REVIEW OF FIBRE OPTIC SENSORS IN THE MARKET

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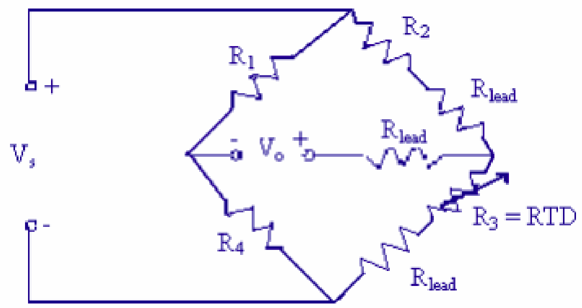
Physical Principles of Temperature sensors

Temperature is an often measured environmental quantity as chemical, electronic, biological and physical systems are affected by temperature. Temperature is measured using sensors and this is done in contact with the heating sources or without contact and the use of radiated energy instead [1]. The types of temperature sensors are:
1.) Thermo-Resistive, 2.) Thermo-Junctive , 3.) Mechanical devices and 4.) Radiative

Thermo-Resistive

The types of thermo-resistive measuring devices are resistance temperature detectors (RTD) and thermistors.
The RTD works when the resistance of metal changes in a linear way with changes in temperature, and any non-linearity is very expectable and repeatable. When a change in resistance happens, that is how change in temperature value is gotten. The resistance is measured using a two-wire RTD bridge circuit or three-wire RTD bridge circuit which are both quarter bridge Wheatstone bridge circuits. The resistance calculation between the two arms of the bridge is: $\frac{R1}{R3} = \frac{R2}{Rx}$ R1, R2 and R3 are all known resistances and the unknown value "Rx" is the RTD value can be found and used to calculate temperature. The three-wire RTD bridge circuit is more accurate because there are two wires in the two-wire circuit and some parts of the lead wires are open to changing temperatures which multiplies the error by two. The three-wire circuit is designed in such a way that an extra lead wire has been added, and with this, if two of the lead wire resistance are the same, they cancel each other out and the output voltage will have no net effect, therefore removing the error. [2]. RTD is typically built from platinum.



[2].

Thermistors are sensitive semiconductors that show a large resistance change over a small range of temperature. A thermistor has more sensitivity than an RTD which is good for set-point applications[1]. The temperature-resistance relationship of a thermistor is non-linear unlike that of the RTD, and it isn't characterized by one coefficient. The resistance of a thermistor decreases with increasing temperature, therefore thermistors cannot be used to measure high temperatures in comparison to RTDs.[2]

Thermo-Junctive

The Thermo-Junctive (Thermocouples) operates on the principle that when two dissimilar metals are joined at one end. In choosing the metals, there should be a thermoelectric difference which will give rise to a better thermocouple performance. A small voltage referred to as thermojunction voltage or EMF(electro-motive force) is generated at the hot junction which is the joined end. This the Peltier effect. When the temperature of the hot junction is changed, the voltage changes too and this is measured by the input circuits of an electronic controller. There is another effect called the Thompson effect and this is the output voltage being proportional to the temperature difference between the hot junction and cold ends. These two effects come together to measure temperature by giving a junction a known temperature and then measuring the voltage, the temperature at the other junction can then be gathered. [2]

Mechanical Devices

Principle of Operation: Materials expand with an increase in temperature so changes in temperature allow for mechanical motion. A scale shows the mechanical motion.
They include:

Liquid-in-glass Thermometer

This is a glass tube with a bulb filled with liquid at one end. As the temperature of the liquid increases, it expands, moving up the capillary tube. The liquid is usually mercury or an alcohol. The liquid level in the column corresponds to a certain temperature, and this is marked on the outside of the glass. [3]

Bimetallic Strip Thermometer

Two metals with different rates of expansion when heated are bonded into what is called a bimetallic strip. If metal x has a smaller coefficient of thermal expansion than metal y, as temperature increases, metal y will expand more than metal x, causing a deformation in the bimetallic strip. Bimetallic strips are used in air-conditioning operations as the arm of a switch between electrical contacts. When room temperature changes, the bimetallic strip curves and when it curves far enough, contact is made with leads that turn the air conditioning on or off. [2]

Sealed Bellows

Sealed bellows is filled with a liquid, gas or vapor and this reacts to changes in temperature by pressure and volume changes leading to an expansion or contraction. Bellows filled with gas makes the sensor sensitive to external pressure and temperature. [4]

Bulb and Capillary Sensor

The bulb in a bulb and capillary sensor is filled with fluid and when the bulb is heated, the temperature rises as this system has a speedy response to temperature. The fluid then expands therefore exerting pressure via the capillary to the diaphragm Expansion of the fluid in the heated bulb exerts a pressure which is transmitted by the capillary to the expendable diaphragm to close or open the contacts.

Pressure thermometer

This operates by the expansion of a gas. A pressure thermometer measures temperature by measuring pressure. The gage used is a pressure gage and it is typically calibrated in units of temperature.

Radiative

There are two types of thermo-resistive measuring devices: Infrared pyrometers and Optical pyrometers.
The Infrared temperature sensors work when any object emits a certain amount of energy that is a function of its temperature. The temperature is determined by measuring the intensity of energy from the object. The physics behind infrared sensors is from these three laws: 1.) Planck's radiation law: "Any object at a temperature not equal to 0K is emitting radiation". 2.) Stephan Boltzmann Law: "The overall energy emitted at all wavelengths by a black body per unit area is directly proportional to the fourth power of the temperature. 3.) Wein's Displacement Law: " Black body radiation of different temperature emit spectra that peak at different wavelength.[5]
Optical pyrometers measure high temperatures between 700 to 4000°C meaning it can measure flame. An infrared radiation-sensitive sensor compares the photometric brightness from a heated unknown source with that of the brightness from an internal incandescent source.[2]

Physical Principles of Strain sensors

Strain gauges are commonly used to measure the change in resistance due to an application of external forces on an object. They are used in the geotechnical field to measure strain directly on diverse structures, to indirectly determine stress, pressure, torque, and other measurements. A strain gauge has a metal foil insulated by a flexible backing to support this structure. The leads pass current through the gauge, and as the surface of the measured object contracts or stretches, the object becomes deformed due to force or tension causing a change in the electrical resistance. The change in resistance is proportional to the change in length of the surface of the object. A Wheatstone bridge measures this change in electrical resistance through the gauge factor. The gauge factor is the sensitivity of the strain gauge.[6]
A Wheatstone bridge has four resistive arms and an excitation voltage, V_E, along with two parallel voltage divider circuits. R1 and R2 is one voltage divider circuit, R3 and R4 is the second voltage divider circuit. The output voltage is given by:

$$\mathbf{V} = \left[\frac{R3}{(R3+R4)} - \frac{R2}{(R1+2)}\right] * V_E$$

If R1/R2 = R4/R3, the bridge is a balanced bridge as the output voltage is zero.
A change in the electrical resistance gives rise to a nonzero output voltage. If a strain gauge replaces 'R4', any changes in the resistance of strain gauge will unbalance this bridge and the output voltage will be nonzero. [7]
The types of strain gauge devices: Quarter Bridge Strain Gauge and Strain Gauge Rosettes

Quarter Bridge Strain Gauge

This strain gauge operates on the principle that one of the four resistors is variable whilst the remaining three are fixed. The value of this variable resistor is then determined so the circuit is balanced but with an applied force the bridge will become unbalanced. A precision voltmeter is in the centre of this bridge to get an accurate reading of the imbalance. [6]

Strain Gauge Rosettes

This is an arrangement of two or more strain gauges to get strain measurements in multiple directions. Theis measures the complete strain state of an object i.e. the normal, shear and principal strains. These gauges are mounted at certain degree angles depending on the measurements required.

Physical Principles of Pressure sensors

A pressure sensor converts pressure signals to an analog electrical signal. This digital signal includes modifications in capacitance, or changes in resistance of a strain gauge or piezoelectric component that is proportional to the deflection size when pressure is applied. Pressure sensors have a signal processing unit and pressure-sensitive element. [8]
There are five types of pressure sensors: strain gauge, piezoresistive, piezoelectric, capacitive and Micro Electro Mechanical System (MEMS) pressure sensor.

Strain Gauge Pressure Sensor:

As described above, these are structured as a Wheatstone bridge and the signal in turn provides a transmitter-current or transducer-voltage output of the applied pressure. [8]

Piezoresistive Pressure Sensor:

These manipulate the change in the resistance of a material to measure pressure. The force applied deforms the material and changes its electrical properties. The electric signals that change are transmitted out with thin bonding wires and this allows the adjustment in the electric signal be measured. Types of piezoresistive pressure sensors are the silicon, metal thin film and ceramic piezoresistive pressure sensors. [8]

Piezoelectric Pressure Sensor:

Piezoelectricity is the ability of a material to acquire charge when mechanical stress is used. These are made from materials like quartz as they generate electric power when under strain as an electrical charge is created across the surface of such material. These are used to measure dynamic pressure not fixed pressure. The real world applications of this is to measure vibration of shock in planes, ships, buildings and more. [8]

Capacitive Pressure Sensor:

These include a capacitor with an inflexible plate with a membrane of layer for electrodes. The value of capacitance is proportional to the gap between the electrodes. There is a deflection that happens when the pressure to be measured is applied to the membrane side. This deflection leads to an alteration in the capacitance and this is measured with a circuit.

The two types of this are the metal capacitive pressure sensing and ceramic capacitive sensing. [8]

MEMs Pressure Sensor:

This is a chip-based tool that has a suspended object in between two capacitive plates. It is created with silicon and uses etching and doping techniques. When the sensor is tilted, there is a difference in the electric potential and this difference is measured as capacitance therefore producing an electronic output. [8]

Currently marketed Temperature, Strain and Pressure Measurement Using Optical Fibre Methods.

Fibre optic sensing devices for the measuring these parameters:
They include: 1.) Blackbody Radiation Sensors 2.) Fluorescence-Based Sensor/Crystal Luminescence 3.) Fibre Bragg Grating 4.) Interferometric Sensors

Blackbody Radiation Sensors

Blackbody optical fibre sensing device consists of a metallic oxide coating on the sensing tip to form a blackbody cavity. This blackbody cavity produces thermal radiation depending on the room temperature, the spectral range of detection and the emissivity of the object. Temperature readings are gotten by measuring the spectral intensity at the end of the fibre at two wavelengths. This device operates on the principle of Planck's Law which is expressed as:

$$E(\lambda,T) = \frac{2hc^2}{\lambda^5} * \frac{1}{e^{(\frac{hc}{\lambda kT})}-1}$$

Parameters: T- temperature , λ- wavelength, h- Planck's constant, k- Boltzmann's constant and c- speed of light.
This sensor is cost-effective, is suitable for harsh environments as they are almost chemically neutral, measures high temperatures and has an immunity to electromagnetic interference. In 2019 it was suggested that this issue can be improved by about 38% by using tapered fibres with a larger receiving aperture rather than the end-flat fibres. Blackbody sensors generate self-emission as resulting from contact with elevated temperatures. This is not ideal as it leads to errors. For the development of this issue, two possible methods to eliminate this is the two-fibre optical fibre thermometry whereas a fibre with a reflective coating is positioned parallel to the blackbody thermometer. As both fibres are exposed to the same thermal environment, the intensity measured at the end of the fibre with the reflective coating eradicates the error as there is an emission of the fibre. The second method is spectral remote sensing which in which the intensity is measures with visible and 'near and short-wave infrared' reconstructing the temperature profile along the fibre. [9] [10]

Fluorescence-Based Sensors

Fluorescence-Based Sensors are single point temperature sensors that work by attaching rare-earth fluorescent materials to an end of a silica or single-crystal fibre and the other end of the fibre is connected to a light source that excites the fluorescent material. When this fluorescent material is excited, fluorescence is generated and then decays depending on the fluorescence lifetime. This sensor usually has a measuring range of -40°C to 400°C but can reach about 600°C when a metal-coated optical fibre is used. [9] [11]
There are two methods used by these sensors namely:
1.) Fluorescence Lifetime method(FL) and 2.) Fluorescence Intensity Ratio method (FIR)

Single-crystal optical fibres were used as the melting point was high (2000°C) and has a good resistance to oxidation. The table below shows the development of temperature sensing in fluorescence-based sensors with several doping materials in recent years.

Table 2 showing the development of temperature sensing in fluorescence-based sensors with several doping materials

Test Method	Sensing Materials + Doped Rare Earth	Temperature Range	Sensing Performance	Year
	YAG: TM^{3+}	0-1400°C	±5°C	2003
	YAG: CR^{3+}	-20-500°C	1 µs/°C @500 °C	2006
	YAG: CR^{3+}	-25-50°C	0.1°C	1995
FL	YAG/KGW/YVO4: Nd^{3+}	0-1000°C	±2°C	1997
	YAG: Yb^{3+}	1600°C	3°C	2002
	YSZ/YAG: Dy^{3+}	0-1200°C	-	2009
	YAG: Dy^{3+}, Er^{3+}	24-1700°C	10°C	2020
	SiO2/YAG: Tb^{3+}	300-1200K	-	2006
	YAG: Pr^{3+}	293-573K	$0.0025K^{-1}$	2016
FIR	YAG: Yb^{3+}	500-1000K	$0.3\%K^{-1}$	2018
	YAG: Sm^{3+}	303-1028K	$3.04610^{-4}K^{-1}$	2022

[9]
The FIR method measures temperature by sensing the fluorescence intensity ratio of two wavelengths at two different excited states and is used in commercial sensors. The FL method does not need a defined measurement of output intensity and fluctuations in light source intensity does not have an effect on this measurement, hence it is more marketable. The fluorescent material defines the sensitivity and strength of the signal under detection. The burst effect of Er3+- doped YAG above 600 °C causes swift decay of fluorescence lifetime and intensity, ensuing in different sensitivity of the sensor in different temperature intermissions. Tm-doped Y2O3 has a fluorescence intensity that's weak, therefore, the signal-to-noise ratio is not good enough and not fitting for high-precision measurements. [9]

Fibre Bragg Grating (FBG)

FBGs are formed in optical fibres when changes occur in the core of refractive index. They operate periodically from the changes in the refractive index along the optical fibre.
FBG is achieved by periodically modulating the refractive index along the fibre axis. The Bragg condition must be met when the broad-scale light spectrum hits the FBG. The equation is: λBragg = 2neff Λ, Λ being the distance between each grating and neff is the effective refractive index of the fibre. FBGs are reliable, have high stability, have small dimensions, multiplexing ability and used for a lot of things such as communication, filtering and the creation of fibre lasers. Changes in the temperature, pressure or strain lead to a change in the refractive index of the distance between each grating resulting in a linear drift of the wavelength. When FBG experiences uniform uniaxial tension, the photo-elastic properties have a linear relationship with the increased wavelength and the axial strain. FBGs measure both low and high temperatures(using high-temp resistant materials). FBGs are very sensitive to any temperature change which widens the distance between each grating. To overcome this, a material with a higher thermal expansion should be joined with the FBG. FBGs are highly requested as apart from the uses mentioned above, they are also used to measure torques and deformations. [9][12][13]

FBGs are used in industries that deal with power generation due to their immunity to electromagnetic interference, mining, oil and gas, and water treatment. Over the years, FBGs have been developed for use in medical applications such as for profiling a humans body during a hypothermia treatment. In terms of pressure, mechanical amplification allowed room for improvement of the sensitivity factor. As there has been an increase in the use of FBGs over the past ten years, different FBG interrogator systems have been developed including one utilising a Mach-Zehnder interferometer. However, this is new age technology and does not meet some standards due to failure in the system as a whole.

Interferometric Sensors

When a wide-spectrum light hits an optical interferometer, a multi-beam interference forms due to the optical path difference (OPD) forming an interference pattern. The output intensity interference of the fibre interferometer is:

$I = I1 + I2 + 2(\sqrt{I1I2})\cos(\frac{2\pi}{\lambda}.OPD+\phi0)$ [9]

When an interference between two coherent beams that have along different paths, the interferometric sensor measures the phase shift. This shift causes a delay from one wave to another leading to a difference in their electromagnetic field hence possibly cancelling the intensity. When the length of arms and the refractive index is the same as the wavelength, the interface is constructive and the output results will be at a maximum value. When the length is not the same as the wavelength or not in multiples of it, the output result will be a minimum. Any changes in the wavelength, path length and refractive index will lead to a change in the phase of the wave.

Interferometers are hyper sensitive to any disturbance to the optical path where the measurements are taken which can cause more drifting than necessary. In relation to this, any disruptions could lead to the reference being lost meaning there is no indication of the measurement going on. The most common optical fibre interferometric structures are the Mach-Zehnder, Michelson and Fabry-Perot. The Michelson and Fabry-Perot are rarely used. Sensor heads in this technology was being developed but with the development of the FBGs this stopped. The Fabry-Perot are still available in the commercial market. [9] [13]

Interferometers are used in astronomy industries, engineering metrology, oceanography, seismology and spectroscopy.

The global distributed fibre optic sensor market is estimated to grow exponentially at an annual rate of 7.3% from now to 2030 to reach about USD 2,533.5 million. North America is the global leading market for fibre optic sensors then Asia-Pacific. The telecommunication industry is the largest end-user of these sensors and the market drivers is the oil and gas industry in forth coming years. The demand from the civil engineering and oil and gas sector increases the fibre optic sensors in the market. Fibre optic sensors endure trying environments such as in pipes, reactors where physical interaction is not practical. This is advantageous in border security to avoid intrusions, in industrial automation and use in high-class residential structural projects, transportation projects such as railways, roads and dams. Fibre optic sensors are being looked into being integrated with the Internet of Things and having more future developments. New technology will be followed through and other areas in the micro-electromechanical (the technology of microscopic materials) sector will benefit as these sensors can be fitted in the tightest of spaces. [14][15]

Markets available for the Fibre Optic Sensors

Fibre optic sensors are used in the environmental monitoring sector, which monitors temperature and humidity, air quality, atmosphere, wind and speed direction, soil, radiation, rainfall, water level and pressure, gas and food and water quality. Temperature and humidity has to be at a level range, not too high and not too low for body cells to be at a regulated temperature. Air quality has to be measured suspended particles in the air for health and safety reasons so as to avoid toxic substances in the air to avoid chronic conditions such as poor lung and heart health. Atmospheric pressure is necessary to make predictions about the weather. This affects the agricultural sector as light is a requirement for the growth of plants due to the process of photosynthesis. Wind speed and direction is measured for the purpose of getting meteorological information and give farmers ample time to gear up for possible wind disasters. The involvement of sensors to note information about soil is very important for the agricultural industry as the moisture, texture, phosphorus and pH of soil for better crop growth can be monitored. Solar radiation predicts energy used up in gas and electricity, and apart from gas and electricity UV rays have an effect living organisms, hence humans, animals and crops therefore monitoring radiation intensity is necessary. Monitoring and measuring pressure in bodies of water is helpful to predict disasters such as floods and drought. [16]
The applications of fibre optic sensors in the civil engineering field encourages sustainability as avoidance of calamitous damage is ensured by locating specific damage prone issues before they happen. This is cost and time effective. In monitoring these structures insight can be gotten on the optimization of alike structures to be done in the future. The maintenance of structures can be attacked from the material point of view and structural point of view. In the material point of view, the performance of certain materials are observed under trying conditions especially such as during weather issues most effective way to use a resource. In the structural point of view, this building as a whole viewed from a geometrical stand point. [17]

Case Study example:

Monitoring San Giorgio pier:
The San Gorgio pier is a quay structure made of concrete with length of about 400metres is used for importing coal. This has been further developed with the addition of another section to increase docking space and future developments in increasing the water depth of the east basin from 11m to 14m is being looked into. The quay walls have seventy two sensors with sixty seven endlessly performing and three sensors measuring the strain and curvature of the wall at each section. It was earlier suggested that this structure should use conventional sensors for monitoring but with this the data gotten would only be for a short period and data to actually keep track of what is going on with the structure would need to be measured over a long period of time. This is when fibre optic sensors were employed to monitor as fibre optic sensors are long-base strain sensors measuring strain values for huge areas on the pier. The precision of fibre optic sensors is better than of the conventional sensors hence the decision to be made was clearly obvious. This study on the San Giorgio pier was to determine the safety of the structure as a lot operations take place on it. [17] [18]

Future Applications of Fibre Optic Sensors

The use in fibre optics sensors to enhance electronic products, in sensing and instrumentation, photonics, laser industries, in computer and data handling to interpret data from large arrays. [15]

Advantages of Fibre Optic Sensors over the conventional sensors

1. Fibre optic sensors are smaller than the conventional sensors which is advantageous as most sensors are to be embedded in objects and fitted into tiny spaces.
2. Fibre optic sensors are more lightweight.
3. They have a higher resistance to electromagnetic (radio-frequency) interference.
4. Fibre optic sensors can conduct distributed measurements.
5. They use up less electrical power or none compared to the conventional sensors.
6. These sensors have higher bandwidth and higher sensitivity compared to conventional sensors.
7. Fibre optic sensors have a better precision over a bigger dynamic range.
8. Fibre optic sensors can be multiplexed
9. They have better environmental resilience and can stand the harshness of extreme conditions
   [17]

Disadvantages of Fibre Optic Sensors

1. Fibre optic sensors are more expensive than traditional sensors hence less accessible than conventional sensors as cost is a major factor in decisions.
2. These sensors can be more delicate than the conventional sensors.
3. Fibre optic sensors have a non-linear output which is not convenient is some areas.
4. They are not as known as the conventional sensors hence they are unfamiliar and more people are less educated about them.
   [17]

Competitive Landscape

This section identifies the direct and indirect competitors in this field and some options an industry would rather employ than this new product. The fibre optic sensor market comes across heavily thought out and calculated leads such as mergers and acquisitions, expansion and collaboration, and the inclusivity of advanced technology. In this field, the providers are known for optimizing the production such as working on challenges such as reducing the price of fibre optic sensors for bigger marketing presence.

Commercial players in this field include:

Yokogawa Electric Corporation in Tokyo, Japan
Luna Innovations Incorporated in Roanoke, Virginia
ABB Ltd in Switzerland
Sumitomo Electric Industries Ltd in Osaka, Japan
Deltex Medical Group PLC in Chichester, West Sussex
OmniSens S.A in Morges, Switzerland
Finisar Corporation in Carlifonia, United States
Schlumberger Limited in Paris(France), Houston(Texas), London(United Kingdom) and the Hague(Netherlands)
Qinetiq Group PLC in Farnborough, Hampshire
Halliburton Company in Houston, Texas

Each of these employ organic and inorganic growth schemes and offer different types of sensors apart from fibre optic sensors. The high demand for this product in the infrastructure sector pushes the growth of this during the forecast period whilst the price challenges the growth. This lack of diversity, with the increasing price of this product and how convenient it is all constitutes as factors to the competitive landscape. North America leads this field with 34% of the market growth. [19]

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