For fiber gratings with a full width half maximum spectrum of less than 0.2 nm this allows clear spectral separation between the peaks. When transverse force is applied along one of the polarization axes the relative difference in the index of refraction between the peaks changes. The spectral changes can then be used to measure transverse strain.

In this paper the application of multi-axis fiber grating sensors[1,2,3] that may be used to measure transverse strain will be overviewed with emphasis on their application to aerospace platforms.

2. TRANSVERSE STRAIN MEASUREMENT CAPABILITIES

In Figure 1 a basic multi-axis fiber grating is shown where a single fiber grating is written onto polarization maintaining fiber that is birefringent. When the transverse strain applied to the fiber is uniform along its length the dual peak spectral output is preserved. When transverse loading along one of the axes is non-uniform as is illustrated by Figure 2 the spectral peak will split or broaden. These features can be used to quantitatively measure transverse strain gradients and are very useful in supporting diagnostics internal to adhesive joints as well as in composite structure nondestructive evaluation.

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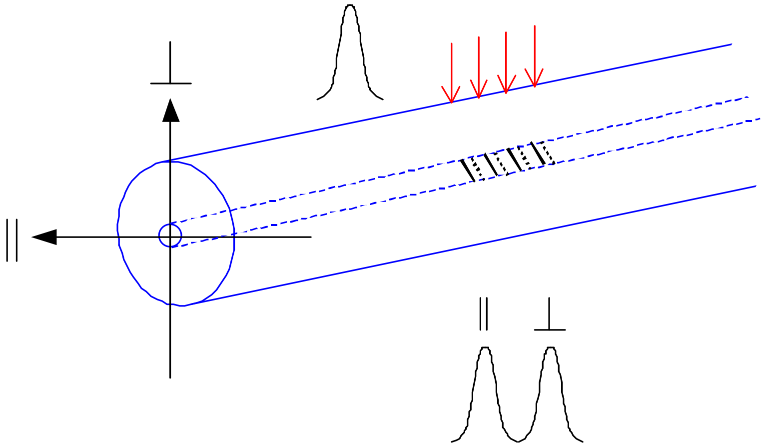

Figure 1. Multi-axis fiber grating sensor used to measure transverse strain. When uniform transverse strain is applied the peaks move apart or together depending on the axis of loading.

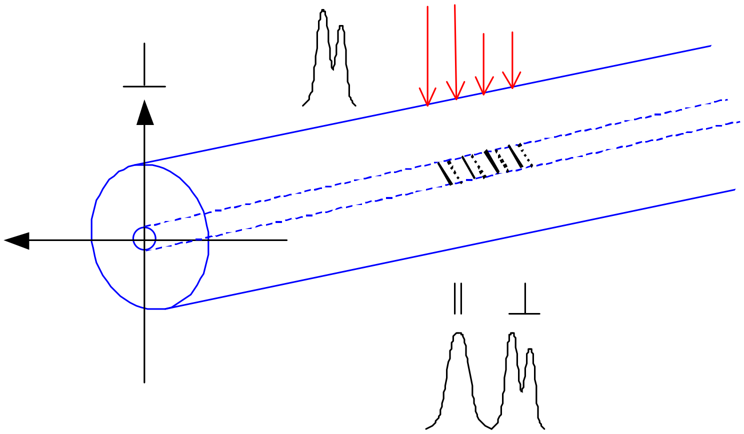

Figure 2. When a non-uniform transverse load is applied across one of the principle axes of the multi-axis fiber grating strain sensor multiple peaks result that can be used to quantitatively measure transverse strain gradients.

As an example of how the transverse strain measurement capability of the multi-axis fiber grating strain sensors may be effectively applied to an aerospace application, Figure 3 illustrates nondestructive measurements interior to an adhesive joint bond[4]. In this case a multi-axis fiber grating sensor is placed in the edge of the bond line where failure is anticipated to initiate. The sensor is oriented at 45 degrees so that shear strain can be measured. From Figure 3 when loading starts to occur the two principal spectral peaks move apart indicating increasing transverse strain. As the load level continues to increase the adhesive joint starts to degrade and the longer spectral peak breaks into two. The difference between the two new peaks is about 0.2 nm corresponding to a change 600 micro-strain. The magnitude of the two new peaks is approximately equal which indicates that approximately half the length of the multi-axis fiber grating strain sensor has been unloaded. The overall shift of the entire spectral profile towards longer wavelengths indicates that axial strain is increasing. Thus this example illustrates the ability of the multi-axis fiber grating strain sensor to measure shear strain, transverse strain, transverse strain gradients and axial strain.

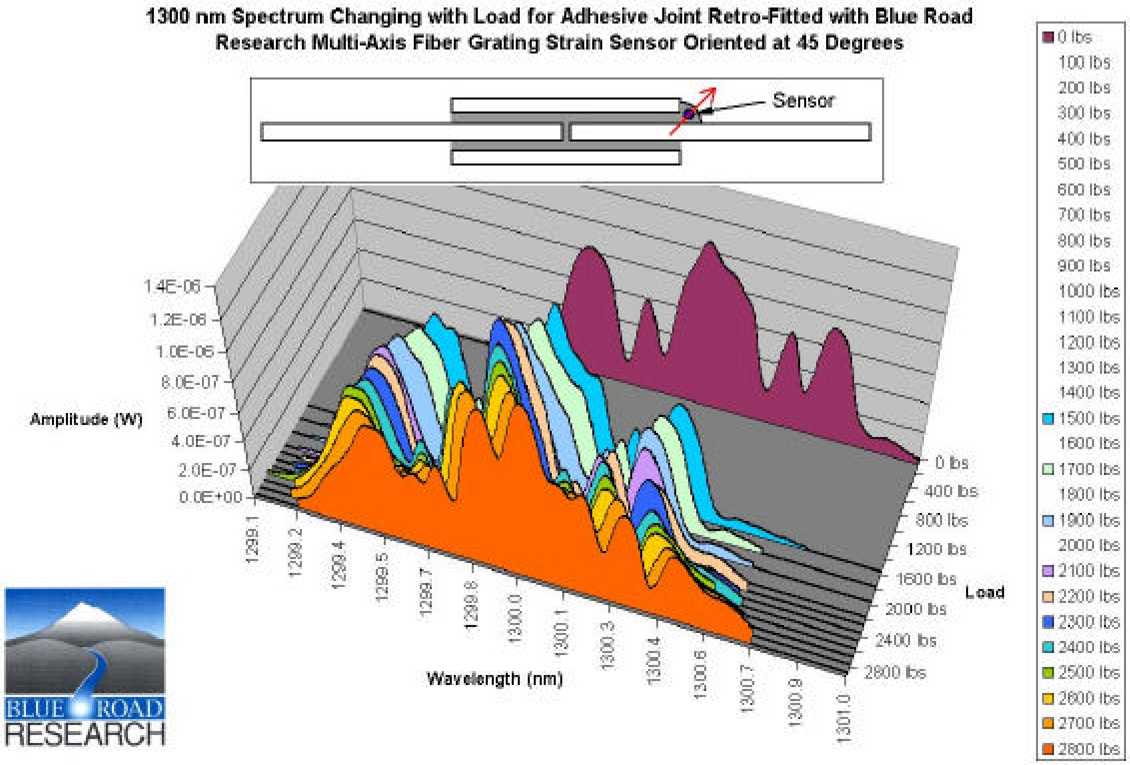

Figure 3. Using a multi-axis fiber grating strain sensor to measure transverse strain, shear strain and transverse strain gradients in an adhesive bond.

Another major aerospace application of the multi-axis fiber grating strain sensor involves embedding the sensors into composite materials. Figure 4 shows the orientation of multi-axis fiber grating strain sensors that have been placed in a composite panel to measure axial, transverse and shear strain fields[5]. By embedding arrays of multi-axis fiber grating strain sensors into wings, tail and fuselage sections of aircraft and spacecraft, the technology offers the prospect of multi-dimensional conformal mapping of deformations of structures. Figure 5 shows the composite panel that was used to support multi-dimensional strain field mapping. In this case the input/output connectors have been integrated directly into the panel.

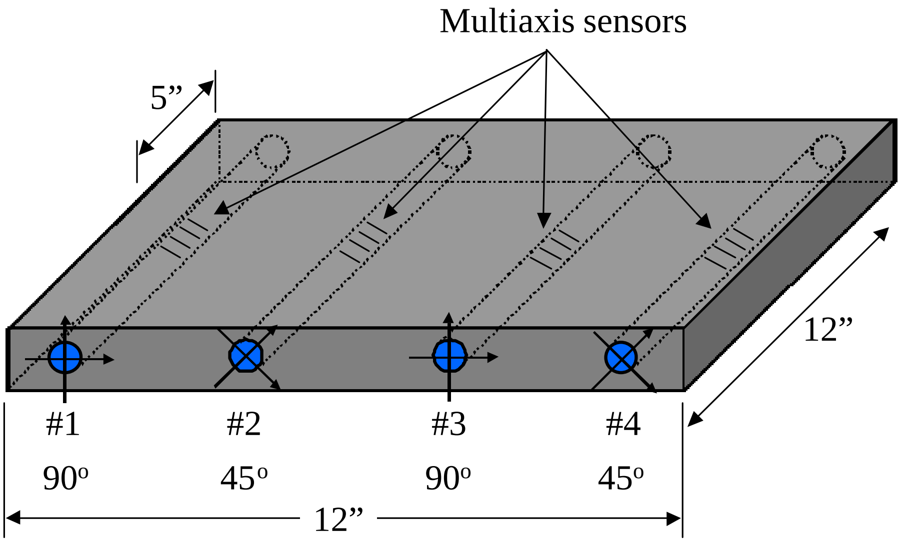

Figure 4. Layout of multi-axis fiber grating sensors in a carbon epoxy panel

Figure 5. Carbon epoxy panel with four embedded multi-axis fiber grating strain sensors to measure transverse, axial and shear strain.

3. USING TRANSVERSE STRAIN SENSING FOR PRESSURE AND CORROSION

In addition to measuring strain fields directly in aerospace structures new classes of fiber grating sensors can be created using transverse strain. As a first example consider the case of fiber grating pressure sensors[6]. If a fiber grating is used directly to measure pressure by placing it into a pressure chamber it will compress with increasing pressure and its spectral output will move toward shorter wavelengths. One of the main issues with this direct approach is that the fiber also changes in wavelength as the ambient temperature changes. The net result is that in order to make a highly sensitive pressure sensor very good temperature compensation is necessary. Figure 6 shows the relationship between pressure and temperature changes for a 1300 nm fiber grating written into Corning SMF-28 fiber. From the graph it is evident that measurements on the order of 1 psi would require temperature compensation on the order of 0.001 degree C.

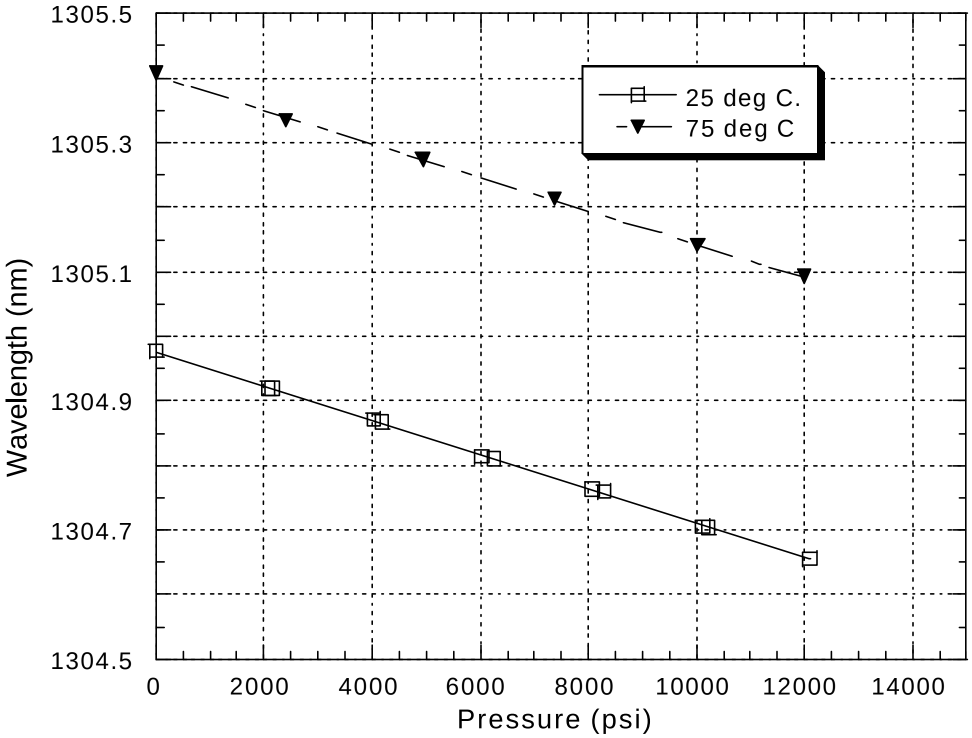

Figure 6. Response of normal FBG with pressure and temperature.

An alternative approach is to utilize transverse strain induced by pressure. As an example optical fiber that has side-holes can be used to support fiber grating sensors. In this case ordinary single mode fiber can be used to splice in short lengths of side-hole optical fiber with fiber gratings. When pressure is applied the result is induced transverse strain fields through the core of the fiber resulting in a spectral split and two peaks whose spectral separation is proportional to pressure. Figure 7 illustrates the effect of applying pressure to such a fiber grating strain sensor. One extremely important aspect of this approach is that since the actual fiber core is quite small the temperature across it is very nearly uniform as a result the temperature sensitivity of this sensor is at least a factor of 70 less than that of the conventional fiber grating used as a pressure sensor.

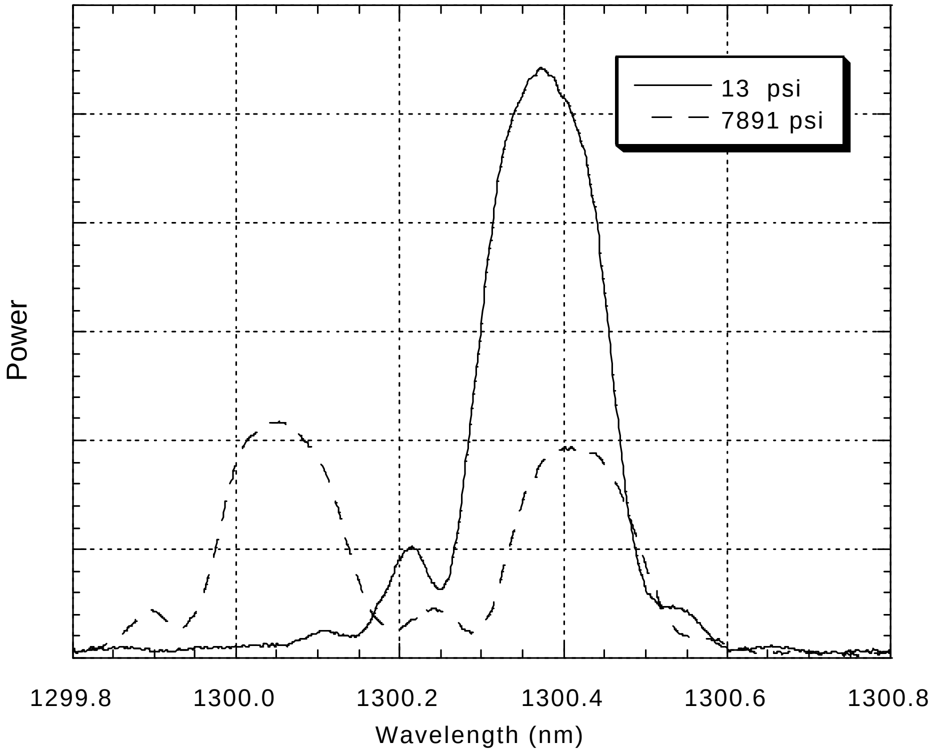

Figure 7. Splitting of Side Hole FBG under pressure.

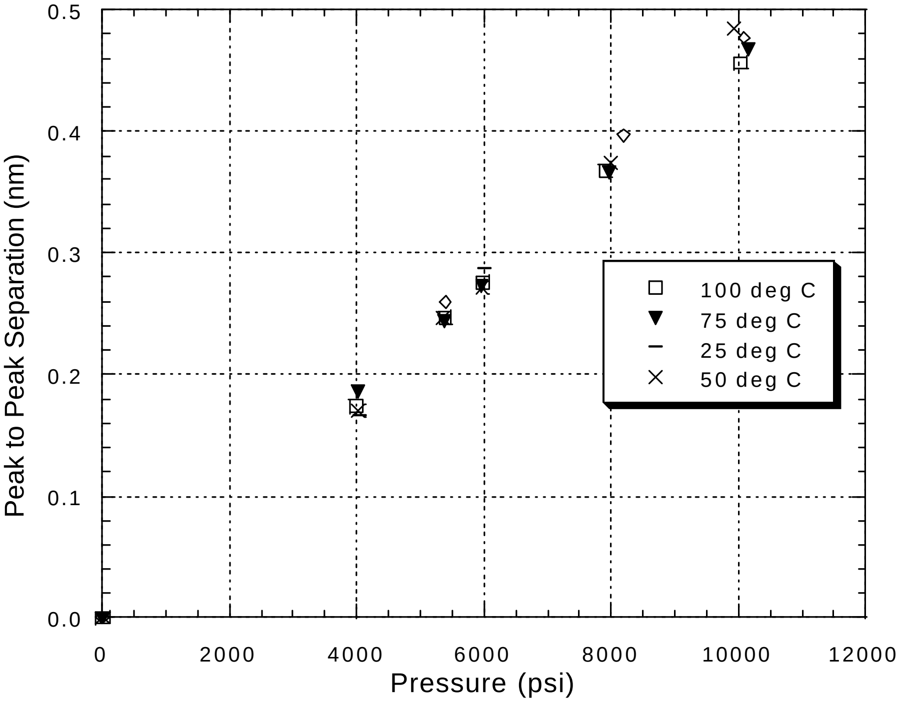

Figure 8. Response of Side Hole FBG with pressure and temperature.

For comparison the temperature versus pressure response of the side-hole fiber grating pressure sensor is shown in Figure 8. The measurements indicate that temperature effects are reduced to a much lower practically manageable level.

Boeing and Blue Road Research have used transverse sensing to create a series of fiber grating based corrosion sensors. In this case a fiber grating is placed between two halves of a split cylinder and a preheated metallic sleeve is slipped over the assembly. When the sleeve cools the split cylinder is compressed resulting in transverse strain loading. The net result is two spectral peaks induced by strain. When corrosion occurs the peak to peak separation changes resulting in a measure of the degree of corrosion.

4. PUTTING TOGETEHR A MULTI-AXIS FIBER GRATING STRAIN SENSOR SYSTEM FOR AEROSPACE APPLICATIONS

One of the great strengths of multi-axis fiber grating strain sensor technology is that it allows for the creation of a series of fiber sensor types that are extremely compatible with one another allowing the usage of similar read out equipment for a variety of applications. As an example Figure 9 illustrates how a multi-parameter fiber grating system can be used to support the measurement of corrosion, transverse strain, axial strain, pressure and ice along a single fiber line. These sensors are multiplexed using wavelength division multiplexing which means they can be easily interchanged with one another and supported by a variety of wavelength measurement equipment. Interpretation of the data associated with each sensor can often be reduced to programming changes where there are no issues associated with variations in data acquisition speed.

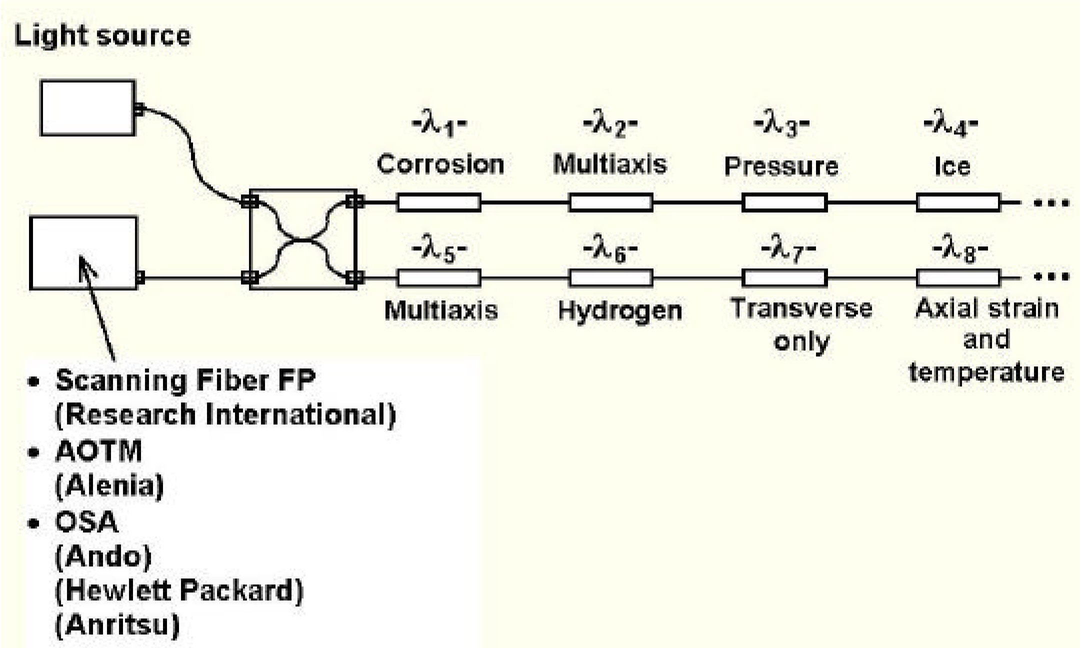

Figure 9. Multi-parameter sensing system

The entire system can then be integrated into an aircraft or spacecraft to support health management, flight control and other functions. Figure 10 illustrates how the system might be implemented in a launch vehicle, reducing inspection costs, increasing readiness, improving safety and offering new possibilities in flight control.

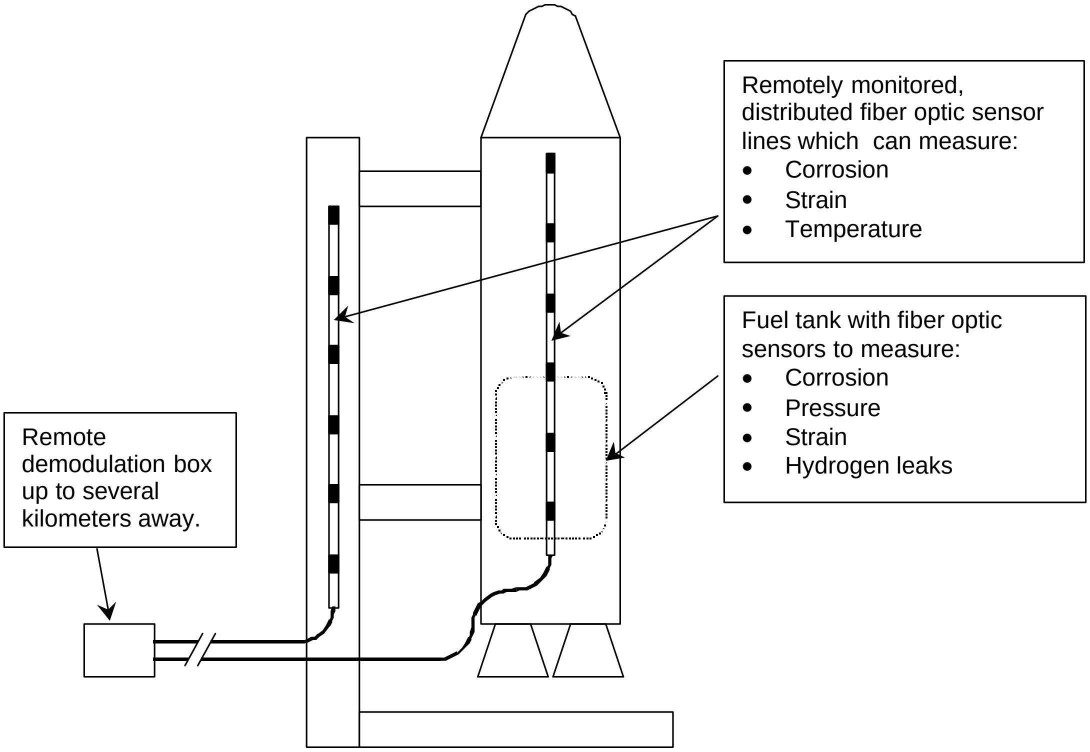

Figure 10. Multi-parameter fiber grating sensors used to support diagnostics on a launch vehicle

5. SUMMARY

A series of multi-axis fiber grating strain sensors and their application have been described. Systems comprised of these sensors offer the prospect of greatly improving health management systems for aerospace vehicles and enabling new capabilities.

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