Fiber optic sensing: The past, present, and exciting future

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Over the past 60 years, fiber optic sensing (FOS) has been used to enhance and test the integrity, efficiency, safety, and durability of structures, vehicles, medical devices, and more across a multitude of industries. Advancements over the past five years have enabled FOS to expand its abilities to include unprecedented levels of data and sensing density across applications in aerospace, energy, and even the medical field. This is helping engineers solve problems they are faced with today, and innovate to advance their designs. Today there are a vast number of real-world implications for fiber optic technology, as well as a realm of possibilities for the future.

This article will discuss the recent advancements in intrinsic FOS technology, including 3D shape sensing and optical frequency domain reflectometry. It will also address how engineers can utilize the technology today, and provide a preview of what to expect in the future.

A brief history

The first fiber optic sensor was patented in the 1960s and relied on free space optics. Roughly 10 years later, researchers developed the first intrinsic fiber optic sensors. This enhancement offered significant engineering benefits over free space sensors for obtaining reliable mechanical measurements. The use of fiber allows signals to be transmitted inside a deployable medium whereas free space optics relies on line of sight, and cannot be deployed in operating structures or vehicles. Commercialized in the 1980s, the fiber optic gyroscope was one of the earliest applications of fiber optic sensors and has become a critical component in stabilization and navigation systems. In the early 1990s, the civil industry began implementing various types of fiber optic sensors in multiple applications to measure temperature, strain, pressure, and more.

Engineers also began experimenting with fiber bragg grating (FBG) based sensors. FBG sensors, with their multiplexing and quasi-distributed capabilities, had a distinct advantage over existing fiber optic sensing technologies. By 2000, some common applications in the civil industry included deflection monitoring of critical elements in historic buildings, monitoring strain on critical points on bridges, and observing the behavior of concrete as it cures. Most of these applications used a variety of interferometric sensors, most of which were not able to be multiplexed.

FBG sensors have largely replaced these technologies in civil, oil and gas, and aerospace applications. For instance, FBG sensors found a place in oil and gas by monitoring pressure and other parameters on critical down hole tools. Similarly, the aerospace industry continues to use FBG based sensors primarily for structural health monitoring, load testing, and fatigue testing.

In the early 2000s, distributed sensing, another fiber optic sensing technology, emerged and has shown the greatest potential in the oil and gas industry. These technologies are used primarily to
take temperature measurements along the entire length of the fiber to help improve various down-
hole processes, including leak detection, monitoring the injection process, and creating flow profiles.
While they provide distributed measurements, these technologies have slow refresh rates (a few
seconds between acquisitions at best) and spatial resolution on the order of meters.

Recent FOS advances

Intrinsic and extrinsic sensors are two broad categories of fiber optic sensors. Extrinsic sensors use
the fiber to guide the light to a sensing region where the optical signal leaves the waveguide and is
modulated in another medium. In the case of intrinsic sensors, the light remains within the
waveguide so that it measures the effects of the optical signal as it moves down the fiber.

Intrinsic FOS technology, whereby the fiber optic cable itself is the sensor, has undergone
significant advancements in recent years. Within the division of intrinsic sensors, there are two
different technologies: scattering or FBG. While scattering techniques offer fully distributed data
points along a fiber, FBG techniques can have a handful of sensing points or can be fully distributed.
By placing FBGs throughout the fiber, engineers can analyze the changes in the way the light
reflects and interpret this information to provide accurate measurements. Scattering techniques do
not use FBGs at all, but depend on naturally occurring random imperfections in the fiber optic cable
to attain readings. Since FBGs are fabricated to be well-defined sensors, they have a much higher
signal to noise ratio than scattering techniques.

While strain gages, thermocouples, and liquid level sensors only look at critical points, distributed
FOS can provide a profile between critical points, which allows engineers to obtain precise
measurements of full strain fields, temperature distributions, and other parameters. Both scattering
and FBGs use different demodulation techniques. Scattering techniques obtain data by observing
changes in naturally occurring Raman, Brillouin, or Rayleigh backscattering patterns. Wavelength
division multiplexing (WDM) is the most common demodulation technique for FBG based technology.
However, optical frequency domain reflectometry (OFDR) offers significant advantages over WDM in
certain circumstances.

WDM can cover large distances and obtain data quickly, and the technology supports multiple
gratings on a fiber; however, every grating that is added significantly reduces the refresh rate.
Typical parameters measured by WDM include strain and temperature, although it is also possible to
attach a single accelerometer or pressure sensor in certain circumstances. WDM also only allows
users to monitor critical points rather than the entire field of information. For this reason, an
application requiring very high-speed acquisition and only a handful of data points, such as
monitoring components in automobile crash testing, would be a good fit for WDM.

Raman, Brillouin, or Rayleigh scattering techniques can cover kilometers of distance and provide a
distributed profile of information. Unlike WDM, the scattering techniques are fully distributed which
means that they obtain data along the entire length of the fiber instead of at critical points. Although
Rayleigh scatter can obtain strain data, many systems on the market only measure temperature or
acoustics and are referred to as distributed temperature sensing (DTS) or distributed acoustic
sensing (DAS). Applications that must cover multiple kilometers, but do not require high precision
and refresh rates work well with scattering technology. For example, monitoring a pipeline for
tampering only requires spatial resolution on the order of meters and does not require high-speed
acquisition.

OFDR is a different demodulation technique primarily used with FBG based sensors where gratings
are placed end-to-end resulting in a fully distributed sensing fiber. OFDR has significantly higher
spatial resolution than the scattering techniques and has exponentially more gratings than WDM. One advantage that is unique to OFDR is that it is able to maintain high refresh rates even as the number of sensors increases. The combination of high spatial resolution, quick refresh rate, massive number of sensors, and full distribution set OFDR apart as one of the most sophisticated sensing technologies on the market today. Unlike scattering and WDM, some applications of OFDR can consolidate multiple technologies into a single, robust platform. In addition to sensing strain and temperature, OFDR technology can determine 2D deflection, 3D shape, liquid level, pressure, operational load, and magnetic fields. Due to the versatility of the platform, engineers can solve multiple problems with a single system, which can make the industry more efficient and effective.

**Real-world use cases for OFDR**

**Aerospace**

Stress and strain are the parameters that determine the longevity and operational safety of any flight-bound vehicle. Airlines and aerospace agencies are constantly searching for safer equipment and processes. However, existing technologies make it difficult and costly to monitor and maintain the structural safety of planes and spacecraft. In addition, existing methodologies don’t clearly indicate when a plane or shuttle has reached its end-of-life cycle.

With thousands of sensors contained in a hair-thin fiber, FOS solutions can provide a detailed picture of the health of an aircraft. For example, by using FOS in aerospace, engineers can:

- Minimize aircraft downtime and fine-tune maintenance schedules
- Improve fuel consumption through intrinsically safe fuel level measurement
- Monitor the shape of the wing and other deformed components
- Determine when an aircraft is reaching end-of-life
- Understand the response of complex airframes to flight conditions
- Provide in-flight feedback to control systems
Figure 1 Maintaining the structural safety of planes and spacecraft is a real-world case for FOS. Thousands of sensors are contained in a hair-thin fiber.

By using FOS technology, engineers can test, monitor, and analyze the integrity of structures and capture aircraft component positioning feedback through the continuous monitoring of strain, temperature, stress, loads, out-of-plane deflections, and 3D shapes. Armed with this data, engineers can improve safety, prolong the life cycle, reduce maintenance, and enhance in-flight efficiency of aircrafts – all resulting in reduced costs.

Medical

The small diameter and chemical inertness of optical shape sensors make the technology an excellent fit for medical applications. These features allow FOS to be integrated with existing minimally invasive technologies. By utilizing FOS technology, surgeons are provided with information about the location of the entire length of the instrument without the use of x-rays or ultrasound. The 3D data can be plotted in real-time and displayed visually on a monitor to show the position of the instrument. The image can also be compared to known coordinates of locations within the body, enabling physicians to pair the visual reference from the tip of an endoscope with knowledge of how and where the rest of the instrument is positioned. This improved positional awareness can help with real-time guidance of the instrument, minimize the injection of foreign material into a patient's body, and do away with radiation.

Benefits of using FOS in the medical industry include:

- Improved imaging technology in MRI systems
- Assistance with vascular procedures as well as detection to identify the severity of an artery blockage
- Determine shapes of objects during minimally invasive surgeries and probes
Enable higher resolution instrument tracking while minimizing the complexity associated with traditional imaging methods

Minimize the injection of foreign material into the body

**Energy**

FOS is ideally suited for subsea riser monitoring because it enables the advanced collection of real-time tension, torsion, and shape information. Subsea risers are designed to withstand some of the most complex loads and harsh environments that engineers have ever faced. The dynamic nature of the riser, its components, and its environment subjects it to structural stresses, fatigue stresses, material wear, mechanical degradation, impacts, and environmentally induced loads. Due to these and other factors, the ability of sensors and instrumentation to measure the riser’s structural response to loads is critical.

By using FOS across a variety of energy applications the industry can:

- Maximize integrity of risers and rigs
- Provide control system feedback for wind turbine blades based on deflection and rotation
- Monitor the structural integrity of wind turbine blades
- Sense nuclear power plant component structural health and alignment

**FOS in the future**

The price point of FOS and its size are two of the barriers to adoption that the technology currently faces. Once these issues are resolved, we can expect more use cases across new industries.

Take, for example, the fashion industry. In the future, one could insert sensors into meshes in a piece of clothing, providing data and insight into everything about an individual’s shape, height, weight distribution, etc. This data could then be used to create clothing specific to the wearer. This would completely disrupt the fashion industry, changing the very method in which clothing is made. Imagine shopping online and having your clothes tailored to fit you perfectly before arriving on your doorstep.

Let’s also consider the automobile industry. By inserting FOS throughout the structure of a car, we could receive real-time feedback on how the car reacts to changes in its surroundings, or monitor when a car part needs to be replaced. This would be done in real-time, alerting the passenger to a possible emergency situation before it happens.

In construction, fibers could be placed into buildings or roads to monitor and determine how the structures are affected by the environment over time to detect structural issues before they occur.

**Conclusion**

The advancements of intrinsic FOS technology, its spatial resolution, refresh rate, and sensing length, have helped to progress the problem-solving capabilities of a multitude of industries. The data and insight FOS can collect is helping engineers progress beyond the problems of today and innovate into the future. As the technology continues to evolve, so will the designs and sophistication of applications across sectors like aerospace, energy, and medical. As engineers continue to push the boundaries of technology with their innovations, they will need sensing systems that can adapt
to solve problems that don't exist yet. FOS is flexible enough to be implemented as a platform that can be incorporated into designs as a component of critical systems where real-time monitoring is necessary or stand alone as an advanced testing suite.

Also see:

- 1000 sensors, one line, using optical fiber
- Subsea position sensor is CiA 443-compliant
- MEMS gyroscope precision inertial sensing in harsh, high temperature environments