Adding sensors to systems for purposes such as predictive maintenance is an application of growing interest in the Internet of Things (IoT) era. But if wireless sensors are not appropriate, developers can quickly run into a massive wiring problem as they try to connect large arrays of individual strain gauges, temperature sensors, and other sensor types. Happily, there is an emerging technology that employs optical fibers.

When most systems developers think of fiber optics, they generally envision fiber's ability to carry extremely high speed data over long distances with little loss and no EMI issues. But at the VITA Embedded Tech Trends forum earlier this month, I learned about the use of fiber as a sensor array. A specially configured optical fiber with a powerful back-end processor can be used to measure such diverse things as mechanical strain, temperature, the presence of liquids, and even the fiber's 3D position at thousands of points along its length. And the best news was, such a sensor system is commercially available.

There are two keys to this fiber optic sensing system (FOSS) technology. One is the use of a specialty fiber that has fiber Bragg gratings (FBGs) inscribed along its length. The other is the use of optical frequency domain reflectometry (OFDR).

The fiber Bragg grating is essentially a series of partially reflecting mirrors fabricated in the fiber core. One technique for fabricating such mirrors is to expose the optical core to a striped pattern of ultraviolet (UV) light. The UV permanently damages the core where it has struck and these damaged areas will partially reflect light travelling through the fiber. Because the pattern of damage (i.e., the arrangement of mirrors) has carefully controlled spacing, the reflections will interfere with one another at a specific optical wavelength, causing stronger reflection at that wavelength than at any other.
A pattern of partially reflective mirrors in the core of an optical fiber can form a Bragg filter that selectively reflects a specific wavelength. Any phenomenon, such as thermal expansion, that alters the mirror spacing will affect that wavelength, creating the basis for sensing that phenomenon.

Optical frequency domain reflectometry (OFDR) is a technique for determining the distance to a reflection point along a fiber through the use of light with a varying wavelength. The more well-known optical time domain reflectometer measures such distance directly by looking at the time delay between transmission and reflected return of an optical pulse sent along the fiber. OFDR sends a swept-wavelength signal and examines the time-varying interference patterns that result from mixing the return signal with a reference signal. A reflection point at a fixed distance along the fiber will yield an interference pattern that oscillates with a frequency proportional to the reflection point's position along the fiber.

Using OFDR on a fiber containing FBGs allows a system to locate each such grating individually. Each grating reflects more strongly at a specific wavelength – called the central frequency -- which the system can also determine. Together, these features form the basis of a distributed sensor series. Depending on the system's ability to resolve the various optical wavelengths and interference pattern frequencies involved, the distribution of FBG sensor points can virtually continuous along the length of the fiber.

Anything that changes the spacing in an FBG will change its central frequency. Thermal expansion, for instance, will yield a change proportional to the temperature at the FBG. Similarly, mechanical strain (tension or compression) along the fiber will yield a change. Bending the fiber will have an effect, as can magnetic fields (via magnetostriction-induced strain) or the presence of liquid around the fiber. With an essentially continuous FBG distribution along an appropriately-constructed fiber, measurement profiles for these parameters along the entire length of the fiber are possible.

The method of using a fiber sensor will vary with the parameters to be measured. By bonding a length of fiber to a surface, for instance, the fiber will measure the strains along its length due to flexure of the surface. To measure temperature at a point, bond the fiber to that point and provide strain relief on either side to eliminate strain as a signal source. One means of measuring liquid level in a tank would be to heat a fiber that is dangling into the liquid, then monitor the temperature profile along the fiber's length as the fiber cools. The cooling rate for the fiber in the liquid will be different from that of the fiber in air, and the point where the cooling rate changes is the surface of
Three fibers bonded together can serve as a 3D shape sensor. As the bonded fiber flexes, the individual fibers experience differences in compression and tension, differences that depend on the amount and direction of the bend. Examining these differences at points all along the fiber's length will yield a description of the fiber's shape in three-space.

While the principals involved in such fiber sensors have been known for some time, the practical aspects of measuring and analyzing the signals involved face considerable difficulty. The amount of signal processing needed to extract precision data out of a fiber with thousands of sensor points at a useful sample rate, for instance, is enormous. Further, the raw data from the sensors needs to be converted into appropriate units and assigned to a specific parameter (i.e., linear strain, temperature, degree of bending, etc.). All this requires both highly efficient algorithms and powerful computational capabilities.

Fortunately, these challenges have been overcome. Technology for building a fiber optic sensor system (FOSS) using these principals, for instance, recently came out of the NASA Armstrong Flight Research Center.

Further, the technology is becoming commercially available. NASA licensed its FOSS technology to Texas-based Sensuron, which has developed both commercial (RTS-150) and ruggedized (RTS-125) multi-channel sensor systems. The RTS-150, for instance, can handle up to 32 fibers, each having 2048 sensor points sampling at up to 100Hz. Windows or Linux software for making and displaying real-time strain and temperature measurements and for 3D shape sensing is built in.

Based on NASA's FOSS technology, Sensuron has created multichannel fiber sensors available in both benchtop and ruggedized versions for laboratory or field work. (Source: Sensuron)

Development is taking place elsewhere, as well. Luna out of Virginia produces a fiber optic sensor that uses OFDR but without the need for Bragg gratings. Europe's Technobis Group offers FBG fiber sensors with gratings tuned to different wavelengths so they can be distinguished. And universities are actively investigating methods for 3D shape sensing using only a single fiber.
The end result is the emergence of a technology that system developers can start using in sensing tasks that were heretofore impractical due to the coarseness of sensor placement and the number of wires involved. With continuous sensing along the entire length of a single fiber, developers can now monitor in real-time the mechanical and thermal behavior of large systems with high resolution. The data obtained from such sensing can prove invaluable in applications such as predictive maintenance on machinery and improvement of design models, as well as finding new and innovative uses.