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Monitor Optics Technology Briefing

White Paper

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Summary: This paper describes the technology underlying Monitor Optic Systems Solutions. It outlines the technology underlying the solutions and highlights the advantages and applications of these solutions.

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Introduction

Monitor Optics Systems provides Structural Health Monitoring Systems for use on Civil Structures. The application of Fibre Optic Sensors is core to our solution.

Monitor Optics Systems specialise in the integration of leading edge technology with industry standard components and systems, targeting mid range solutions where traditional technology is not able to fulfil customer needs.

Monitor Optics Systems aspire to deliver high quality solutions that are simple to install and operate, whilst driving for the lowest cost units possible.

Monitor Optics Systems actively promote the education of our customers in the use of our technology to gain maximum benefits from their investment.

Monitor Optics Systems believes in the validity of long term structural monitoring as an answer to the requirements of a sustainable, more cost effective approach to the management of civil structural assets.

The ageing and degrading of a large part of existing structures together with the ever increasing utilization and the increasing effects on the local communities of off-service times are making the development of maintenance and repair plans more and more difficult. At the same time, the increase of maintenance and survey costs is making the same plans more and more expensive.

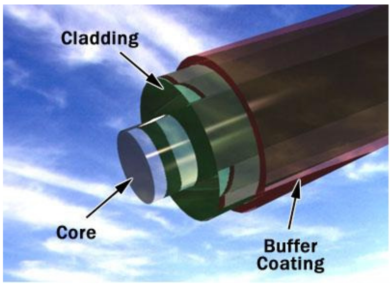
The effect on the public opinion of a number of catastrophic structural failures in the near past also means that new catastrophes and Extreme Environmental Impacts are to be avoided at all cost.

Long term structural health monitoring is a cost effective solution to the problem of developing proper maintenance and repair policies while keeping the associated costs at a minimum for the structural asset owners and guaranteeing the maximum safety for the structural assets end users.

This paper aims to introduce the technology behind Monitor Optics Systems Structural Health Monitoring Systems, illustrate their advantages and provide concrete examples of their application.

Optical Fibres Sensing Technology

Optical Fibres (OF) are today a well established product and they form the backbone of land communication networks that impact everyday life. OF are also employed to carry signals from conventional electric sensors in structural monitoring applications. The same OF can be used as the basis of sensing techniques where the fibre acts as both the transducer and the signal carrier.



Optical Fibres (OF) are flexible optically transparent fibres through which light can be transmitted by successive internal reflections. This type of transmission allows the propagation of a light signal along a fibre for very long distances with minimal attenuation. This ability to carry data over long distances together with the OFs capability of carrying a high number of different signals along a single fibre, are the reasons for their widespread use in telecommunication.

External actions on an optical fibre can induce variations of properties of the light travelling into the fibre and these can be accurately measured. The properties that can be most usefully employed are:

- Amplitude
- Phase
- Wavelength (through the use of Fibre Bragg Gratings)

The effect of external factors on a fibre's properties is the basis of OF based sensing technology. There has been a number of sensing techniques based on all of the above properties, however only the phase and wavelength variation techniques can provide the kind of performances that structural monitoring requires and these techniques have been commercially exploited with increasing success over the last 10 years.
Monitor Optics has always chosen to exploit wavelength variations, through the use of optical components known as Fibre Bragg Gratings (FBG). Monitor Optics believes that the advantages of FBG based sensing makes this technique the best suited for most structural monitoring applications. At the same time, Monitor Optics continues to explore other sensing techniques to be able to offer the best solution for any customer requirements.

Fibre Bragg Gratings (FBG)

FBGs are selectively modified areas of special telecom-grade optical fibres that have the property of reflecting a narrow bandwidth signal centred on a certain wavelength. This is a function of a number of design parameters and shows the property of varying linearly when strain or temperature variations are applied to the FBG. This wavelength can be measured very accurately using a dedicated demodulation unit capable of converting the wavelength shift in a digital signal.

By measuring the wavelength signal through an FBG, it is possible to turn an OF into a strain or temperature transducer. This can then be packaged into a number of sensors dedicated to different measurands. As the size of an FBG is the same of a standard optical fibre, very small sensors can be designed easily. The linear response of an FBG makes it perfectly suited to its use as a strain transducer, although a temperature compensation system is required because of its sensitivity to temperature. This compensation is usually achieved by using a second FBG that is made sensitive to temperature only.

FBG are manufactured in high quantities for the telecom component market and for this reason they are cheap and easily available in different configurations and properties.

Sensors Design

While the FBG is used as a strain/temperature transducer, the use of bare optical fibres with FBGs is not practical because the bare fibre is too fragile to be handled securely during the installation. It is therefore necessary to design a package capable of protecting the fibre while allowing the FBG to be sensitive to measurand of interest.

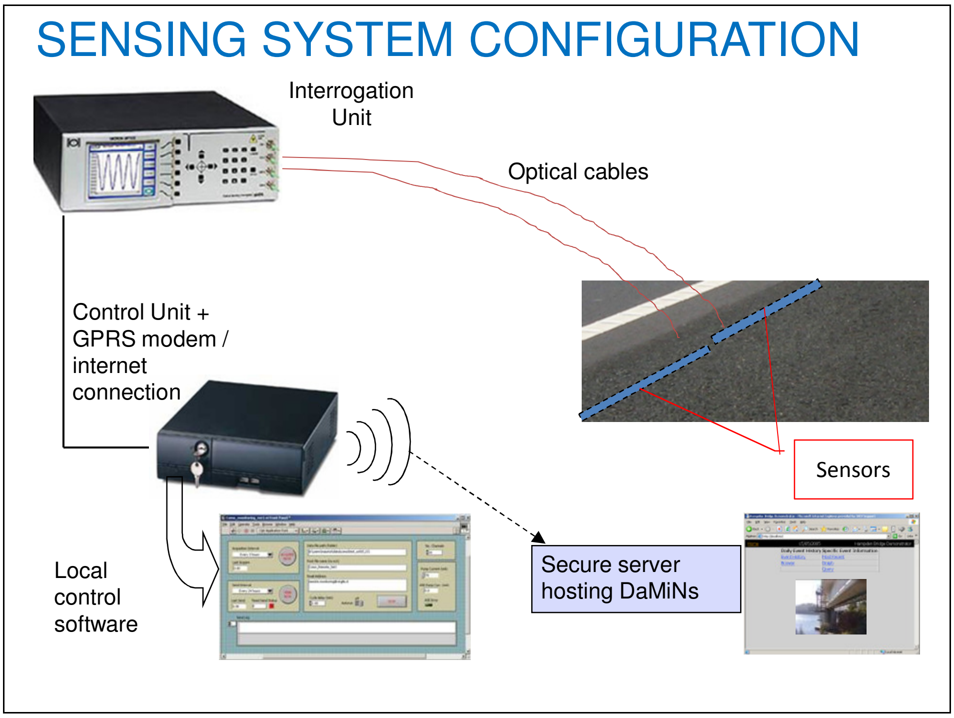
Monitor Optics provides a range of sensors for the most common applications of structural monitoring.

The most innovative sensor design from Monitor Optics is the sensing cable: this includes an array of FBGS embedded in a Glass Fibre Reinforced Polymer (GFRP) cable. The sensing cable allows a much easier installation of a high number of sensing points over long distances when compared to the use of individual FBG based strain sensors.

While Monitor Optics can provide and install all the demodulation equipment required for use with its sensors, these can be employed with any demodulation unit designed for the use of FBG based devices that might already be owned by the customer.

Sensing System Configuration

The key components of a sensing system using FBG based sensor are outlined below:



- **Sensors:** A number of sensors of different types (strain and temperature but also displacement or other).
- **Optical Fibre:** An optical fibre cable network that can go from 1 single fibre to as many as required for more complicated sensing networks.
- **Interrogation unit:** An opto-electronic device that converts the optical signal from the FBGs to a digital signal.
- **Control unit: A** small rugged PC, that converts the digital signal from the interrogator in the measurand of interest, performs initial data processing if required and controls the communication of the data to the end user.
- **Local control software:** Installed on the control unit, this software can vary from a simple acquisition and communication software to sophisticated software capable of processing data to high levels.
- **MOS DaMiNs:** MOS proprietary on-line structural data management and visualisation system, DaMiNs receives the data transmitted by the control unit and automatically provides the customer with a number of processing and visualisation options. Access to DaMiNs is through a secure on-line server from anywhere an internet connection is available.

Advantages of FBG Sensors

OF sensors have many advantages over traditional sensing technologies, specifically in the context of long-term structural monitoring. FBG based sensors introduce further advantages that make these sensors the most widely used OF sensors on the market.

- **No Drift / No Re-Calibration:** FBG based sensors do not suffer from drift because the sensing principle is based on a reversible physical modification of the FBG structure. As the FBG structure does not degrade with the time, these sensors can provide reliable measurement over many years. Even the most advanced electrical-based systems using strain gauges or LVDTs for example, simply cannot match this level of performance. Moreover, as the signal of an unstrained FBG is function only of the initial design parameters, FBG sensors are self-referencing so they can be disconnected from the interrogation unit between acquisitions without losing any reference. This makes the use of FBG sensors in scheduled monitoring campaigns very easy with no requirement for recalibration of the sensors or start-up time.

- **Accuracy and range:** FBG based systems, when used to measure strain, have a resolution of 1-2 microstrain. The range can vary between 5000 and 20000, depending on the sensor. This means that the resolution over range can be as high as 1/20000. FBG sensors also have a wide dynamic range and can be successfully used to perform dynamic measurements up to several kHz. If required special equipment can be employed to achieve sub-microstrain resolution and very high acquisition frequencies, for example to study explosive phenomena. When FBG sensors are used to measure temperature, the resolution is typically 0.1°C.

- **Electro-Magnetic Noise Immunity:** FBG sensors and optical fibre cables are passive (spark-free) devices that are immune to electromagnetic interference and do not require any signal pre-amplification. As the fibre carries light, this is not affected by any electromagnetic source. This allows the installation of sensing networks in structures subject to heavy EM noise, such as antennas or power distribution stations. This also allows the cables carrying the signals to be routed through existing electric cables conduits. FO sensors also do not emit EM noise, and therefore do not affect any EM sensitive equipment that might be located in proximity of the sensing network.

- **Passive Spark Free Operation:** Thanks to the very low attenuation typical of OF, FBG sensors can be installed at long distances from the interrogation unit without the need to supply electrical power to each sensing location. This is also a significant advantage in retro fit situations or in locations where power is not easily available, e.g. Highways and Bridges. The sensors and the connection cables are totally spark free and can therefore be safely employed in underwater applications or in chemical plants or anywhere electric sensors can cause hazards. The spark free nature of these sensors also makes them very robust in case of lightning strike.

- **Long Term Reliability and Survivability:** Optical fibre sensors and cable networks are packaged to telecom standards which makes them highly resistant to the elements, allowing them to survive indefinitely in harsh environments, be it the bottom of the sea or a small rat infested town building. Because of their operating principles, the operation of optical fibre sensors does not cause wear to the sensors or other parts of the sensing network. By selecting the appropriate installation methods and materials, FBG based sensors can be successfully installed under very difficult conditions and have shown very good survival rates even when embedded in hot asphalt and concrete. Small diameter, heavy duty connection cables can be employed to build the sensing network in the harshest environments.

- **Small Size and little intrusivity:** Optical fibres have a diameter of 250 micron. This means that a fibre can be easily integrated in very small structure and FO sensors can have small size. FO sensors can also be embedded in composite materials. Sensing cables typically have a diameter of 1 mm and therefore their inclusion in road pavements or concrete structures does not affect the structural properties. The optical cables used to connect the sensors to the demodulation equipment are also characterised by a small size when compared to electrical cables.

- **Easy Installation of Large Sensor Networks:** As each FBG reflects a signal that is function of its design parameters, FBGs can be employed in high numbers on a single optical fibre (in-series multiplexing), a capability that is a unique feature of the FBG. The use of standard FO couplers and switches and the use of multi-channel interrogation equipment allow a number of different fibres to be connected to a single interrogation unit (parallel multiplexing). This allows the creation of large and sophisticated networks. The low attenuation of the light signals in OF allow these networks to span over distances of several km. Moreover, as each FBG sensor converts the measurand in a wavelength shift, sensors for different measurands can be interrogated by the same unit without the need for dedicated conditioning modules typical of other electric sensors.

- **Sensing Systems Integration:** Thanks to the multiplexing capability of FBGs, monitoring systems based on this technology can be easily upgraded to manage an increasing number of sensors. It is therefore possible to expand the sensing network over the years without having to replace all the components of the network but simply adding new components. Single demodulation units can be expanded to increase the number of channels available while several demodulation units can be interconnected using TCP/IP based connections. The demodulation units can also be interfaced through a control computer to a number of non-OF based systems. These can include existing monitoring systems, traffic control systems, data transmission and management systems, security systems or any other system that can be computer controlled.

The advantages listed above clearly show how FBG sensors are very well suited to the use in long term monitoring systems. FBG sensors also allow the implementation of sensing networks in conditions where conventional electric sensors can not be employed. The availability of FBG based sensors is a very important addition to the portfolio of products of any company providing structural monitoring as part of their services.

Applications

The effective application of fibre optics sensing techniques has been demonstrated in many sectors. In the **Oil Industry**, both extraction equipment and pipelines have been widely instrumented with fibre optics sensors. In **Transport**, **Aerospace** applications have been the main scope of fibre optics sensing, although this has not yet materialised in a vast commercial market. Shipping is now becoming a more and more interesting market segment and some specially designed equipment is now available.

In **Civil Structures**, the use of fibre optics is a vast market that has seen considerable research activities in the application of fibre optics sensors. An increasing number of commercial projects have also been carried out in this field and this market is now mature to see true commercial exploitation.

Within the Civil Engineering sector, there are several categories of structure on which fibre optics sensors and long term health monitoring systems can be applied. These include:

- Highway and Rail Bridges
- Roads
- Commercial Buildings
- Pipelines and Oil/Chemical Processing Plants
- Piers / Docks
- Dams
- Retaining walls & Embankments

The commercial value for each category of structure is driven by the number of assets and the operational value of each asset. This has a direct impact on the need for long term monitoring. Typical types of measurements are:

- **Strain measurement** on steel and concrete structural members using externally welded/glued sensors. Both FO strain gauges and sensing cables can be used.

- Measurement of **internal strain** fields and cracks in concrete structures using embedded strain and displacement sensors.

- Measurement of **relative displacements** between adjacent structural components using externally mounted displacement sensors, particularly useful in measuring displacements between stone components in cultural heritage buildings or in measuring cracks openings.

- Measurement of **ground strains** using distributed embedded sensing cables.

- **Temperature** control and fire detection systems using temperature sensors both externally mounted and embedded.

- **Dynamic** measurements up to 1 kHz can be performed on all the type of measurements simply using different demodulation equipment.

Applications Examples

Fibre Optic sensors can be employed in a wide range of structural monitoring applications on both new-build and existing structures. These are just a few examples of applications where FO sensors have been successfully used.

Roads

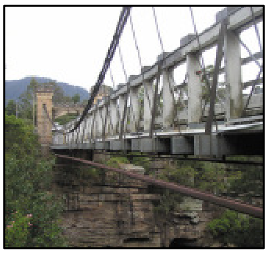
Sensing cables are particularly well suited to monitor road pavement.

Sensing cables can be laid over long distances while providing measurements at the required discrete intervals. This makes possible the automatic monitoring of ground strains, especially important where the pavement is subject to subsidence phenomena

Sensing cables can be laid in slots cut in pavements by a 2-man crew using a cable laying trolley.

Bridges

On bridges it is particularly important to verify that the strain in the structural components do not trespass certain safety values. Strain measurements at constant loads are also a standard approach to the verification of structural health. FO strain sensors can be installed on a bridge and left in place for years, while the measurements can be undertaken either continuously or during the scheduled test campaigns. FO sensors can also be used to monitor continuous traffic induced strains. These in suspension bridges can be often directly related to the number and weight of the vehicles, therefore providing a traffic management tool together with the structural monitoring tool.



Cultural Heritage Buildings

Cultural heritage buildings are often subject to loads that were not foreseen when they were first built. It is important to keep their structural health continuously under control and to have a reliable method of verification of the validity of restoration and conservation programs.

Often these buildings present structural and aesthetics considerations that force the use of minimally intrusive sensors. FO thanks to their small size are perfectly suited for these applications. Strain gauges can be glued like conventional strain gauges or spot welded on steel structures.

Retaining Walls

The control of landslides is a critical issue in mountain areas. Often the only way to protect towns and roads is by the use of retaining walls.

The capability of FO sensors to survive the concrete element manufacturing process allows them to be embedded into the retaining wall elements. The sensors can in this way provide information on the strain field inside the concrete element that cannot be acquired by any other type of sensor. Embedded sensors have proved able to survive for several years in temperatures varying from -15 to +40℃ and have been used to monitor the elements during the manufacturing process, the on-site tensioning and verify their long term structural behaviour.
Other FBG based sensors can be integrated within the same monitoring system to measure other phenomena that might affect the retaining walls efficiency, such as subsidence or landslide movements

Other Applications

New Builds

Displacement sensors and some strain sensors can be embedded in concrete structures during the manufacturing process while displacement sensors can be bolted to concrete and stone structures. Strain sensors can be glued or welded. The use of an integrated monitoring system on new build structures allows the designers to start monitoring the structural behaviour right from the construction phase.

Tunnels

Tunnels require monitoring both during the construction and the operation phases. Moreover fire detection in road tunnels is very important and can be implemented as part of the structural monitoring system. Axial and circumferential strains measurement and Fire detection are typical requirements.