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Applications of Fiber Bragg Grating Sensors in the Industry

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***Abstract*—*Industrial Revolutions marked periods of exponential growth in the industrial sector. Among the technologies immersed in this area is fiber optics, which was initially used in the telecommunications industry, but is currently present in several industrial sectors. More specifically, this work addresses its applications in Instrumentation associated with the concept of Bragg grids. In this paper is published a brief introduction to fiber Bragg gratings (FBG), aiming to present an analysis of the most recent articles related to the use of fiber Bragg grating in industrial sensors. We selected 19 papers to show the results and the positive and negative data of this technology. Although it is a promising technology, it still needs standardization with the conventional industry environment.*
***Keywords*— fiber Bragg gratings, fiber optic sensors, Instrumentation, sensors.**

I. INTRODUCTION

The industry is based on a set of economic activities, sequential or not, to convert raw materials into manufactured products for subsequent marketing. Since its emergence in England, between the XVIII and XIX centuries, the industry has gone through three revolutions, where fundamental changes occurred. Even with these significant changes, production has not stopped evolving, and because of this, studies in new techniques, new instruments, and equipment relentlessly continue to satisfy the increasingly critical global market.

Among the main difficulties demanded by the Market is the quality of the final product, the high indices of productivity and availability of equipment, the safety of the collaborators, and the preservation of the environment. It is in this context that Instrumentation stands out, being the field of engineering which studies, develops and applies devices for measurement, indication, registration, transmission, and conversion for the control of the most diverse variables of industrial and non-industrial processes, with the purpose of guaranteeing greater safety, efficiency, reliability and environment preservation [1].

Before instrumentation, operators carried out the control of variables manually. Later, it started using the pneumatic signal, therefore already improving the processes. Following arose the electrical and electronic sensors, which are the most commonly, used sensors nowadays. The instrumentation system can be utilized in two sorts of control processes, being the first of these the open loop systems, when the process does not require an automatic or manual control of the controlled variable; i.e., it is only necessary to analyze how the process behaves without interference for corrections. The second type of system and the more employed one is the closed-loop system, which requires the manipulation of one or more variables to keep the output variable close the programmed parameters, in other words, when the output signal can be controlled according to the needs of the process [2].

Among the electronic sensors, there are fiber optic sensors (FOS), which emerged soon after the invention of the optical fiber in the 1970s. In this period, the optical devices such as the laser, photodetectors, and the optical fibers were too expensive; as a result, only telecommunication companies used this technology, using it to improve the telephone network. With the evolution of the optical fiber during the 1980s, the optoelectronic devices became more affordable, which favored their utilization as sensors. The FOS can be applied in many branches of the industry, measuring different variables such as temperature, deformation, pressure, vibration, gas concentrations, among others [3].

An optical fiber generally is made of glass or plastic, consisting of the core, a cladding, and a coating from inside to outside [4]. The Fiber Bragg Grating sensor is similar to a standard optical fiber, but with Bragg gratings inserted into the core of the thread with specific spacing between them. These gratings reflect light differently from the rest of the fiber. When the optical fiber is submitted to a positive or negative deformation, these spacing change, making it possible to analyze the measured values through this variation by use of an optical interrogator.

The objective of this present work is to present a review of the recent papers related to the application of fiber Bragg grating sensors in the industry. This kind of sensor is one of the FOS options most used to carry the measurements of variables mentioned in the previous paragraph, because of their pure fabrication and the reflective signal being relatively stable. Despite its great benefits, these sensors still find profound resistance to their implementation in industries, in consequence of the lack of reliance and standardization of the technology. However, it is relevant to the application of these sensors where the conventional sensors are not useful or do not have a claim, due to their limitations.

II. METHODOLOGY

Due to this review, it was necessary to follow a sequence of research stages. Firstly, were defined the theme, the overall objective, and the specific objectives; further, it was described the following generic logical expression: ("Applications") AND ("FBG OR Fiber Bragg Grating") AND ("Industry"). This valid expression was suited to the advanced search syntax of each search mechanism of the following knowledge databases: Web of Science, ScienceDirect, MDPI and IEEE Xplore. Other filters were applied according to what each database allowed, refining the search, for example, year of publication of the paper, subject, journal, type of the article, among others. Using the MDPI base for example, by applying the logical expression solely, 380 articles were found. Proceeding with the filters available, the first was a year of publication, diminishing the number of articles to 264. Finally, by applying the filter for exclusively, the sensors journal resulted in the name of 187 articles.

On the carried search, only articles fitting the logical expression were included. It was necessary to analyze the title and abstract of the articles found in the selections, due to the significant amount of papers found, despite the filters applied. In the initial search, we found 373 articles, being 56 on Web of Science, 122 on ScienceDirect, 187 on MDPI and 8 on IEEE Xplore. After the initial search, the inclusion criteria were applied. These are:

- The articles must present applications of the fiber Bragg grating sensors;
- The forms must have applicability in the industrial environment;
- There should not be papers on the same application with the same type of Bragg gratings;
- The articles used in the results should not be older than six years of publication.

In the remaining articles were verified the field of application, the types of sensors of Bragg gratings, and the magnitudes of measurement, to have better control of the selection, avoiding similar or even identical papers. The application of these criteria reduced the number of articles from 373 to 60 articles matching the proposal of this paper. From these, 41 articles were selected for being utilized as a reference in the Introduction and Theoretical Foundation sections, while the other 19 were chosen to be exposed in the Results section respecting the inclusion criteria.

III. THEORETICAL FOUNDATION

3.1. Fiber Optics Sensors

Despite many believing that fiber optic sensors are a novelty, they studied for around four decades. Several approaches have been utilized to measure various physical parameters, but only some types of FOS are commercially attractive. In fact, in many cases, the systems of these sensors are not available in complete form, which is, including electronic components for detection and signal processing [5].

The future of these sensors is promising since they present very know benefits, such as compaction, immunity to electromagnetic interference and ionizing radiation, high sensibility, high bandwidth, and minimum weight. These properties make FOS essential photonic devices in dangerous environments, as nuclear power plants, where the detection and evaluation of the radiation levels and changes in temperature are crucial, especially in case of accidental restrictions [6]. These sensors were developed to measure electrical current and voltage, mechanical tension, temperature, pressure, gas, chemical contaminants, rotation, vibration, acceleration, bending, torsion, movement, biomolecules among others [7].

3.2. Fiber Bragg Grating Sensors

3.2.1. Working Principle

Periodic or aperiodic modulation of the effective refractive index (RI) in the core of an optical fiber possessing a diameter of around 4 to 9 micrometers formed the Bragg gratings in optical. Usually, the disturbance is between 5 mm to 10 mm, and the period is in the order of hundreds of nanometers, or longer, as in the case of long-period gratings. The development process of these gratings will be exposed further in the section named Manufacturing techniques. The RI disturbance leads to reflection of light in a narrow range of wavelengths, presenting an optical reflection spike at a specific wavelength, known as Bragg peak. This name was given due to the similarity to Bragg's

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law for X-ray diffraction [3]. In Fig. 1, presents the sensor structure and its working principle.

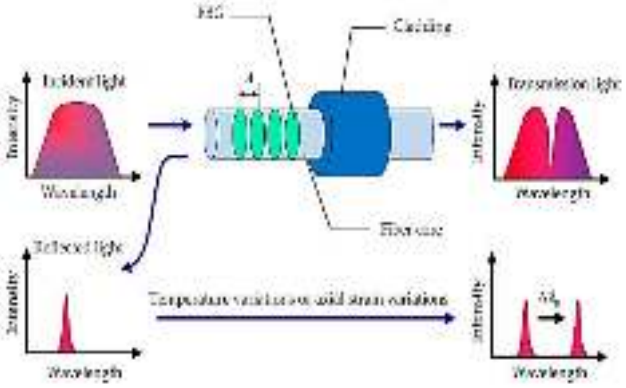

Fig. 1: Diagram of the working principle of the Bragg gratings. Source: image from [4].

Bragg's diffraction occurs to electromagnetic radiation whose wavelength is in the same order of magnitude of the atomic spacing when incident onto a crystalline material. In this case, the radiation is scattered in a specular manner by the atoms of the material and experiments constructive interference according to the Bragg's law. This law describes the condition for constructive interference of several crystallographic planes of the crystalline network separated by a distance d as shown in Equation (1).

$$2d \sin\theta = n\lambda \qquad (1)$$

In which θ is the angle of incidence, n is an integer and λ is the wavelength. A pattern of diffraction is obtained measuring the intensity of radiation spread in function of the angle θ [8].

These results in an optical filter aligned with periodic regions of variable RI. The multiplicity of internal reflections of periodic interfaces results in a narrow Gauss waveform being reflected (the Bragg's peak). All other waveforms are transmitted through the sensor. Bragg's wavelength is determined by Equation (2) [3].

$$\lambda bragg = 2\, neff\, \Lambda \qquad (2)$$

In which Λ is the grating period, λbragg is the Bragg's wavelength, and neff is the effective RI of the light in the fiber. Essentially, this condition means that the wavenumber of the grating corresponds to the difference of the (opposite) wave vectors of the incident and reflected waves. In this case, the complex amplitudes corresponding to the contributions of fields reflected from different parts of the grating are all in phase, so that they can be summed constructively; this is a type of phase correspondence [9].

In general, when the thermomechanical loads act on the Bragg gratings, the change in wavelength Δλbragg is given by Equation (3).

$$\Delta\lambda bragg = \lambda bragg\left(\frac{1}{neff}\frac{dneff}{dT} + \frac{1}{\Lambda}\frac{d\Lambda}{dT}\right)\Delta T + \lambda bragg\left(\frac{1}{neff}\frac{dneff}{d\varepsilon} + \frac{1}{\Lambda}\frac{d\Lambda}{d\varepsilon}\right)\Delta\varepsilon \qquad (3)$$

The first term on the right-hand side of Equation (3) represents the effect of temperature on the shifting of the Bragg's wavelength.

With $\left(\frac{1}{neff}\frac{dneff}{dT}\right)$ being the thermo-optical coefficient and $\left(\frac{1}{\Lambda}\frac{d\Lambda}{dT}\right)$ the coefficient de thermal expansion coefficient. The second term on the right side of Equation (3) represents the contribution of tension to the shifting of the Bragg's wavelength. It corresponds to a change on the periodicity of the grating and the change induced by optical tension on the refractive index. Assuming isothermal conditions and deformation are acting solely in the longitudinal direction of the fiber, Equation (3) becomes Equation (4).

$$\Delta\lambda_{bragg} = \lambda_{bragg}(1 - p_{eff})\Delta\varepsilon \qquad (4)$$

In which $peff = \frac{neff^2}{2}\left[p12 - \upsilon(p11 + p12)\right]$, p_{11} and p_{12} are the components of optical fiber tension and υ is the Poisson's ratio [10].

3.2.2. Temperature Compensation

Temperature has a powerful impact on the signals of the Bragg grating sensors. Naturally, the fiber, like any other material, expands when the temperature rises and contracts when temperature decreases, consequently the RI also suffers alteration. The deformation measurement, depending on the ambient temperature would be completely compromised if it were not by the temperature compensation. To carry out this compensation it is necessary to take some steps, the fundamental ones are:

- To install an extra sensor, close to the deformation sensor to measure temperature: consequently, it would be possible to make a mathematical compensation through comparison of data and subtraction of the effects of temperature;
- Position two sensors in a push-pull configuration so that when under deformation, one of them is compressed while the other suffers an opposite deformation;
- Encapsulate the fiber with protection, which expands in the opposite direction, in a manner that the tension applied on the sensor cancels the effect of temperature and it is not necessary to employ any mathematical compensation [11].

3.2.3. Key Types of Sensors

In the first years after its device, the attention was attracted to traditional methods of fabrication, such as the uniform FBG and long-period gratings (LPG). Recently other types of sensors-based Bragg gratings have appeared which will be presented concisely further. These new types of sensors are differentiated by the structures inscribed into the core

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of the optical fiber [12]. In Fig. 2 it is presented four of the main sorts of fiber Bragg grating sensors.

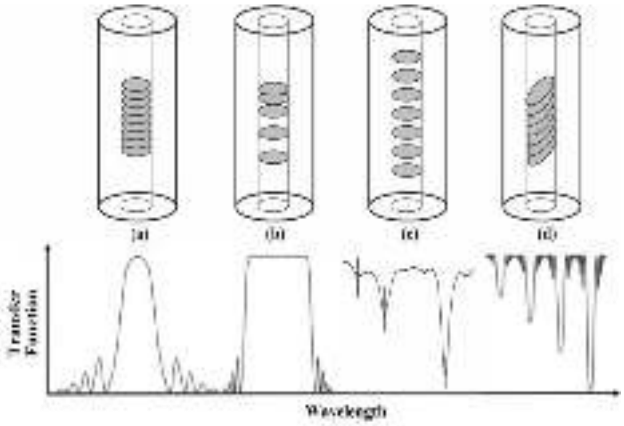

Fig. 2: Differences of the types of Bragg grating sensors: (a) standard; (b) chirped (c) long-period and (d) tilted, with their correspondent transmission signals below. Source: Image adapted from [12].

3.2.3.1. Long-period Bragg Grating Sensors

Long-period Bragg gratings are generally designed so that there is coupling between the propagating mode of the core and the first cladding. The system of coupled equations and corresponding boundary value conditions holds valid for the calculation of the transmittance function of a long-period network. However, on behalf of the interaction occurring between distinct environments, the coupling coefficient cannot be calculated in a simplified manner as it happens with traditional Bragg gratings [13].

These sensors are utilized primarily in systems, which analyze the refractive index, due to the high sensibility to the RI of the medium around the sensor. This sensibility has been being applied on the production of sensors, to monitor the concentration of the solution of a substance during a chemical process or to measure the level of a fluid inside a container [14]. Similarly, to what occurs on conventional Bragg grating sensors, these can be utilized to produce sensors for the detection of many physical parameters, including external reflective index, temperature, curvature, load, and liquid levels among others [15].

3.2.3.2 Chirped Bragg Grating Sensors

The chirped Bragg grating possesses a variable period between gratings which generally results in the reflected spectrum being significantly increased; consequently, these are frequently used as band-pass filters [16], [17].

3.2.3.3. Tilted Bragg Grating Sensors

On tilted Bragg gratings, the grating is in an angle concerning the optical axis resulting in the light being coupled outside of the fiber core, generating a change on the reflected wavelength and the bandwidth [18]. Generally, tilted Bragg gratings are used in optical interrogators as spectrometers [19].

3.2.4. Interrogators

The information from each sensor must be separated and understood. For this to take place, it is necessary for an interrogation system. For Bragg grating sensors, typically, the interrogation system monitors the signal reflected by the gratings. To that end, the system must be composed basically by a coherent light source which emits a broadband signal, an optical circulator with three optical ports to separate the message, one or more sensors in an optical fiber and an interrogator, which measures the value of the external parameter based on the wavelength of the spectrum reflected from the Bragg grating sensor [11]. In Fig. 3 it is shown, in a simplified manner, an interrogation system with the equipment and essential components.

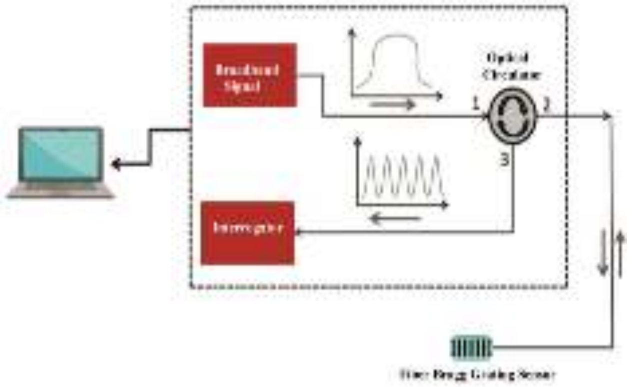

Fig. 3: Schematic diagram of the interrogation system. Source: Image adapted from [20].

Initially, the interrogators were enormous unities, complex and expensive; however, since the late 1990s, several groups of different researchers attempted to minimize and simplify them without losing functionality. When Bragg gratings suffer deformation, the wavelength of the reflection peak is altered. For the measurements, it is necessary to quantify these changes accurately. There are many different means to analyze these optical spectrums. For laboratory tasks, interferometers are the most commonly used [21]. The interferometric schemes convert changes in the wavelength to changes in phase but are not suitable for robust industrial applications. In industrial environments, other principles dominate. Two of these will be briefly explained below.

The edge filter principle utilizes special optical filters with transparency dependent of the wavelength, is considered the most straightforward technique and requires a narrow bandwidth sensor ($\Delta\lambda \approx$ 0.05 nm to 0.3 nm)

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whose wavelength deviations of the reflected signal are transformed in intensity changes by a linear variable filter. It is a band-pass filter with higher sensibility [22].

For the C band (1550 nm), the interrogators with tunable lasers represent first-class instruments. A tunable laser concentrates all of its energy in an extremely narrow band, and all the range of bandwidth sweeps the spectrum with high power and can provide an excellent signal to noise ratio [23].

Comparing the three techniques mentioned above, according to the characteristics of possible resolution, measurement speed, long-term stability, compatibility of signal multiplexing and the potential cost of application, it was observed that the tunable laser technique presents better results for industrial applications according to the Table 1.

Table 1: Comparison of different interrogation techniques. Source: Adapted from [24].

Characteristics	Interferometry	Edge filter	Tunable laser
Resolution Range	10^3 - 10^4	10^2 - 10^3	10^3 - 10^5
Measurement speed	High	High	High
Lon term stability	Good	Good	Good
Multiplexing capacity	High	Low	High
Potential cost	Medium	Low	High

3.2.5. Fabrication Techniques

The interest for Bragg gratings started with the possibility of writing the gratings laterally in the fibers, as seen on the work of [25]. The first technique used to inscribe Bragg gratings in fibers was the interferometer, which can be used in various configurations. A laser beam is divided in two by a prism. Each part is reflected in mirrors to meet again and form an interference pattern over the fiber to be inscribed. The cylindrical lenses concentrate the beams in the area of an inscription of the fiber, around 5 mm by 200 µm, to increase the density of the UV dose.

The most used technique at the moment is known as the phase mask, which is a diffractive optical element which spatially modulates the UV light beam with a specified period. Phase masks are formed on a fused silica substrate by a holographic technique. When a laser beam strikes the phase mask, the diffraction occurs, and the shaft is divided into several orders of diffraction. These two orders start at the same point on the other side of the phase mask but are divergent. The optical fiber is placed in contact or close to the phase mask, inside of the close range where the interference pattern is produced. The main advantage of this technique is its simple configuration since it is not necessary for the laser to present a good coherence and there are not mirrors to align [21].

Although this process is conceptually direct, there are many significant constraints to be overcome when producing these sensors. The first one is the cost of the equipment, specifically the excimer laser, as well the phase mask. Next, there is also the positioning of the components in such a way that gratings with precise characteristics of RI variation and correct spacings can be produced accurately along the fiber [26].

A contemporary example of equipment for manufacturing Bragg gratings is the automated system by Northlab Photonics, which was developed to fulfill the need for flexible fabrication of consistent Bragg grating sensors and high quality in a production basis. The phase masks are all kept in a spinning disk to allow switching between manufacturing of different types of these sensors, without handling by the operator. The Optical fiber is mounted onto a modular device and is positioned in a linear stage which allows the Bragg grating fibers to be inscribed along the fiber in a precise position in an automated fashion [26].

3.3 Bragg Grating Sensors Applications

The use of FBG has been growing continuously, and the applications of this technology have become more advanced [27]. Although initially restricted to communications purposes, currently associated with the Instrumentation area, this technology has been applied in the form of sensors in several industrial sectors.

3.3.1. Telecommunications

The investigation of telecommunication systems is of great significance to obtain greater spectral efficiency and a total capacity of information and reduce the performance degradation caused by transmission impairments. It is essential to calculate the transmission of the dense wavelength division multiplexing (WDM) for broadband access. The Bragg gratings technology undertakes a vital role on the systems of dense WDM, facilitating the filtering of specific wavelengths of the system. An optical add-drop multiplexer (OADM) is a device used in WDM systems for multiplexing and routing of different light channels inside or outside a single-mode fiber (SMF). It is a sort of optical node, generally utilized for the production of telecommunication networks [28].

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3.3.2. Electrical Industry

The Bragg grating sensors are excellent for use in the electrical energy industry due to their protection against electromagnetic interference. Also, these can be used in long-distance configurations, on account of the low transmission loss in the fiber. The temperature of electrical transformers, transmission lines, and high electrical currents have been calculated with these sensors [29].

One of the leading causes of fires in power systems is high temperatures, which in turn are usually caused by short-circuits and high leakage currents. Thus, defective or damaged equipment can be detected by continuously monitoring variations in temperature of the winding of electric machines, whose temperature can increase even with the operation of the cooling system of the machine. Jia et al. [30] present a sensor for an application in which the temperature of a transformer winding is measured with the optical fiber Bragg grating technology. The temperature monitoring system is divided into three parts: a man-machine interface developed with LabVIEW, an FBG wavelength demodulation system and fiber Bragg grating temperature sensor.

In the electrical energy sector, there are two factors, which may cause the breakdown of an electronic sensor: the presence of high voltages and high electromagnetic interference. Therefore, depending on where one wants to measure a parameter, it can be pretty difficult or even impossible to use a conventional sensor. The best option to deal with this is to make use of fiber Bragg grating sensors, due to their characteristic of immunity to electromagnetic interference; thus, it is possible to place them very close or even atop a high potential cable. Also, these do not necessarily require electrical energy on the location of the sensor [8]. Bragg sensors detect the most different electrical variables in several work ranges, as can be seen in Table 2.

Table 2: Different variables measured utilizing Bragg gratings. Source: Adapted from [8].

Variables	**Units and ranges**
Electric Current	A to kA
Leakage Current of Insulators	μA to mA
Voltage	mV to MV
Impedance	μΩ
Vibration of Structures and Equipment	m/s^2
Temperature	°C
Gas Concentration	Ppm
Pressure	mBar to Bar
Distance Between Stationary and Rotating or Moving Parts	1 or 0

3.3.3. Petrochemical industry

With the oil and gas industry rapidly growing, increasing the efficiency and profit demands improvements in the technology for cost-effective production in key areas of exploration of reservoirs an in the production management of oil wells. The Bragg grating sensors are used for seismic exploration and are required to be able to measure multiple physical parameters, as temperature, pressure and acoustic waves, in a harsh environment. This application requires high sensibility over the broad range of vibration frequency ranging from 5 Hz to 2.5 kHz, which contains essential geological information [31].

In the oil and gas industry, there is the necessity of measuring the interface level between the fluids in wells, reservoirs, processing vessels and storage tanks for liquids of different densities, corrosivity, and viscosity. Moreover, the processes involve high ranges of pressure and temperature, which raises the requirements of complexity and robustness for the instrumentation [32].

3.3.4. Construction industry

Applications in civil construction structures [33], [34] as bridges, roadways, skyscrapers, and mines may have as target different stages of the construction: monitoring the stress during and after building. The measurements during construction include pre-stressing forces applied to precast concrete components; weight on critical locations; dissolved between the concrete and metallic beams; concrete shrinkage and chemistry (pH) during hardening. The post-construction measurements include continuous detection of incidents and impacts; evaluation of the aging and splits in concrete and asphalt; and weigh-in-motion. Both the static and dynamic analyses are taken from a surface mounted Bragg grating sensor [35].

3.3.5. Environmental industry

Chloroform is released into the environment through numerous anthropogenic sources, where industries utilize it on the production lines. Exposition to 50 ppm of chloroform may harm human health. The traditional methods of chloroform detection include spectrophotometer and metallic oxide. These methods are not suitable for on-line monitoring because they are easily affected by environmental factors, such as ambient temperature and air humidity. Ahad et al. [36] developed a new sensor with Bragg gratings coated with polyaniline film, which was used as an optical sensor to the detection of chloroform.

In this study, the effect of synthesis parameters, such as different proportions of dopants and different temperatures of polymerization for the efficiency of the sensor was being investigated. Polyaniline showed the highest conductivity (1.627×10^{-2} S/cm) and the best ability (sensibility = 0.0015) with a response time of seven seconds. The mechanism during the detection of chloroform was studied through the infrared analysis by Fourier transform (FTIR) and ultraviolet-visible (UV-Vis), and the results revealed the physical interaction of the partial negative charge of chloroform with the partial positive charge of the polyaniline chain. Moreover, the performance of the sensor, as recyclability, selectivity, detection limit (DL), quantification limit (QL) and analysis of the real sample were studied in this research.

3.3.6. Chemical industry

The IR constitutes a property inherent to each substance, and it is through it that, particularly in the domain of optical monitoring of substance concentrations, settles the communication between state alterations of the measurand and the response of the sensor system. Areas comprising biochemistry, chemical analysis, and in particular, the control of different parameters in natural or industrial settings constitute the primary targets for the monitoring of the refractive index value [8].

Bragg gratings can be used in sensors, which carry the real-time monitoring of material concentrations in aqueous solutions, or materials placed in inaccessible locations or potentially explosive environments, and for the quality control of industrial production. The levels of solutions as ones of sodium chloride and calcium chloride were measured with sensibility equal to or higher than measurements with conventional Abbe refractometer [37].

3.3.7. Medical industry

Besides the diverse applications on the industrial fields for monitoring several physical variables, Bragg gratings have a promising future in medical applications. Janting et al. [38] highlight spectral multiplexing capability, biocompatibility, and small size is favorable characteristics making an excellent potential for use in-vivo sensing.

The FBG sensors have been widely employed to monitor physiological and cardiac parameters, in microsurgeries, blood pressure on the feet of diabetic patients, in biomechanical studies, temperature monitoring during the thermal ablation of cancer, in systems of respiratory control and the tactile sensor, thanks to its biocompatibility characteristics, full bandwidth, flexibility, small size, non-toxicity among others. Additionally, they are suitable for application in environments with high electromagnetic noise, because of their immunity to electromagnetic interference and their intrinsic compatibility with magnetic resonance. This last characteristic makes the FBGS adequate for monitoring biological parameters (for example, respiratory and cardiac monitoring) during magnetic resonance procedures [39].

3.3.8. Aviation and aerospace industry

In the aviation and aerospace, a significant challenge is faced, which is service monitoring and perceiving in real time the integrity of the structures with an onboard sensor system. For this application, it is used as a distributed Bragg grating sensor system [40].

It is of great importance to calculate the temperature and stress simultaneously to correct thermal stress and the measurements of static deformation. Several approaches were proposed for simultaneous measurements of temperature and strain [41]. Another example was the deployment of a system with eight strain sensors and six temperature sensors on the Airbus A 340-600 fuselage, which was successfully tested in parallel with electrical strain gages to measure the load in real conditions [42].

IV. RESULTS

Werneck et al. [8] observed the occurrence of problems concerning the internal temperature measurements in a hydroelectric generator, as sensibility, lack of linearity, accuracy, among other errors. Faced with this, they applied Bragg gratings for correction of these problems. After deployment, the researchers observed precision of 99%, even after 2.5 years after implementation the system continued to be effective. The system also provided immunity against electromagnetic interference when compared to conventional sensors, as well as reduced costs as a consequence of the substitution of kilometrages of cables by merely some optical fibers.

Basumallick et al. [43] modified an optical accelerometer based on cantilevers. The sensibility of the accelerometer was effectively enhanced nearly twice when changed with Bragg gratings in comparison to the conventional conception, due to the architecture requiring a simpler and more robust design.

Jiang et al. [44] compared several techniques based on Bragg gratings for varied applications, such as measurements of vibration and temperature applied to the aviation industry, monitoring of the water sublimation status, and parameters for improved safety in airplanes. The sensor was immersed in liquid nitrogen for 200 hours to explore the stability in cryogenic temperature, which

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revealed a result of 9 pm of reflected wavelength fluctuation and a standard deviation of 0.76 pm.

Rodriguez-Cobo et al. [45] modified a fiber Bragg grating sensor for application in monitoring pressure in the manufacturing of plastic molds, during the compression phase, efficiently monitoring the structural integrity of the manufactured parts as well monitoring deformation while the structure is in operation. The sensor is embedded in composite material and exhibits a linear response to both strain and temperature, rendering it suitable for structural integrity monitoring.

Zaynetdinov et al. [46] constructed Bragg grating sensors with a polyimide coating in order to give the sensors active sensibility in diverse temperature ranges due to the capacity of this compound to be resistant to low and high temperatures (-271 °C to 300 °C), what lead to better sensibility, stability and precision in the detection in the temperature range of -271 °C to 127 °C. The researchers demonstrated as well the possibility of multiplexing, that is, measurements in several points with a single fiber.

Sarkar et al. [47] applied Bragg gratings in sensors for electrical transformers, monitoring online and identifying partial overloads sustained by them, due to the fiber Bragg gratings being composed of a dielectric material dispensing the necessity of an isolation arrangement for insertion in the transformer. The conventional sensors require electrical connections near the measurement locations and amplifiers for transmission of the harvested signals, which is a difficult task for the installation of such sensors. The suggested sensor presented experimental results superior to the conventional ones, presenting higher sensibility and immunity to interferences from the high voltages of transformers.

Osuch et al. [48] investigate the application of tilted Bragg gratings for utilization in sensors of simultaneous measurement of temperature and liquid level. After the modifications with the gratings, the researchers observed that it was possible to identify values in wider coverage ranges, differently from when utilized without the Bragg gratings. The liquid level and temperature in this application can be measured independently, and due to the 3.5° angle of the gratings inserted in the core of the fiber, good sensitivity responses were achieved. The system featured is capable of being applied in the chemical, food and automotive industries; as well, because of its all-fiber structure, in potentially dangerous environments where immunity to electromagnetic fields and electrical insulation is necessary.

Marignetti et al. [49] studied the demonstration of the Bragg's law principle, of an optical fiber operating as an electric field sensor. The system is based in a semiconductor laser diode, emitting light around 1577.5 nm, which interrogates the fiber sensor around its point of maximum reflectivity. The application of an active electrical filed triggers a small variation of the light path length of the waveguide due to electrostriction and, thus, disturbs the wavelength of the reflectivity of the peak of the grating, being necessary a quadratic compensation of the field amplitude.

Sridevi et al. [50] utilized Bragg gratings coated with graphene oxide for detection of nitrogen dioxide (NO2) in low concentrations (0.5 ppm – 3.0 ppm) after the insertion of the Bragg gratings it was observed an improvement in the sensibility of the detector.

Luo et al. [51] developed a sensor for detection of dissolved hydrogen, a byproduct of oil decomposition in transformers, which reveals the necessity de changing the transformer. This sensor utilized Bragg gratings for detection of different ranges of wavelength, to determine the need or not of replacing the transformer.

Bremer et al. [52] unified in a Bragg grating sensor the measurement of 3 parameters: pressure, temperature and refractive index, all measured simultaneously for tabulation systems focused on physicochemical parameters. Moreover, these parameters are essential for the detection of concentrations of chemical products in liquids, which is of great interest in efficient operations.

Lyu et al. [53] proposed a differential pressure sensor with magnetic transference utilizing Bragg gratings where the measurements do not impose direct contact between the sensor and the fluid, the test reveals that the sensor is adequate for measuring pressure in the range of 0-10 kPa with sensibility of 0.0112 nm/kPa, which can be used in locations with high temperatures, strong corrosion and high measures of overload.

Jiang et al. [54] attempted to solve the problem of an explosion in measurements of thermal gas flow caused by conventional electronic sensors. In light of this, they developed a sensor using Bragg gratings for fluid temperature measurement through a heat dissipation unity, substituting conventional photoelectric transducers.

Light in the C band from the amplified spontaneous emission (ASE) light source is divided, with a part being used to heat the coating and the other being used in the signal processing unity. In heating unity, an absorbing layer is introduced to replace the traditional resistance-heating module for minimizing the risk of explosion. The results of measurement demonstrated proper consistency between the difference of flow and temperature in the simulation.

Zhao et al. [55] optimized a conventional flow meter with optical fibers for application in water flow

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measurement (0 m³/h a 22.5 m³/h), utilizing Bragg gratings, they reduced imprecision to almost zero, leaving only 3.6%, in accordance to the resolution of 0.81 m³ demanded by the study. As a result, the addition of the Bragg gratings to the gauge showed several benefits such as good sensibility despite the compact size, a wide range of measurement, simple manufacturing, and minimum pressure losses.

Liu et al. [56] studied and have made possible a new pressure sensor for application in the windings of transformers, this sensor was designed with Bragg gratings and the measurement is monitored in real time, even in different positions the data keeps consistent and with good repeatability, demonstrating the excellent efficiency of the sensor.

Chiu et al. [57] coated a relative air humidity sensor made with Bragg gratings in graphene. After coating, they verified enhanced sensibility and detection of the relative air humidity, evidencing the excellent potential of the Bragg cell for monitoring air moisture.

Bieler et al. [58] due to the constant breakage of motor rotors, developed a magnetic sensor based on Bragg gratings, composed of Terfenol-D particles immersed in epoxy resin to detect broken rods on rotors of induction motors. Regardless of the low cost of an induction motor, production losses caused by a functional failure on the engine can be higher than the price of the motor itself.

The conventional technique has failed to indicate the extent of the damage. In contrast, with the sensor proposed it is possible to distinguish with precision the evolution of the damage on the motor shaft, even in the initial stages of failure. Moreover, for being a fiber optic sensor, it has the capacity of being inert even in systems of a dangerous atmosphere.

Liu et al. [59] applied Bragg gratings in the measurement of cutting force, vital process in machining. In work was implemented a new carbon integrated rotating dynamometer with Bragg gratings, implemented and tested with a cutting effect of four components. Verifying a high sensibility in the four elements as possible.

Leal-júnior et al. [32] evaluated the application of sensors with Bragg gratings in the oil industry due to the production of petroleum also involving the production of water, gas and suspended solids, which are separated from the oil in triphasic separators. They present a description of the problem of the multiphasic level in the petroleum industry and a revision of the current technologies for evaluation of the multi-interface level.

The technique of the Bragg grating sensors presented good chemical stability, intrinsic safety, small size, and multiplexing. The results revealed that the proposed sensor system is capable of measuring the interface level with a relative error of only 2.38%. Furthermore, this sensor system is also capable of measuring the oil density with an error of 0.8 kg/m3.

For better comprehension of the results mentioned in this section, it is presented in Table 3, where are listed, in chronological order, technical data complementary to the articles analyzed. This table possesses data related to the application field, measured variable, type of sensor, sensibility, the range of work, if there is temperature compensation or not, maximum error and the interrogation sensor utilized.

V. DISCUSSION

In the course of this search and verification of the articles selected for this revision, it was quickly noticed that most of the applications of these sensors are very specific and of experimental nature, evidencing that this technology needs adaptations in the conventional industrial processes. Nevertheless, the superiority of these sensors concerning the conventional ones can be effortlessly perceived, as it was observed in [54], in which the researchers developed an intrinsically safe flow sensor for thermal gas, in other words, explosion-proof, a characteristic that is of extreme importance in industrial processes.

In addition to being intrinsically safe, the Bragg grating sensors carry other significant advantage in relationship to traditional sensors, which is the immunity to electromagnetic interference [47], [49], [58] proved this with the application of these sensors in hydroelectric power plants, electrical generators windings, high voltage transformers, and induction motors respectively.

Another important feature of these sensors is their chemical stability, which favors their application in the measurement of interface level of fluids, especially in the chemical and oil industries. Leal-júnior et al. [32]
achieved satisfactory results in measuring the multiphasic level in the oil industry. Whereas Lyu et al. [53], highlights the resistance of the sensor to high corrosion levels when measuring differential pressure in direct contact with the fluid to be probed.

Among all its benefits, the most remarkable one is its multiplexing capability, that is, the potential to measure different parameters as deformation, temperature, vibration, pressure, displacement, among others, with a single fiber or a unique setting, but in various points. This advantage is evidenced in [44], where it was compared with other optical sensors in the measurement of temperature and vibration in the aviation sector.

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Table 3. Comparison of information from the selected works.

Author	Year	Field of Application	Variable Measured	Type of Sensor	Sensibility	Coverage	Temperature Compensation	Maximum Error	Interrogation System
Basumallick *et al.*	2012	Experimental	Acceleration	Standard	450 pm/g	-	No	-	Micron Optics SM130
Werneck *et al.*	2013	Electrical Industry	Temperature	Standard	13 pm/°C	20 to 85°C	No	0.007 °C	Spectral Eye 400-FOS&S
Jiang *et al.*	2013	Aviation and Aerospace Industry	Pressure, Temperature and Vibration	Standard	-	0 to 103.75 kPa -253 to 150 °C	Yes	0.1 kPa 0.76 pm	Fabry-Perot Filter
Rodriguez- Cobo *et al.*	2015	Construction Industry	Pressure	Standard	-	0 to 0.8 kgf/cm^2	Yes	-	-
Zaynetdinov *et al.*	2015	Experimental	Temperature	Standard	6.8 pm/°C	-271.15 to 126.85 °C	No	8.25%	Micron Optics SM125
Sarkar *et al.*	2015	Electrical Industry	Pressure and Temperature	Standard	1 pm $\mu\ \varepsilon^{-1}$ and 10 pm $°C^{-1}$	> 50 μ ε-1 and 28 to 80 °C	Yes	-	BaySpec's WaveCapture F1360550
Osuch *et al.*	2016	Experimental	Level and Temperature	Tilted	-0.456 ± 0.009 dB/mm and 11.4 ± 0.2 pm/° C	0 to 9 mm and 30 to 60°C	Yes	-	-
Marignetti *et al.*	2016	Electrical Industry	Electrical Field	Standard	10 pm/°C	1 to 20 kV	-	-	Tunable Laser
Sridevi *et al.*	2016	Experimental	Gas Detection	Standard	0.8 pm/min	0.5 to 3 ppm	No	-	Micron Optics SM130
Luo *et al.*	2016	Electrical Industry	Hydrogen Detection	Standard	1.96 (μ/L)/pm	-	Yes	12%	Micron Optics SM130
Bremer *et al.*	2017	Experimental	Pressure, RI and Temperature	Standard	-	20 to 80 °C	Yes	-	Ando AQ6330
Lyu *et al.*	2017	Experimental	Differential Pressure	Standard	0.0112 nm/kPa	0 to 10 kPa	-	-	-
Jiang *et al.*	2017	Experimental	Flow	Standard	13 pm/°C	-	Yes	-	Fabry-Perot Filter
Zhao *et al.*	2017	Experimental	Flow	Standard	-	0 to 22.5 m3/h	No	0.386%	-
Liu *et al.*	2017	Electrical Industry	Pressure	Standard	0.133 pm/kPa	-	Yes	2.70%	-
Chiu *et al.*	2017	Experimental	Humidity	Tilted	0.002 to 0.01 nm/%RH	20 to 80% RH	Yes	-	-
Bieler *et al.*	2018	Electrical Industry	Magnetic Detection	Standard	2.2 με/mT	50 to 250 mT	Yes	-	Fabry-Perot Filter
Liu *et al.*	2018	Machining	Force	Standard	1.067 με/N, 1.080 με/N, 0.148 με/N and 7.861 με/N	-	Yes	5.35%	-
Leal-junior *et al.*	2018	Oil Industry	Density Level	Standard	2.89 pm/cm	-	Yes	Level = 2.38% Density = 0.8 kg/m3	Micron Optics SM125

Leal-júnior et al. [32] present the possibility of measuring level and density in oil tanks in oil rigs and Bremer et al. [52] who demonstrate a sensor capable of measuring pressure, temperature and refractive index of a fluid in a single point simultaneously.

Alternatively, these sensors, even with these advantages still are not being applied in large scale on the traditional industry, mainly on account of the initial cost of implementation. Although the Bragg grating sensors are not expensive themselves, the interrogation systems still hold high value, compared to the traditional sensors, which readily adapt to the already existent technologies.

Despite being emphasized among the studies mentioned, the problematic implementation of the technology due to the high cost involved, with respect to Bragg gratings for application in temperature measurements, Zaynetdinov et al. [46] and Werneck et al. [60] developed a sensor capable of proportioning parameters as high reliability, multiplexing capacity, fast response time and low cost, based in their existent necessities, both with need of improvements insensibility of acquisition of temperature results.

Another negative factor of the technology of FOS, in general, is the lack of awareness of the technology. As optical fibers are generally utilized in telecommunications [61], when they are mentioned industrial sensors, it comes to mind the image of a fragile fiber which would not have applicability in a hostile environment as industrial. Jiang et al. [44], Osuch et al. [48], Bremer et al. [52], and Werneck et al. [60] make it clear in their work the excellent relationship of Bragg grating sensors and the heavy industrial environment.

VI. CONCLUSION

It can be concluded that the Bragg grating sensors, among the FOS, are one of the most popular options for measurement of different parameters due to their pure fabrication. In the last years, these sensors were applied in a vast diversity of industrial sensing applications, monitoring the most several variables such as deformation, temperature, pressure, vibration, flow, humidity, among others.

Sensors based on the Bragg technology present numerous advantages if compared to the conventional electrical sensors. As examples may be listed their immunity to electromagnetic interference, they were intrinsically safe, possessing high reliability, multiplexing capability, their fast response time, covering long transmission distances, among others.

In contrast, despite the studies involving Bragg gratings having started in the 1970s, the insertion of these sensors in the industry has been little explored. The main reasons for the slow diffusion of this technology in the market are the lack of awareness, low confidence in this equipment, as it is no standardization in its use, and simplification of measurement systems based on this technology. This consequently generates a considerable expense and limits these sensors to specific applications, as in petrochemical industries, monitoring of structures integrity, chemical analyses and in telecommunications.

So that the Bragg grating sensors can earn more confidence, these must possess the capacity to fit in with the existent control structures. These sensors hold a great potential to substitute the conventional sensors in specific applications where these do not function adequately, or even their installation is not possible, due to certain characteristics as the environment being explosive or with high electromagnetic interference.

The integration of a matrix of fiber sensors in a control system would be a logical first step. A fiber system can be connected to a programmable logic controller (PLC) through a simple interface module. This would eliminate the necessity of additional training, therefore, reducing the costs and the suspicion on this technology, allowing the use of fiber sensors to become a standard engineering practice on industrial processes. Furthermore, this would open the path for almost all types of optical control in the future.

For better integration of these sensors in the industry, qualified professionals are needed both from the area of industrial instrumentation as of telecommunications. The combined work of these two fields is necessary, since most of the concepts of the functionality of these sensors come from telecommunications, although the knowledge of the industry needs comes from industrial instrumentation.

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