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Introduction

As industrial control requirements expand, more innovative sensors are urgently needed. In fact, there are presently several sensing requirements going unmet because adequate sensors are not available. Fiber optic sensors may go a long way toward meeting these needs due to their unique properties and distinct advantages. They are inert to hazardous or extreme environments and they have the potential to work over a wide temperature range. They are immune to radio frequency interference (RFI), electromagnetic interference (EMI) and toxic environments. They allow access into normally inaccessible areas. System flexibility is enhanced by remote sensing. Fiber optic sensors are in many instances passive and as a result, much more reliable than mechanical or electronic sensors. Systems can be designed with very high accuracies which can be easily interfaced with fiber optic data links back to control centers. Systems are now available to tie optical sensors into fiber optic data communication highways.

Most physical properties can be sensed fiber optically.¹ Light intensity, displacement (position), temperature, pressure, rotation, sound, strain, magnetic field, electrostatic field, radiation, flow, liquid level and vibration are just some of the phenomena that can be sensed.

Historically, most fiber optic sensor applications have been relatively simple absence or presence situations such as counting objects, tool break detection and rate counting. Technology has taken fiber optic sensors to the other extreme. Much research and development^{2,3,4} has been completed on ultra high accuracy military applications using interferometric techniques where accuracies of one thousandth of an angstrom have been achieved. Such high accuracies are required for gyroscope and hydrophone sensors.

A large number of both military and industrial applications will require analog physical property sensors more advanced than absence or presence sensors but considerably less complex than interferometers. It is important to note that the primary driving force for using fiber optics in these particular applications has been freedom from electrical noise.

Sensor Types

Intensity Modulated Sensors

Intensity modulated sensors^{5,6,7,8} are advanced versions of the simple absence or presence sensors. While counters and switches use the digital nature for an on/off pulse, transmissive and reflective fiber optic sensors are analog in nature. Such sensors modulate the intensity of the light output for measurement. Reflective sensors are the most widely used in this category.

Phase Modulated Sensors

Phase modulated sensors generally use interferometric techniques.⁹ Instead of using intensity, they measure a phase shift between two beams which causes an interference as a result of perturbations from the environment being sensed.

Due to their extreme sensitivity (5 orders of magnitude more sensitive than intensity modulated sensors) they have found potential use in hydrophone applications for the military. However, this sensor approach has been prohibitive from a cost standpoint for industrial use.

Applications

Digital Switches and Counters

Fayfield⁵ gave a review of switch/counter applications, such as broken thread detection, register mark detection and object detection in general. Transmissive and reflective sensors are primarily used. Figure 1 shows transmissive and reflective fiber optic sensors. In switch, counter applications, the lightpath is interrupted and the absence of signal is detected at the electro-optic interface. Fiber optic limit switches are especially attractive due to their non-contact nature which eliminates wear. As a general comment, fiber optic absence/presence sensors are more expensive than their photoelectric counterparts. The driving force for their use is almost always environmental difficulties. As the environmental problems become more severe, fiber optic sensors become more cost effective.

There is a large potential switch application in the machine tool area. Sensors can be used to gauge parts or determine if the cutting tool is present.

In almost all situations there is a high volume of liquid coolant flowing in the vicinity of the cutting tool. The coolant and the debris that it is carrying are fouling the optics by essentially blinding the optical probe.

There are commercial systems that have addressed this problem. The probes can be kept clean even in the presence of high volumes of coolant by using an air wipe concept. With a slight positive pressure over the end of the probe, coolant and debris are kept off the optical surface. The system is further enhanced if a spoiler is used in the air flow. The spoiler causes a turbulent swirling air flow which enhances the cleansing action. In normal field applications, most of the machinery that uses cutting tools has compressed air sources in close proximity so that installation is simple.

Target/background contrast is a major problem in reflective systems. Cutting tools and objects that are dirt or grease covered generally have poor reflectivity. With a reflective system, to detect such objects, the reflected light intensity must be maximized. There are basically two approaches. The first is to maximize the light output of the sensor. Almost all commercial units have a gain adjustment which should be set at the maximum value. It must be realized that commercial units from various manufacturers vary greatly with output differing by as much as 300%. Another approach is to place a highly reflective target, such as a retro-reflective material, on the object to be detected. There are situations in which reflectivity is too low for a reliable sensing function. In such cases, a transmissive system, which is independent of reflectivity is recommended.

Widespread use of digital fiber optic switches and counters has also been limited due to functionality. Most applications have been limited to absence/presence, since these are the simplest sensors to develop and use. Furthermore, they are essentially the only ones available. Digital sensing is now expanding to liquid level, temperature, and pressure.¹²

For the expanded digital sensor, the target provides the sensing function. If a target can be fabricated such that its position or state relative to the probe end is a function of some physical parameter to be sensed, then physical property sensors can be fabricated. Consider a reflective bimetal disc as one such target. As the surrounding area reaches its set point temperature, the disc defects. The distance between the probe and target changes correspondingly, affecting the amount of light reflected back to the probe which provides the basis for switching. Pressure sensing via fiber optics is provided by a method analogous to the bimetal temperature disc. A flexible pressure sensitive diaphragm with a reflective inner surface varies its distance from the fiber optic probe tip in

response to a pressure input. Using a snap diaphragm, a pressure set point is achieved.

Another technique for utilization of fiber optic probes involves the use of a prism tip for liquid level sensing.¹ Light traveling down one leg of the probe is totally internally reflected at the prism/air interface. Note that air (index of refraction=1) acts as a cladding material around the prism. As the prism contacts the surface of a liquid, light is stripped from the prism, resulting in a loss of energy at the detector. With the proper electronic circuitry, discrimination can be achieved between liquid types, such as gasoline and water, by the amount of light lost from the system, a function of the index of refraction of the liquid.

Displacement

Fiber optic reflective sensors are non-contact displacement sensors and, as such, have a broad application range. Much like inductive displacement proximity sensors, non-contact reflective fiber optic sensors provide excellent resolution and repeatability. Fiber optic sensors are not limited to metallic objects, but can be used with any material. Reflective fiber optic sensors have the potential of one microinch sensitivity. As the dynamic range of the sensor increases, however, the sensitivity decreases.

Used as a single point sensing system, they can be used for vibration monitoring, gauging parts, as well as measuring film thickness, shaft runout, eccentricity, axial motion and rotation. Fiber optic proximity sensors are affected by dirty environments which degrade the analog signal. This problem is minimized by working in the IR where light scattering is minimized; and by incorporating a positive air pressure at the probe tip as discussed earlier for digital applications.

The lightsource is typically an LED which varies in intensity by 1/2% per degree centigrade. To resolve this problem, a reference can be used which detects the intensity variations and corrects the LED output. The overall system effectiveness can often be enhanced by using a dual probe system with a common light source. The dual outputs can be divided to normalize light source variations as well as increase the output for a given movement, thereby increasing the accuracy. Dual probe sensors are positioned so that as the object comes closer to one probe, the output of that probe changes in a manner just inverse to that of the opposing probe. As the value of one goes down, the other goes up. The relationship holds true as long as both probes function either on the front slope or the back slope of the response curve (See Figure 1c). In addition to magnitude, such a configuration can provide directional information. Similar positioning effects can be achieved if one probe is working on the front slope while the other is working on the back slope. The

advantage is that the sensing probes can be placed on one side of the

object and no longer have to oppose one another. Dual probes are employed in applications such as measuring sheet thickness, concentricity, deviation or servo positioning, shaft diameter and alignment

Physical Properties

Temperature and pressure are two of the most important physical phenomena to be measured.¹² A bimetallic element attached to the end of reflective fiber optic probe provides the basis for an analog temperature sensor if the snap action is replaced with a smooth continuous movement. With this type of configuration, a linear temperature response can be obtained from 0 to 200° C with an accuracy of ± 1 ° C. Using a similar configuration, but replacing the temperature sensitive element with a diaphragm, produces a pressure sensor. Sensors with a dynamic range of 0 to 500 psi and accuracies better than 1% have been developed.

Other techniques for measuring temperature have been devised.^{14, 15} One approach uses a fiber optic probe on which the probe tip has a coating of rare earth phosphors. The phosphors emit fluorescent radiation when excited by UV light. The intensity of fluorescent radiation is a function temperature which can be detected fiber optically. This sensor approach has extreme accuracy approaching 0.1° C. The range is expanding. Initially temperatures could be measured up to about 200° C. Now temperature can be measured up to 1000° C using similar optical techniques. The major drawback to this approach is cost.

Analog fiber optic sensors are not in widespread use, but have been used in many trial industrial applications. Nearly all these sensors use intensity modulation. The major problems include: variations in lightsource intensity which directly effects the analog sensor output; microbending in the leads to and from the sensing region; and intensity variations associated with coupling and decoupling connectors.¹¹

Microbending losses in the fiber leads present a problem only if the leads move while the sensor is in operation. Large core plastic clad silica fibers (PCS) are the least sensitive to bending loss and the best suited for sensor leads. Furthermore, the sensitivity of the leads can be reduced if a protective cable construction surrounds the fiber to retard bending loss. Losses in the leads, if not properly controlled, can cause errors in excess of 5%. An interesting point is that as the lead length increases, the light level in the sensing systems decreases. Analog sensors function best when the leads are 100 meters or less. Digital sensors can work well to 1000 meters.

Connectorization also presents a problem in analog systems. Connectors vary slightly each time the connector is mated. Each connector, although precise, has some misalignment. The misalignment affects the light level in the system (fiber/fiber or fiber/device) and therefore, the sensor output. Typically, the reference fiber is not helpful here, since the reference leg and the sensor leg connectors each have their own characteristics upon mating. Once the system is assembled and calibrated, mating is not a problem if the connectors are not disconnected and reconnected. The problem is further minimized if high precision connectors are used.

Sensing/Communication System

As the requirements for factory and process automation increase, it will be necessary for several sensors to work together¹² and communicate over a common system. The sensors, both analog and digital, interface to a node which performs an electro-optic conversion and supplies digital sensing information which is multiplexed onto the fiber optic communications network. The information is then transmitted back to the host computer. The node is electrical and performs two conversions, opto-electrical for digital conversion and electro-optical for digital transmission. Electro-optic components to achieve the sensor/communication system integration are now commercially available.

SUMMARY

Fiber optic sensors are being widely used in digital applications for switches and counters. Applications are expanding to include temperature, pressure and liquid level switches. Analog fiber optic intensity modulated sensors are being used in a number of trial applications. Analog sensors still have a number of deficiencies including lightsource variations, microbending of optical leads and connector losses.

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FIGURE 1 FIBER OPTIC SENSORS