Fiber Optic Shape Sensors: A comprehensive review

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Abstract

Fiber Optic Shape Sensing is an innovative Optical Fiber Sensing Technology that uses a fiber optic cable to continuously track the 3D shape and position of a dynamic object (with unknown motion) in real-time without visual contact. This technology offers a valid alternative to existing shape sensing methods, thanks to a combination of advantages (including ease of installation, intrinsic safety, compactness, flexibility, electrically passive operation, resistance to harsh environments and corrosion, no need for proximity or computational or numerical models to reconstruct shape) that can bring remarkable improvements to the fields of Civil, Mechanical and Aerospace Engineering, Biomedicine and Medicine. A considerable research effort has been dedicated to this subject in the last twenty years.
This paper presents an ambitious review of the current state of the art of Fiber Optic Shape Sensors (FOSS) based on Optical Multicore Fibers (MCF) or multiple optical single-core fibers with embedded strain sensors and provides a comprehensive analysis of a wide range of aspects, comprising: (1) existing alternative technologies; (2) an overview of optical fiber sensors (3) characteristics and advantages of fiber optic shape sensors; (4) historical achievements; (4) performance and error analysis; (5) applications; and (6) present and future perspectives.

Keywords: *Fiber-Optic Shape Sensor; Optical Curvature Sensing; Optical Fiber Sensor; Fiber Bragg Grating; Distributed Sensing; Optical Multicore Fiber*

1. Introduction

Fiber optic shape sensing has recently captured the attention of academia and industry and has been investigated by research groups worldwide. This outstanding technology enables the remote 3D shape reconstruction of dynamic objects in real-time in the absence of visual contact. A Fiber Optic Shape Sensor (FOSS) can be defined as fiber optic cable with multiple cores and embedded strain sensors. The working principle is the following: in each instrumented section the three-dimensional curvature is calculated through the simultaneous measurement of strain in different cores. The longitudinal curvature function is determined from the values of strain sensed in the instrumented sections by means of interpolation or curve fitting, while the shape is reconstructed through numerical integration of the curvature.
The great interest of this technology is due to its remarkable potential in a multitude of applications fields, such as Civil, Mechanical and Aerospace Engineering, Biomedicine and Medicine and its improvement over existing methods. Several alternative technologies can be employed for shape reconstruction, such as electrical strain sensors [1–3], accelerometers [4–12], optoelectronic sensors [13,14], electro-mechanical systems based on tilt sensors [15–18], cameras [19,20], RAdio Detection And Ranging (RADAR) [21–23] and laser scanners [24]. Nevertheless, optical fiber shape sensors are significantly more competitive, thanks to the numerous advantages of Optical Fiber Sensor (OFS) technologies [25–32], including: compactness, small size, flexibility, intrinsic safety, resistance to harsh environments and corrosion, and their multiplexing and embedding

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capability.

FOSS can be classified into two main categories: (I) shape sensors based on optical multicore fibers (a single fiber with multiple cores) and (II) shape sensors based on multiple optical single-core fibers. In this last case, the sensor is composed of several fibers attached to a support, for instance a tube or a bar. The first option ensures compactness, monolithicity (no need for sensor assembly, being manufactured as a single piece), flexibility and small size. The second alternative has higher resolution thanks to the greater core spacing, the distance between the outer cores and the sensor's axis. Other classifications can be made considering the number of cores or the technology employed to sense strain, e.g. Fiber Bragg Grating (FBG), Rayleigh scattering or Brillouin scattering.

The objective of this paper is to conduct a multiple-perspective review of the main recent advances in fiber optic shape sensing and aspires to be an exhaustive guide for anyone interested in entering this field of study and a valid support for the experts looking for a thoroughly up-to-date view of the state-of-the-art of this topic.

Although other authors have provided an admirable review of patents and research papers on fiber optic shape sensors [33], the present review is probably the most ambitious so far as it takes into account a wide range of aspects, comprising:

- An analysis of the existing technologies used to reconstruct shape, with particular attention to characteristics, advantages and disadvantages (Section 2);
- A concise overview of optical fiber sensors (Section 3)
- An extensive description of fiber optic shape sensors, considering characteristics, classification and advantages and a special focus on the strain sensing technologies used (Section 4);
- A bibliographic review of the historical achievements and the recent developments of fiber optic curvature, twisting and shape sensing (Section 5);
- An examination of the performance and error analyses conducted (Section 6);
- A summary of the applications in which these sensors have been used or have potential to be implemented (Section 7);
- The authors' considerations on present and future perspectives (Section 8).

2. Existing technologies for shape sensing

Shape measurement plays an important role in the fields of Civil, Mechanical and Aerospace Engineering, Biomedicine and Medicine, for applications such as the structural health monitoring of civil structures and infrastructures (buildings, tunnels, bridges and roads), reconstruction of the displacement field of critical components (wings and aircraft) and tracking robots and medical instruments (needles, catheters endoscopes) inside the human body. For the foregoing reasons, many researchers and industries have developed several shape reconstruction methods exploiting diverse technologies, including:

- ➢ Shape sensing based on electrical strain sensors [1–3];
- ➢ Vibration-based shape sensing using accelerometers [4–12] ;
- ➢ Monitoring systems consisting of acquisition devices, computers, and processing software able to reconstruct shape using data collected by cameras [19,20,34], radio detection and ranging (RADAR) [21–23] or laser scanner [24,35,36];
- ➢ Electro-mechanical sensing systems that reconstruct shape by measuring angles with tilt sensors [37], such as inclinometers [15–18];
- ➢ Optoelectronic shape sensing [13,14].

This section reviews the existing methods available in the market capable of performing shape sensing, classified according to the technology used.

2.1. *Strain sensors*

Electrical strain gauges are one of the most widely used devices to measure strain [38,39]. The sensing principle is simple: strain gauges are electrical conductors and when attached to the object to be monitored deform together with it. This deformation produces a change in the electrical resistance through which it is possible to calculate the strain to which the object is subject. Optical fiber sensors have also been broadly used for this purpose [40–42], as will be better illustrated in Section 4.3. However, it has to be pointed out that fiber-optic strain sensors are completely different from FOSS, since they only measure strain.

Strain sensors have been intensively employed in Structural Health Monitoring (SHM) [43] for several purposes, including damage detection [44], structural fatigue life evaluation [45] and deformation monitoring [3]. In this last case, firstly, a Finite Element Model (FEM) of the structure under examination is developed. Then a series of points of measurements are selected and the strain gauges are installed in these locations. Finally, the values of strain detected are used as inputs for the FEM and the deformed shape of the structure is determined. This technique has some disadvantages: the installation of the sensors can be costly, the development of complex models is eminently time-consuming and significant approximations are required to interpret the structure behavior from the limited number of measurement points considered [45].

An alternative method of shape sensing consists of flexible sensor systems based on electrical strain gauges. Koch et al. designed and tested a small and ultra-thin flat polyimide foil with 36 bending measurement points, illustrated in Fig. 1, able to reconstruct the shape of surfaces on the basis of bending measurements [1]. This technology can reconstruct shape directly without the development of models but unfortunately the modest size of the sensor limits its scope of applications.

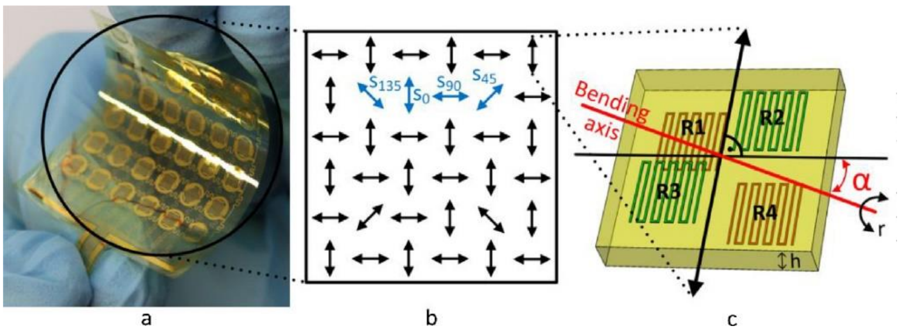


Fig. 1. (a) Hand-bended 6 × 6 bending sensor instrumented foil. (b) Illustration of sensors orientations. (c) Illustration of the sensor under bending [1].

2.2. *Accelerometers*

Accelerometers are able to measure the acceleration (rate of change of the velocity) of an object. Several systems based on accelerometers have been proposed for direct shape sensing [8–12], whose main applications are the analysis of human motions and spine shape monitoring. These systems are constituted by a series of sensor nodes, instrumented with electrical accelerometers rigidly connected to each other and track the shape by means of complex reconstruction algorithms. Regrettably, the range of application of these systems is notably reduced by their limited embedding capability.

Accelerometer-based methods are broadly used in structural health monitoring for damage detection in civil and mechanical structures through mode shape identification [46,47] and permit the understanding of the global structural behavior, considering an extremely limited number of measurement points, conveniently selected [4,5,48]. First, the mode shapes of the structure are identified by means of the accelerometers attached to the structure [4,5,49]. Two different damage detection approaches can then be employed to assess the structural integrity: model-based and data-based. Model-based methods consist of the comparison of the measured structural response with predictions resulting from computational models of the analyzed structure [6]. The presence of damage in the structure, as well as its location and severity assessment, can be determined from the differences between predicted and measured data [44]. The main limitation of these methods is that the development of accurate computational models is not always easy and sometimes not even possible. Data-based approaches rely on pattern recognition algorithms and compare data obtained from the intact and damaged structure [50]. The principal limitations of these approaches are that the data of one or more damaged conditions are generally not available *a priori* and in the case of existing structures even the data from the intact structure are often not available.

2.3. *Monitoring systems based on cameras, RADAR or laser scanner*

Vision-based approaches are widely used in industrial robotics [51] for robot motion tracking and in civil engineering to monitor the deformation of civil structures and infrastructure and assess their integrity, offering a noncontact alternative to the employment of sensors [19,20,34]. A vision-based measurement system consists of image acquisition devices, computers, and an image processing software. The data collected from cameras are processed with specific numerical algorithms to track motions, obtain the mechanical parameters for structural monitoring, detect visual abnormalities and extract the time histories of displacement, deformation and shape. Image processing techniques suffer from a series of limitations [52]: inability to carry out in-field continuous monitoring due to complicated site conditions and infrastructure closure during the data acquisition. When high speed data acquisition is not necessary, in addition to camera-based methods, radio detection and ranging (RADAR) and laser scanner can be used in structural health monitoring [21–24,35,36]. Laser scanners are particularly useful to track 3D shape (see Fig. 2), while RADAR allows the deformation tracking of large structures even if with less accuracy than cameras.

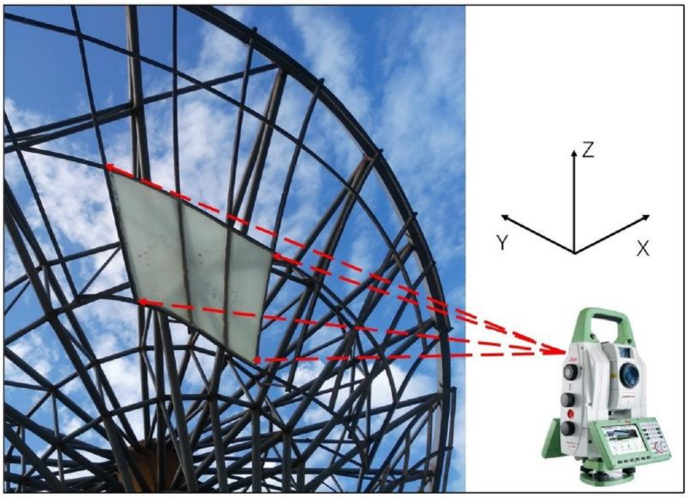


Fig. 2. Three-dimensional shape/position tracking of a civil structure using 3D laser scanning [36]**.**

2.4. *Electro-mechanical systems based on tilt sensors*

Electro-mechanical systems based on tilt (or slope) sensors, mainly known as inclinometers, are used to reconstruct three-dimensional shape based on the measurement of angles [15–18]. These instruments are commonly employed in health monitoring of structures and infrastructures [16,18,53] and geotechnical applications [17], where they are used to measure horizontal displacements at various points of a borehole (slope inclinometers). An inclinometer measurement system is a combination of components: a grooved casing, which can be attached to the structure or installed in a borehole, inclinometer probe and data acquisition equipment. The inclinometer probe is manually moved along the length of the casing to measure angles in two perpendicular planes by means of accelerometers or gyroscopes. Unfortunately, this operation requires time and monitoring personnel to obtain a series of measurements. Alternatively, a fixed In-Place-Inclinometer (IRI) can be employed to collect data continuously [53]. An IRI is composed of a sequence of wheeled probes connected to each other through extension rods. The probes do not need to be manually moved and can operate continuously, saving time and labor. The deformation of structures or the displacement fields of slopes or landslides can be reconstructed from the angles measured at various depths along the casing. The most significant advantages of these sensors are: their great length, generally tens of meters, and accuracy, for instance servo-accelerometer probes, which have the highest resolution of the available inclinometers on the market, reach a maximum system precision of 1.2 mm per 30 m or 1:24,000, while the usual precision is six times lower without corrections for systematic errors [53]. The principal disadvantages are the low speed data acquisition and the continuous exposure of the system to corrosion in the case of in-place-inclinometers.

2.5. *Optoelectronic sensors*

Optoelectronics shape sensors are hybrid systems capable of tracking the shape of an object in real-time, using a combination of light and electrical sensors, such as gyroscopes and accelerometers, and mirrors [14,54,55]. The sensors that belong to this category are very diverse and rely on different operating principles and sensing technology, therefore, is not possible to give a simple definition and a description of their characteristics.

2.6. *Fluoroscopy*

Fluoroscopy is an imaging technique that provides real-time feedback of position and shape of surgical instrument inside the human body using X-rays [56]. This technology finds application in a number of image-guided procedures, such as orthopedic and spine surgery [57,58], cardiac interventions [59], epidural injections [60] and cervical pedicle screw insertion [61]. The fluoroscopic navigation procedure consists of 4 basic steps [62]: (I) reference array attachment to the skeleton of the patient to enable tracking during the operation; (II) image acquisition by means of the fluoroscope and transfer to the computer workstation; (III) calibration to improve and sharpen fluoroscopic images; (IV) superimposition of the predicted shape and position of the medical tool onto the harvested image. Fig. 3 shows a fluoroscopy-based C-arm setup and an example of X-ray image tracking a vertebroplasty cannula.

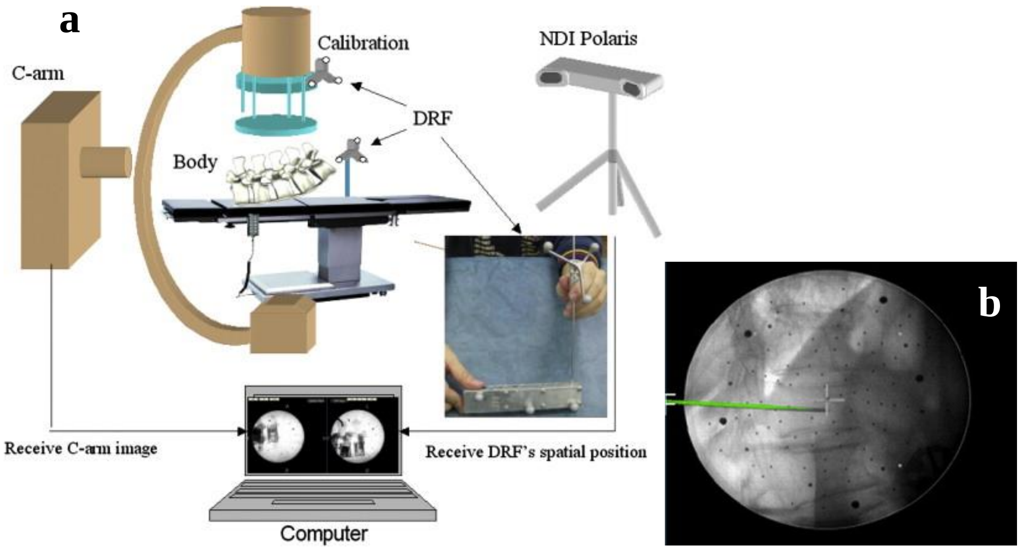


Fig. 3. (a) Setup configuration of the C-arm image-guided. (b) Position of a vertebroplasty cannula displayed and tracked using computer image and fluoroscopy image [63].

Fluoroscopy is widely used to ensure minimally invasive medical procedures, thanks to its fundamental advantages: no need for visual contact and real-time measurements. Nonetheless, this technology presents several drawback, including high cost, bulkiness, low-speed data acquisition and above all prolonged patient exposure to radiation [57,58].

3. Optical Fiber Sensors

Optical Fiber Sensors (OFS) have undergone considerable expansion over the last few decades (see Fig. 4) in several different fields [64], such as the engineering [65,66], industrial [67], medical [68], chemical [69,70] and biological [71,72].

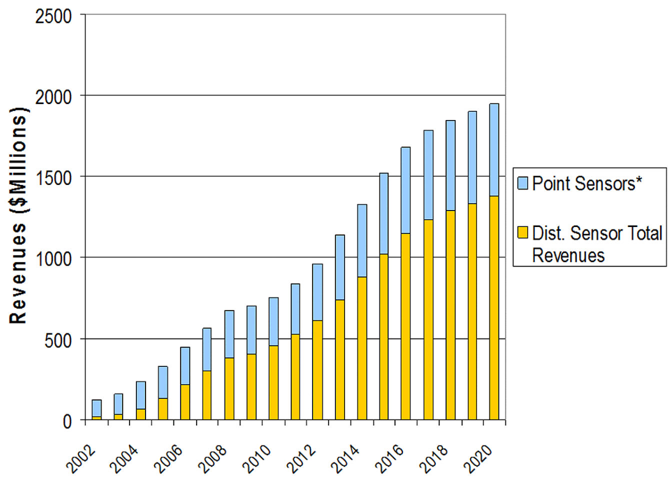


Fig. 4. Point sensor and distributed sensor market revenue and forecast, 2002–2020. Sources: historical data from Light Wave Ventures, OIDA forecast from member input. Courtesy of OIDA.

The principal reasons behind this substantial growth are their inherent ability to sense a variety of measurands (as defined by [73]) in continuous development [74], such as strain [75,76], temperature [70], moisture [77], vibrations [78], chemical agents [72], and many others [37], using the optical fiber itself as a sensor. OFSs have considerable advantages over their electrical counterparts, comprising [25–32]:

- Compactness, small size and lightweight;
- Flexibility;
- Monolithicity (no need for assembly, being manufactured as a single piece);
- Electrically passive operation;
- Resistance to harsh environments, including humidity, severe temperature, chemicals and radiation;
- Immunity to Electromagnetic Interference (EMI);
- Corrosion resistance;
- Embedding capability;
- Multiplexing capability;
- Intrinsic safety (no electricity required in the sensor);
- High sensitivity and accuracy;
- Multiparameter sensing capability [74].

The large majority of optical fibers are made of silica (drawing glass), a material with extraordinary characteristics. Silica has high mechanical tensile and even flexural strength as well as high flexibility and almost perfect elastic behavior. Silica is chemically stable and practically inert [79–82]. The process of optical fiber manufacturing, fiber drawing, developed to provide high speed and high performance data transmission for communication applications, requires extremely high accuracy and specialization. A preformed tip is heated, and then the optical fiber is pulled out in an apparatus known as a draw tower. The combination of the exceptional characteristics of silica and the extremely advanced drawing process guarantees optical fiber sensors these unique properties for sensing purposes. The multiplexing capability, which is the ability to multiplex a multitude of optical sensors on one single fiber and monitor them by a single remote interrogator unit, provides a notable advantage to this technology for sensing applications over the shape sensing alternatives.

4. Shape sensing based on Optical Fiber Sensors

One of the current frontiers of the fiber-optic sensing technologies is shape sensing [33], which consists of the ability to dynamically track position and shape of any point on an optical fiber cable in three-dimensional space. Fiber optic shape sensors are optical Multicore Fibers (MCF) or multi-fiber cables (with a similar section geometry to MCFs, but larger core spacing) capable of sensing multidimensional curvature along the sensor's length by comparing the longitudinal strain detected in different cores and reconstructing the shape [83]. This innovative technology has been an area of great interest for many researchers by reason of its great potential for a number of industrial and medical applications that require curvature, twisting and 2D/3D shape sensing.

4.1. *Advantages*

The existing shape sensing methods present several limitations, in particular the necessity for complex numerical algorithms or computational models for data analysis and shape reconstruction. Shape sensing is particularly critical in applications that require the tracking of a dynamic object in the absence of visual contact. FOSSs offer an extremely valid alternative to traditional methods, allowing the shape to be tracked continuously, dynamically directly and without the need for visual contact or models. As shape sensors need to be attached to the object to be monitored, compactness and small size, flexibility and embedding capability, peculiar characteristics of optical fiber sensors, guarantee ease of installation and efficient shape tracking. Ultimately, immunity to electromagnetic interference, resistance to harsh environments and corrosion and high sensitivity and accuracy make this technology suitable for a wide range of applications. The principal advantages of fiber optic shape sensing can be summed up as follows:

I) Ability to sense the shape of an object directly, without computational and numerical models and with no necessity for approximations, such as assumptions about the characteristics of structures or soil (mass, stiffness, mechanical properties) in SHM applications;
II) Ease of installation, the sensor being a single cable;
III) No necessity for visual contact;
IV) Capability of continuous, dynamic, real-time and durable monitoring, especially convenient for structural health monitoring and industrial robotics applications;
V) All the advantages of optical fiber sensor technologies.

4.2. *FOSS section characteristics*

The section geometry as well as the number of cores and configuration of a fiber optic shape sensor have notable impact on its accuracy in sensing curvature [84,85], twisting [86] and shape [83] and on its embedding capability. Considering a FOSS subject to bending, the curvature induces a longitudinal strain in the outer cores proportional to their distance from the neutral axis, according to the Euler-Bernoulli-Saint-Venant beam theory [87–89]. Consequently, at equal values of curvature, the strain generated in the outer cores increases with greater core spacing, the distance between the sensor axis and the outer cores, enhancing the sensor's sensitivity to curvature. Similar considerations can be made in the case of twisting [86]. The increased core spacing requires a larger diameter of the section, reducing the embedding capability of the sensor, due to the greater dimensions. In view of the foregoing, the most appropriate section geometry depends on the application and on the specific characteristics needed. Two different categories of FOSSs have been investigated in the literature: MCF-based [83,86,90–94] and multi-fiber-based [95–100].

The first typology implements optical multicore fibers, a special fiber with multiple cores embedded in a common cladding. The multiple cores make the fiber sensitive to curvature (and potentially to twisting), in addition to longitudinal strain. Unfortunately, the MCFs available in the market and suitable for shape sensing applications are limited, since they are usually the same as those manufactured for telecommunication applications. Normally, their cladding diameter is extremely small (around 125 μm) and the core spacing is between 30 and 50 μm [92–94,101–104]. The manufacture of different and customized MCF geometries for sensing applications would be extremely expensive, as the sensor market is modest compared to telecommunications. In the light of the above, ordinarily MCF-based FOSSs have small core spacing, but offer the following advantages: monolithicity, compactness, flexibility, small size, high embedding capability and high manufacturing accuracy, being manufactured through the extremely advanced drawing process of optical fibers.

The FOSSs belonging to the second category are constituted of fiber bundles, several optical single-core fibers epoxy-molded [100] or fastened to a support, such as a tube or a bar [95,99]. This configuration guarantees a remarkably larger core spacing and consequently higher curvature resolution and enhanced accuracy in curvature, twisting and shape sensing. The fibers can be interrogated without the need for a fan-in/out, as in the case of MCF-based FOSSs. In contrast, multi-fiber-based FOSSs require to be assembled and the wide section limits their embedding capability.

Depending on the application, one or the other variant is the most fit for purpose. For instance, in the case of medical instruments, such as needles and catheters, small size, compactness and high embedding capability are essential features to ensure easy insertion into the human body. Whereas the FOSSs used in geotechnical applications or structural health monitoring require extremely high accuracy in shape reconstruction to detect ground movements, due to the small displacement magnitude, or track the shape deformation of structures because of the modest structural deformability of these elements.

Under the beam theory, three nonaligned measurement points in each instrumented section of a FOSS are sufficient to sense three-dimensional curvature [83–85,93]. In addition to three outer cores, the presence of a central core also allows the twisting to be sensed by comparing the longitudinal strain of outer and central cores [86,105]. Nevertheless, additional cores can be employed to ensure measurement redundancy [106] and improve the accuracy, as shown in Fig. 5. Overall, the FOSSs currently adopted have very diverse section geometries with different core spacing and number and configuration of cores; the most widely utilized are the three- [93,96], four- [94,97,107] and seven-core section [91,92,108–111], with constant angular spacing and core spacing, as illustrated in Fig. 6.

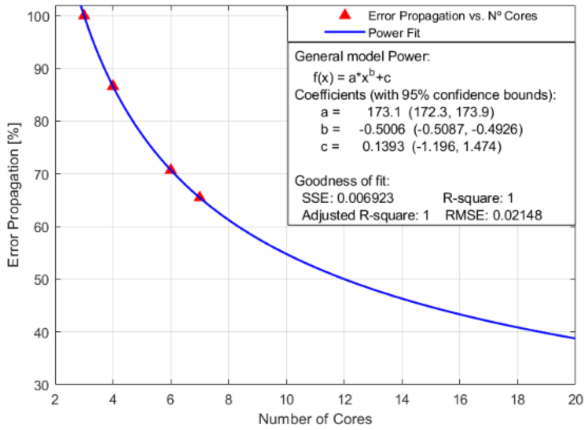


Fig. 5. Representation of the effects of core position errors as a function of number of cores [85].

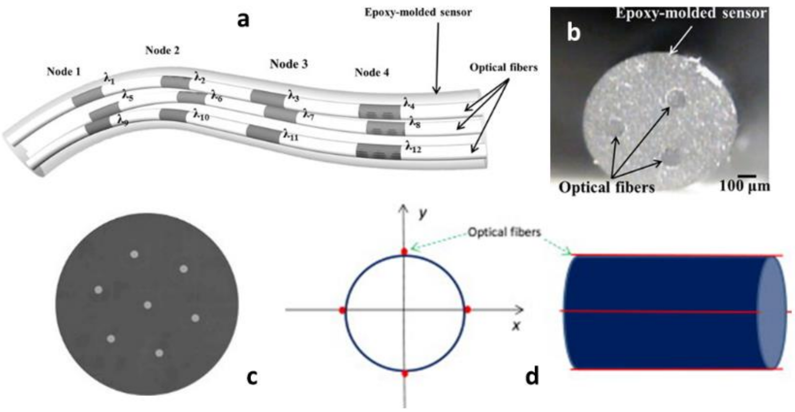


Fig. 6. Example of FOSSs: epoxy-molded three-core shape sensor [100], (a) three-dimensional view and (b) cross-section; (c) seven-core multicore fiber cross-section [112]; (d) optical four-core fiber inclinometer tube [113].

4.3. *Strain sensing technologies*

The process of shape tracking is divided into three phases: strain sensing, curvature calculation and shape reconstruction. It is hence evident that the technology employed to sense strain, being at the basis of the process, strongly influences FOSS performance. The strain sensing technologies most commonly used in fiber optic shape sensing are here briefly reviewed.

4.3.1. Fiber Bragg Grating

Fiber Bragg Gratings (FBG) are Bragg reflectors, well-established as highly sensitive strain and temperature single-point sensors (quasi-distributed sensing) [26,114]. FBGs are the most widely used optical fiber sensors and have a multitude of engineering applications [115–122]. One of the most significant advantages of these sensors is the ability to perform dynamic strain sensing, thanks to their high frequency data acquisition (~ kHz).
FBGs are constructed by laterally exposing the core of an optical fiber to an intense laser light with a periodic pattern [123,124]. The exposure permanently increases the refractive index of the core. This fixed index modulation is a grating and has a period that depends on the exposure pattern. A fiber Bragg grating allows the transmission of some wavelengths and reflects others (see Fig. 7), corresponding to the FBG wavelength peak, which is related to its period. Since the period of a grating varies with temperature and longitudinal strain, it is possible to sense these quantities by tracking the grating wavelength peak.

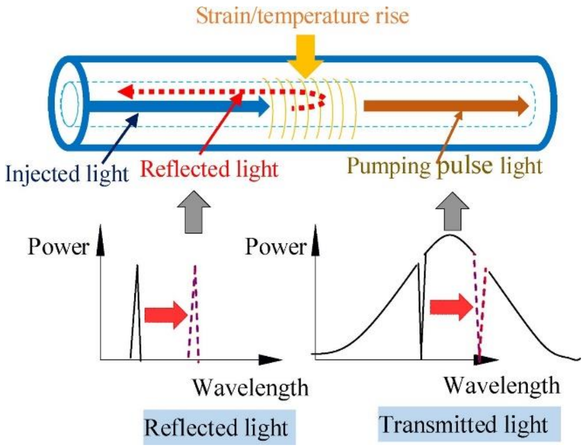
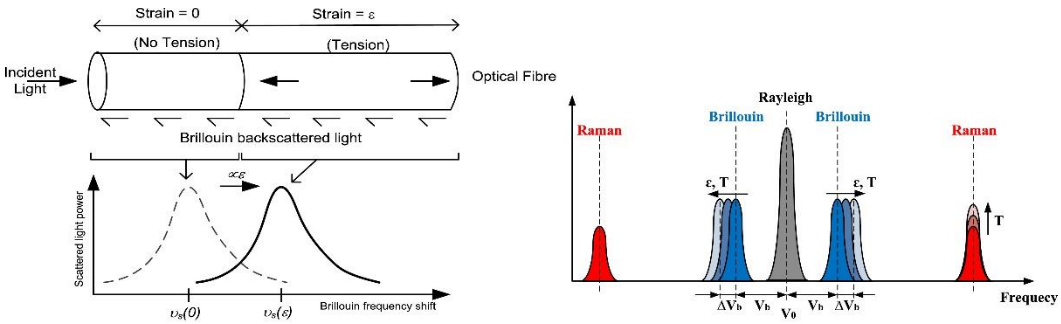


Fig. 7. Sensing principle of fiber Bragg grating sensor [125].

4.3.2. Distributed sensing

Light scattering is caused by the interaction between the atoms or molecules of a medium and the incident electromagnetic (EM) waves that pass through it and consist of absorption of energy and its re-emission in different directions at various intensities. Light scatters through three different processes (illustrated in Fig. 8): Raman (sensitive to temperature), Brillouin (sensitive to both temperature and strain), and Rayleigh (sensitive to strain).



(a) Frequency variation with deformation of fiber optic (b) Spectrum of light

Fig. 8. Principals of distributed optical fiber sensing [126].

Only Rayleigh and Brillouin scattering are able to sense the strain of the medium. In the 80s, this loss in propagation was first exploited for the development of distributed sensing configurations using optical fibers [127]. The idea of distributed sensing consists of a sensing element with linear geometry and a sensing system able to measure the value of the measurand considered, e. g. strain, at any position along the sensing element. The performances of Distributed Optical Fiber Sensors (DOFS) are evaluated by three characteristics that are generally interdependent: the accuracy of the measured quantity, the sensing length or sensing range (range for the position) and the spatial resolution (minimum distance to measure variations in the measurand along the optical fiber, equivalent to the gauge length of a discrete sensor). Compared with FBGs, distributed sensors have significantly lower frequency data acquisition, which depends on the technology and on the sensing range (an indicative value could be ~ mHz / Hz). DOFSs have been comprehensively reviewed in the literature [42,127–130].

4.3.3. Distributed sensors based on Rayleigh scattering

DOFSs based on Rayleigh scattering are usually classified into two categories: Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR).

An OTDR launches a light laser pulse into an optical fiber. The returning light, Rayleigh backscattered light, is collected and is fed into the receiver where its optical power is measured as a function of time (attenuation in the time domain). The evolution of the power over time of the detected signal provides information of position and magnitude of the quantity to be measured distributedly along the fiber length [131]. The efficiency of OTDR is very limited when high spatial resolution (less than one meter) is required, while the common sensing range is around 1/10 km [42,128,130].

OFDR systems have attracted the interest of many researchers driven by the necessity for short spatial resolutions (millimeter scale) and cost effective distributed optical fiber sensors. On the other hand, the sensing range of this technique is notably less than OTDR and, commonly in the range of 10/35m [42,128,130]. OFDR operates in the frequency domain (or Fourier domain): an OFDR sensor system tunes a frequency range and receives a frequency response from the optical fiber which is converted into the time/spatial domain by Fourier transform.

Optical frequency domain reflectometry exists in two variants: Incoherent OFDR (I-OFDR) and Coherent OFDR. The main difference is that in I-OFDR the source is not pulsed, but generates CW light by modulating the optical intensity with radio frequency (RF) signals. While in the case of Coherent OFDR the source is obtained by sweeping the optical frequency [131].

OFDR Rayleigh sensing can be performed simply by utilizing the inherent Rayleigh scattering from the core of the fiber. Otherwise, in order to increase the sensitivity in distributed strain sensing, the Rayleigh signal strength can be enhanced by exposing the optical fiber to ultraviolet (UV) laser

[132] or inscribing a continuous grating into the cores of the fiber [91,110].

4.3.4. Distributed sensors based on Brillouin scattering

The most significant distributed optical fiber sensing techniques based on Brillouin scattering are: Brillouin Optical Time Domain Reflectometry (BOTDR) and Brillouin Optical Time Domain Analysis (BOTDA).
BOTDR refers to the time domain interrogation of spontaneous back-propagating Brillouin scattering. The concept is analogous to the OTDR used in Rayleigh backscattering, but, in this case, the spatial resolution is in the range of 1 meter/tens of meters and the sensing range is up to tens of kilometers [42,128,133].
BOTDA has a more elaborate form than BOTDR and is based on Stimulated Brillouin Scattering (SBS). The BOTDA technique consists of the launch, from both the extremities of optical fiber, of an intense pulse and Continuous Wave (CW) light with a frequency difference equivalent to the Brillouin frequency shift [42,134]. The intense pump pulse interacts locally during its propagation with the weak CW probe and the gain obtained by the probe at each location along the fiber length can be determined by analyzing the probe amplitude in the time domain. This stimulated scattering process produces a more intense Brillouin scattering that requires less averaging to achieve a reasonable Signal to Noise Ratio (SNR) of the system.

5. Historical achievements in fiber optical shape sensing

This section reviews the principal achievements regarding fiber optic curvature, shape and twisting sensing present in the literature, briefly summarized in Table 2.1.

Table 1. Historical progress in fiber optic shape sensing.

Starting year	Contribution	Description	Refs.
1980s	Optical fiber strain sensors	Demonstration of distributed and quasi-distributed strain and temperature sensing using optical fibers.	[114,135]
1980s	Multiplexing technique	The development of multiplexing techniques to interrogate several Bragg grating sensors on a common fiber path enabled quasi-distributed measurements of strain and temperature.	[136–138]
~ 1998	MCF-based interferometric bending sensor	The employment of optical multicore fiber enabled the measurement of degree and orientation of bending by comparing the strain in a pair of cores, using interferometric interrogation.	[139–142]
~ 2000	Bending sensor using FBGs	Curvature measurements were demonstrated by using fiber Bragg gratings. The gratings were written into separate cores of a multicore fiber and acted as independent, but isothermal, strain gauges, providing a temperature-independent measurement of the local curvature.	[143]
~ 2003	3D bend sensor	By employing three or more non-aligned strain sensors inscribed into the cores of an optical multicore fiber section, it was possible to measure the local three-dimensional curvature (curvature magnitude and bending direction).	[94,144,145]
~ 2004	2D and 3D shape sensor	Shape sensing was enabled thanks to the development of approaches for shape reconstruction of optical fiber cables with embedded FBGs, by integrating the curvature sensed	[146–148]

		along the sensor and aligning successive arc segments of fixed curvature.	
~ 2007	Shape sensor using OFDR	Optical Frequency Domain Reflectometry (OFDR) technique permitted distributed shape sensing based on Rayleigh scattering using an optical multicore fiber.	[149,150]
~ 2012	Novel method for 3D shape sensing	An innovative method, based on the numerical resolution of a set of Frenet-Serret equations, was proposed to reconstruct complex three-dimensional fiber shapes as a continuous parametric solution, instead of sequence of arcs.	[93,151].
~ 2014	Twisted seven-core multicore fiber	Optical twisted multicore fibers for sensing applications were designed and manufactured to enable twisting compensation in shape sensing, since the use of twisted MCF increases the sensitivity to twisting.	[86,91,92,108,112,152]
~ 2014	Continuous gratings in multicore fiber	An inscription apparatus and a fabrication scheme that allow the continuous inscription of gratings over meters in all cores of multicore fiber through UV transparent coating were proposed. Continuous gratings increase signal to noise ratio and shape sensing precision, compared to the bare Rayleigh scattering of the optical fiber without gratings.	[92]
~ 2016	Shape sensor using Brillouin scattering	Distributed shape sensing based on Brillouin scattering was performed using an optical multicore fiber and a Brillouin optical time-domain analyzer.	[109]
~ 2016	Force and shape sensor	A force and shape sensors for medical applications was developed using an optical fiber sensor with embedded FBGs.	[95,153]

5.1. *Curvature sensing*

Curvature sensing (also called bending sensing) is the preliminary step for shape reconstruction. The first achievements in this subject were reached in the 1990s. Greenaway et al. filed an international patent and an US Patent, in 1998, describing an optical fiber bending sensor based on MCF able to measure degree and orientation of the bending present along its length [139,140]. In 1999, Blanchard et al. described a novel three-core photonic crystal fiber and demonstrated its ability to measure bending in two dimensions using interferometric interrogation at a single wavelength [141]. Gander et al. (2000) first demonstrated curvature measurements by using Bragg grating inscribed in a multicore fiber [143]. Flockhart et al. in 2003 first demonstrated the use of fiber Bragg gratings written into three separate cores of a multicore fiber for two-axis curvature measurement [94]. Clements filed a patent (2003) illustrating a flexible “smart cable” able to measure the local curvature and torsion along its length [145]. In 2004 MacPherson at al. first reported on the use of a 4-core multicore fiber incorporating FBG strain sensors in each core as a fiber optic pitch and roll sensor [144].

Before this, the attention of researchers mostly concentrated on the development of curvature point sensors, by exploiting fiber Bragg grating technology. A few years before, diverse multiplexing techniques to perform quasi-distributed measurements were established [136]. One of the first examples of these methods was proposed by Kersey and Morey, in 1993, who described a technique for the detection of wavelength shifts in wavelength-encoded fiber Bragg grating sensors capable of interrogating several Bragg grating sensors on a common fiber path using a mode-locked laser principle [137]. With the advent and diffusion of these techniques, quasi-distributed curvature sensing was also finally demonstrated. Chen and Sirkis filed a patent (1998) describing a fiber optic system able to produce multiple strain measurements along one fiber path for determining the shape of a flexible body, by using Bragg grating sensor technology and time, spatial, and wavelength

division multiplexing [138]. Barrera et al. developed a multipoint curvature optical fiber sensor based on a non-twisted homogeneous four-core fiber, using Wavelength Division Multiplexing (WDM) [107]. A novel experimental setup was developed and an array of 15 FBGs was produced and tested by sensing constant curvatures. The sensor was able to sense curvature with high accuracy, obtaining a standard deviation under 1.6% in the applied curvature range.
Alternative technologies to fiber Bragg grating were employed to perform fiber optic curvature sensing. Barrera et al. developed a directional curvature sensor based on long period gratings inscribed in a multicore optical 7-core multicore fiber [154].
In addition to quasi-distributed curvature sensing by means of FBG technology, distributed curvature sensing has also been performed. Zafeiropoulou et al. measured the curvature of a D-shaped multicore fiber using Brillouin optical time-domain reflectometry [155]. Szostkiewicz et al. distributedly sensed the curvature of an MCF using phase-sensitive Optical Time-Domain Reflectometry (φ-OTDR) [156].

5.2. *Shape sensing*

When the ability of optical multicore fiber and multi-fiber sensors to sense curvature was widely recognized, research efforts focused on shape reconstruction, obtained through curvature integration. In 2004, Miller et al. proposed an approach to reconstruct the two-dimensional shape of an optical multicore fiber with embedded FBGs based on the local curvature estimated from distributed strain measurements [146]. The shape reconstruction algorithm estimated the local shape utilizing osculating (or tangential) circles of curvature equal to the curvature measured. Finally, the fiber shape was reconstructed as a sequence of arc segments separated by the grating spacing. Zhanget al. (2004) developed a sensor device comprising a plurality of FBG sensors mounted on the body of a flexible wire and able to sense shape in real-time [147]. The curvature was calculated from the strain measured in the FBGs and interpolated between the sensor nodes. The shape was then reconstructed as a sequence of arc segments with varying curvature.
With the consolidation of approaches for distributed strain sensing, the first studies on distributed shape sensing were carried out. In 2007, Duncan et al. measured shape and position of an optical multicore fiber under a variety of circumstances using two sensing techniques: fiber Bragg gratings and Rayleigh backscatter, and drew a comparison between the results of the measurements [149]. In 2008, Froggatt and Duncan filed a patent describing a fiber optic position and/or shape sensor based on Rayleigh scatter and optical multicore fiber [150].
Previously, research and development efforts mainly centered on two-dimensional shape sensing, while the performance of three-dimensional shape sensors was unsatisfactory and the shape reconstruction algorithms notably complex. A significant improvement was then brought in by Moore and Rogge, who developed, in 2012, an innovative approach for three-dimensional shape reconstruction, based on the numerical resolution of a set of Frenet-Serret equations [93,151]. The method offered remarkable advantages over previous approaches, determining complex three-dimensional shapes as a continuous parametric solution rather than an integrated series of discrete planar bends. Employing the aforementioned approach, Zhao et al. (2016) first utilized Brillouin scattering to perform distributed shape sensing based on a 7-core multicore fiber [109].
Thanks to the technological developments and their remarkable advantages, fiber optic shape sensing has found applications in several fields and a number of instruments based on this technology have been developed [68,90,95,98,100,147,157–161]. By way of example, Chan and Parker filed a patent in 2015 describing a method for rendering the shape of an optical multicore fiber or multi-fiber bundle in three-dimensional space and in real time based on measured fiber strain data with a range of applications, such as manufacturing, construction, medicine and aerospace.[162]. Khan et al. developed (2019) a shape sensor based on optical multicore fiber with fiber Bragg gratings to sense the shape of flexible medical instruments, such as catheters and endoscopes (see Fig. 8) [158].

5.3. *Twisting sensing*

Due to the high flexibility, in addition to bending and longitudinal strain, FOSSs are oftentimes subject to twisting that generates significant errors in shape sensing [86,152,163–165]. The effects of the external twisting were first studied by Askins et al., who proposed, in 2008, a method for estimating the twisting of an optical fiber from internal strain state and designed a large-scale model of a tether fiber, 100X, to study this phenomenon [105]. Performing twisting measurements with FOSSs is extremely challenging, since the state of strain generated by twisting is quite modest, due to the small core spacing [86,152]. A solution to overcome the effects of twisting was designed by Westbrook et al. of OFS Labs. (2014), who manufactured an optical twisted seven-core multicore fiber for sensing applications (inscription apparatus and fiber are illustrated in Fig. 9) with fiber Bragg gratings inscribed along its length and with a twist of 50 turns per meter to increase the twisting sensitivity [91,92]. The optical multicore fiber could be interrogated using two different types of sensing signals: the FBGs inscribed into the optical fiber cores (enhanced signal) or the light scattering from the inherent Rayleigh scattering of the fiber cores. In this way, the fiber twisting could be calculated as the difference between the state of strain of outer and central cores, even if no experiment was performed to investigate the accuracy in twisting sensing. One year later, Cooper et al. of Fibercore designed and fabricated an optical spun (or twisted) multicore fiber for communications and sensing applications with a spin pitch of 15.4 mm (64.9 turn/m) [108,112].

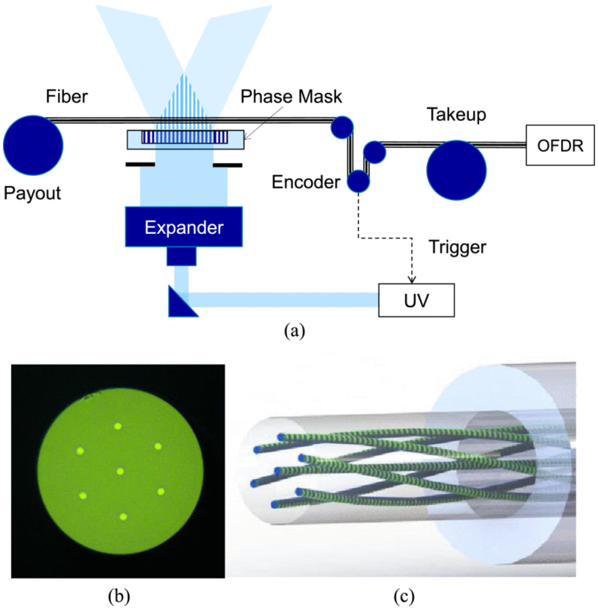


Fig. 9. (a) Array inscription apparatus for continuous fabrication of gratings in all cores through UV transparent coating. (b) Cross-section of an optical seven-core fiber with coating removed. (c) Twisted multicore fiber schematic [33,92].

To the authors' best knowledge, the research works by Xu et al. [153] and Galloway et al. [90] describe the first implementations of twisted FOSSs in sensing applications, specifically to track the complex motion of a continuum of robots and soft actuators.

The accuracy of fiber optic shape sensors based on MCF in sensing twisting was investigated in [86,152] and will be discussed more profoundly in Section 7.

6. Applications

When optical fiber shape sensing became a mature technology, the attention of scientists and engineers was directed to its possible applications in virtue of its notable advantages compared to existing shape sensing methods. This section reviews the current state of the art on applications where fiber optic shape sensing has significant potential, with particular emphasis on the research works, in which this technology was utilized.

6.1. *Civil engineering*

6.1.1. Geotechnical monitoring

Landslides and slope movements are a significant hazard that can result in many fatalities and much property loss [166,167]. Geotechnical monitoring consists of continuous measurements and real-time analysis of the main geotechnical and environmental parameters in order to detect anomalous behavior in the initial phases and promptly intervene. Geotechnical inclinometers are used to determine the shape of ground movements, including the following data: direction, magnitude, rate and depth [17]. Such information is of essential importance to understand the behavior of landslides and slope movements and to develop intervention strategies [168]. Thanks to their resistance to corrosion, the capability of sensing shape with no visual contact and performing continuous and real-time monitoring, optical fiber shape sensors are particularly fit for purpose.

For these reasons, a lot of research has been concentrated on the development of fiber optic inclinometers. Some authors have exploited the capabilities of MCFs to develop monolithic inclinometers [169,170]. In fact, the extremely advanced drawing process of optical multicore fibers guarantees compactness and high manufacturing accuracy, while the small core spacing ensures minimal temperature gradients. More extensive research has been focused on the design of distributed optical multi-fiber inclinometers for ground movement monitoring, obtained by fastening several optical fibers with embedded strain sensors to a tube or a bar, as shown in Fig. 10 [96,97,99,171,172]. These sensors are essentially cantilever beams with one end fixed. The section geometries have the same configuration as optical multicore fibers (three-core or four-core configuration), but with greater core spacing, which differs by several orders of magnitude from MCFs in order to achieve better accuracy in curvature sensing.

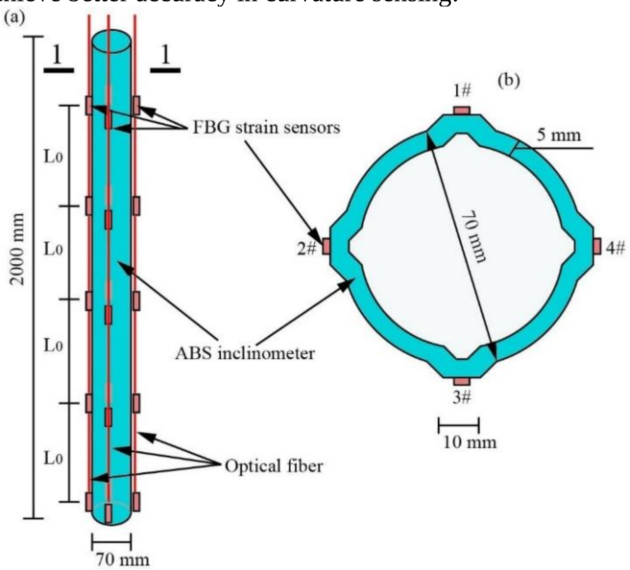


Fig. 10. (a) Schematic diagram of FBG-based inclinometer; (b) Cross-section [99].

6.1.2. Structural health monitoring of civil infrastructures

Structural health monitoring systems provide information about the performance and conditions of structures and infrastructures through the observation of their in-service behaviors [27]. For this purpose, fiber optic shape sensing can represent an efficient nondestructive method for the direct, continuous and real-time monitoring of deformed structural shape and the interpretation of the global structural behavior.

MacPherson et al. first proposed an application in tunnel health monitoring of multiplexed fiber Bragg grating strain sensors based on multicore fiber [173]. A sensor, consisting of a series of gratings, inscribed in the cores of an optical four-core fiber, and able to measure curvature along its length, was configured to monitor displacement between the segments of a concrete tunnel section and was able to reach a resolution of ±0.1 mm.

To the best knowledge of the authors, fiber optic shape sensing has not been employed in bridge health monitoring. Nevertheless, its capabilities of direct shape sensing and continuous evaluation of the structural efficiency during the phases of construction and under service loads have great potential in this field [174–179]. By way of example, Kissinger et al. designed a dynamic fiber optic shape sensor based on multiplexed Bragg gratings inscribed in 4 fibers attached to a flexible support that can be employed to study the response of bridges under dynamic loads [180]. The sensor was tested using a cantilever test object and was able to measure structural displacements and vibrations over an interferometric bandwidth of 21 kHz. In addition, it has been demonstrated that the deflection of a bridge span under designed loads, an important parameter for bridge safety evaluation, can be efficiently measured by using inclinometers similar to those described above for geotechnical inclinometers [18].

Another potential application of fiber optic shape sensors is the monitoring of verticality and deformation of buildings, bridge piles and towers [101,181]. Bang et al. developed a sensor composed of an array of multiplexed FBGs for the measurement of strain and bending deflection of an 1.5 MW wind turbine tower [182]. With the aim of monitoring the dynamic structural behavior of the wind turbine, 10 FBG sensors were arranged on the inner surface of the tower facing the prevailing wind. Similar analyses could be performed by using fiber optic shape sensors with the significant advantage of determining the three-dimensional deformed shape of wind towers (an example is shown in Fig. 11) with a single and easily installable cable.

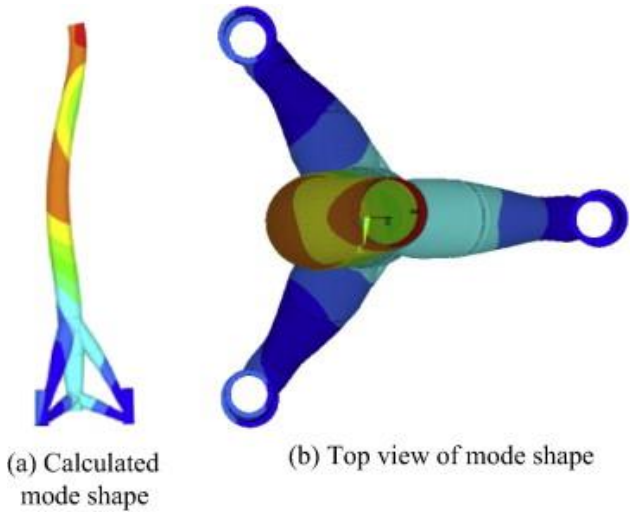


Fig. 11. Calculated mode shape of the wind turbine tower [183].

Thanks to their resistance to high-energy ionizing environments, as demonstrated in [184], FOSSs are particularly suitable for the structural health monitoring of nuclear power stations and spent nuclear fuel stores, which is of vital importance considering that radiation can be extremely hazardous to humans or to the environment.

6.2. *Industrial and aerospace engineering*

6.2.1. Aircraft Wing Shape Measurement

The reconstruction of the displacement field is a fundamental capability for structural health monitoring critical components. One of the common problems in aerospace engineering is the determination of the shape of wings through strain measurements (Fig. 12). The most widely used approaches to achieve this goal are: the inverse Finite Element Method, the Modal Method and Ko's Displacement Theory, comprehensively reviewed in [185]. The three methods require a heavy computational cost in addition to the use of a considerable number of strain sensors.

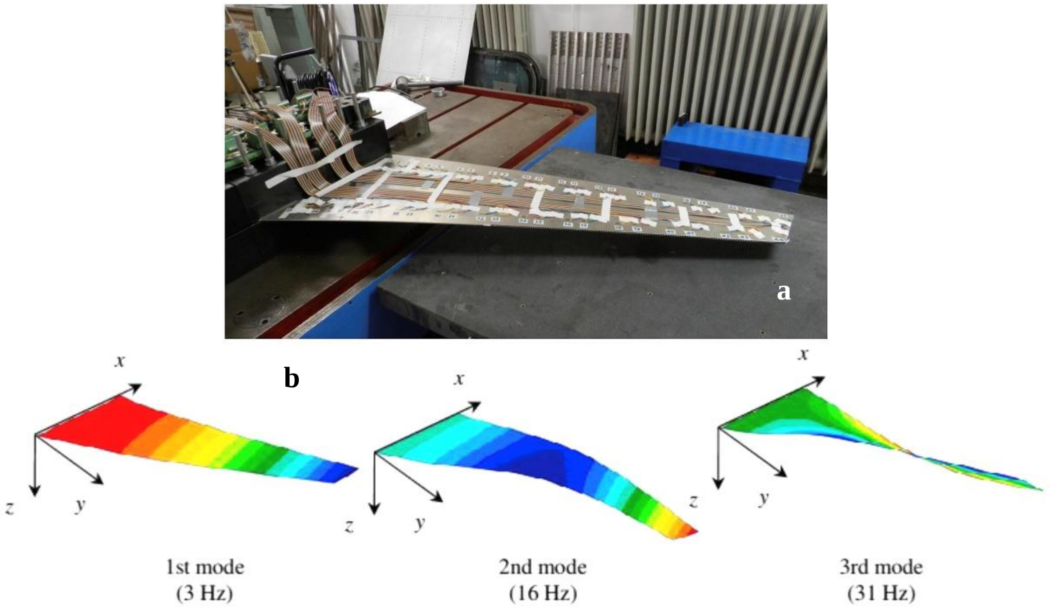


Fig. 12. Aircraft wing shape sensing by using strain sensors: (a) aluminum wing-shaped plate deflected under its own weight; (b) first three mode shapes and corresponding natural frequencies [185].

Optical fiber strain sensors have revolutionized the sector and brought remarkable improvements, thanks to the their advantages over traditional electrical sensors, such as anti-electromagnetic interference, resistance to corrosion and harsh environments, multiplexing ability and the capability of adapting to complex environments [120,186,187]. Nonetheless, fiber optic shape sensing can bring even more significant enhancements, offering an alternative to traditional methods for dynamic and direct shape measurements with no need for developing computational models. In 2006, Klute et al. of Luna Innovations developed a new shape sensing technology which enables the distributed and axially co-located differential strain measurements based on optical multicore fiber and OFDR. This approach generates complex shape data of Variable Geometry Chevron (VGC) that is a (NiTinol) actuator-based morphing system, flight tested by Boeing shortly before [163].

6.3. *Medical applications*

6.3.1. Robotics

FOSSs have a great potential for the implementation in two emerging classes of robots: continuum robots and soft robots.
Continuum robots are "invertebrate-like" or "snake-like"robotic systems, consisting of continuously curving manipulators, highly suitable for surgical interventions, thanks to their high dexterity, in addition to flexibility and small size. The implementation of shape sensors, providing a dynamic feedback on shape and position of these instruments, allows for more accurate control and enables minimally invasive and precise surgery. Xu et al. designed an innovative helically wrapped FBG sensor and a novel theoretical approach to measure simultaneously curvature, torsion, and force [153]. Two sensorized Nitinol tubes were manufactured and tested to validate the design and the model and their ability to accurately measure curvature, torsion, and force at a 100 Hz sampling rate was confirmed.
Soft robots are robotic system composed of flexible and easily deformable materials (as illustrated in the figure below), such as elastomers, gels, fluids, and able to perform complex deformations with simple inputs, mimicking the compliance and mechanical properties of biological organisms [188,189]. Soft robots, in virtue of their extraordinary adaptability and flexibility, are particularly apt for applications fields of medicine and biomedicine [190], and offer a valid alternative to traditional rigid-robotic systems that commonly have limited configurations determined by the joint motions.

Fig. 13. Examples of soft robots [189].

Unfortunately, one of the critical disadvantages of soft robotics is the lack of systems capable of collecting high-resolution shape information [90,188,191,192]. The research conducted by Li et al. [192] and Wang et al. [191] have proved that the employment of FBG sensors can be an efficient solution for shape tracking soft manipulators. Fiber optic shape sensors, by virtue of their embedding capability, compactness and high flexibility, are highly suitable for this purpose. Galloway et al. first implemented a monolithic FOSS in the structure of a fiber-reinforced soft actuator. The optical twisted 4-core MCF sensor interrogated by way of optical frequency domain reflectometry was able to sense shape, position and body twisting with submillimetric resolution [90].

6.3.2. Surgical instruments

During surgical interventions the dynamic tracking of shape and position of medical instruments inside the human body is crucial to ensure accurate manipulation and minimal invasivity [193]. As previously discussed in Section 2.6, fluoroscopy, one of the most frequently used approaches for this purpose during clinical procedures [57–61], has several disadvantages, including high cost, bulkiness, low-speed data acquisition and, foremost, exposure to radiation [57,58]. A widespread alternative practice is the determination of the position of catheters and needles inside the human body by their resistance, which evidently is an arbitrary evaluation criterion.

Fiber optic shape sensors have great potential in numerous medical applications, including epidural administration [68], colonoscopy [157,158], ophthalmic and cardiac procedures (illustrated in Fig. 14) [160], endovascular navigation [159], biopsy [158,160] and minimally invasive surgery [100,161], since they can be efficiently implemented in different medical equipment, such as catheters, needles, and endoscopes, owing to their advantages: intrinsic safety, biocompatibility, embedding capability, flexibility, compactness, light weight and small size. The following are some examples of FOSS integration in surgical instruments.

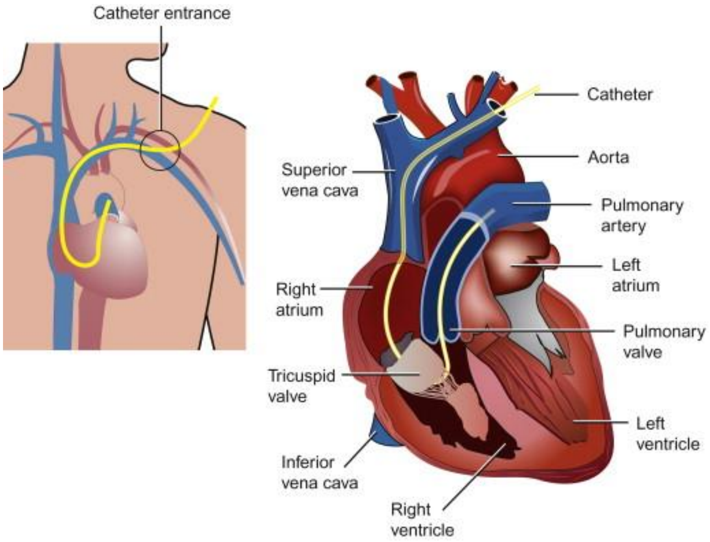


Fig. 14. Thermistor catheter for temperature measurement in the pulmonary artery [194].

A fiber optic shape sensor for intelligent colonoscopy was proposed by Zhang et al. in 2014 [147]. The sensor, consisting in a 900-mm-long flexible wire on which optical fibers were mounted with inscribed FBGs, was implemented in a colonoscope and tested in the colon of a live pig, and was able to reconstruct the shape of the instrument. In 2014, Moon et al. designed a thin and highly flexible FOSS, integrable into minimally invasive surgical systems and capable of dynamic and real-time shape tracking (sampling rate of 3.74 Hz) with an average position error at the extremity of 1.50% of the total sensing length [100]. The sensor was manufactured by assembling and epoxy gluing 3 optical fibers with embedded fiber Bragg gratings in triangular configuration and had a length of 115 mm and could bend up to 90°. Roesthuis et al. (2014) developed a prototype of a flexible nitinol (NiTi) needle with an integrated array of 12 FBGs sensors to enable 3D real-time needle steering [98]. The sensor was able to sense axial strain, curvature and shape with maximum errors between the experiments and the results determined from a model based on the beam theory equal to 0.20, 0.51 mm and 1.66 mm, taking into account the in-plane deflection with single bending, in-plane deflection with double bending and out-of-plane deflection. In 2019, Jäckle et al. designed a MCF-based shape sensor for endovascular navigation [159] by inscribing a set of FBGs written into the 3 cores of a 7-core multicore fiber and was able to measure curvature and track shape. An advanced approach for shape reconstruction was formulated to enhance sensor accuracy that sensed shape with an average error of 0.35–1.15 mm and maximal error of 0.75–7.53 mm over the entire sensor length of 380mm. Khan et al. presented (2019) an innovative method for the shape

reconstruction of flexible medical instruments in three-dimensional Euclidean space using multiple MCFs with inscribed FBGs [158]. This method was used to develop a novel sensing system, consisting of a multi-segment catheter sensorized by inserting four multicore fibers. Experimental tests in diverse configurations demonstrated its ability to sense shape with high accuracy (maximum absolute error of 1.05 mm and maximum mean error of 0.44 mm).
The ability of medical instruments to detect force has been demonstrated to support the correct identification of their location inside the human body with limited tissue damage [68]. In 2017, Khan et al. developed a force and shape fiber optic sensor able to simultaneously estimate the shape of medical instruments and the interaction forces with the surrounding environment [95]. The sensor was composed of 3 optical single-core fibers with inscribed FBGs in a triangular configuration (constant angular space of 120°).

6.3.3. Posture monitoring

Another possible application of fiber optic shape sensing in the medical field is the detection of spinal posture changes. In 2006, Plamondon et al. conducted an experimental study to evaluate a hybrid system composed of two inertial sensors for the three-dimensional measurement of trunk posture, as shown in Fig. 15 [13]. A year later, Wong and Wong proposed a method for monitoring sitting postural changes using 3 tri-axial accelerometers [7]. Artem et al. (2015) developed a tape sensor composed of interconnected and programmable sensor nodes on a flexible electronics substrate and proposed it be used as a wearable posture monitoring device with a deformation sensing algorithm [14]. Compared with these existing methods, shape sensing based on optical fiber has several advantages, particularly suitable for this application scenario: compactness, flexibility, light weight, high sensitivity and accuracy, high frequency data acquisition and embedding and multiplexing capability.

Fig. 15. Experimental setup of the hybrid system for three-dimensional trunk posture measurement: (a) static validation; (b) short dynamic validation; (c) long dynamic validation [13].

7. Error analysis

Several experimental studies have investigated the accuracy of fiber optic shape sensors. It was found that the average accuracy of these sensors in position and shape measurements is ~1 mm [98,149,158,159,161,165,195,196], nevertheless, in some cases, FOSSs achieve submillimetric accuracy [83,90,197]. Regrettably, it is not possible to draw a comparison among the vast multitude of optical-fiber-based shape sensors reported in the literature since their accuracy was not assessed in standardized conditions. Sensor length and the complexity of the shape measured varied widely, parameters that greatly influence their accuracy. Research studies on the error sources of these sensors are extremely limited. The most important are examined below.

High-accuracy shape sensing cannot be separated from efficient strain sensing. In this respect, an experimental study was conducted by Floris et al. in order to define how strain sensor length affects the shape reconstruction performance of FBG-based FOSSs, the most widely used typology of fiber optic shape sensors [83,198]. Two FOSSs were manufactured by the inscription of long and short FBGs, 8.0 mm and 1.5 mm long, into the cores of a commercial MCF. The shape sensor performance was assessed by sensing the shape of a sequence of semi-circles on an aluminum mold by means of a high-precision Computer Numerical Controlled (CNC) machine. Finally, it was proved that shape sensors based on long-FBGs are remarkably more efficient in sensing strain, curvature and shape, in virtue of the stronger and more easily detectable wavelength peak, and better able to average the local errors because of the longer length.

Ordinarily, strain sensors are uniformly distributed along the length of a shape sensor, with a constant center-to-center distance. This is valid for both FBG-based shape sensors and distributed shape sensors; in this last case, the center-to-center distance is equal to the spatial resolution. In each instrumented section, the curvature is determined from the values of strain. Thus, in the non-instrumented portions of the shape sensor, the missing curvatures are determined by interpolation. Finally, the shape of the sensor is reconstructed through numerical integration of the curvature. Hence, it is evident that curvature interpolation is a source of errors in shape sensing, which becomes more relevant with the increase of the distance between the strain sensors. Jäckle et al. investigated the influence of the curvature interpolation method on shape reconstruction, estimating by means of simulations the accuracy of an FBG-based FOSS in sensing the shape of an arc and an s-curve. Three interpolation methods were analyzed: nearest neighbor, cubic and averaged cubic; and the last one was demonstrated to be the most efficient at equal number of measurement points [199].

As mentioned in Section 5.3, external twisting is a significant source of errors in fiber optic shape sensing [163–165], although most of the approaches for shape sensing neglect this phenomenon [93,95,147,180,197]. The first study on this subject was conducted by Askins et al., who presented a method for determining the twisting of optical fibers and manufactured a large-scale model (100X) of a tether fiber to assess the correctness of the method [105], since the twisting sensitivity increases with increased core spacing [86]. Regrettably, the increase of core spacing reduces the flexibility and embedding capability of shape sensors, restricting their field of applications. Thanks to important improvements in the manufacturing process [91,92,108,112] it has become possible to make twisted MCFs to enhance accuracy in twisting sensing without compromising sensor flexibility.

Floris et al. first assessed the performance of a twisted MCF-based shape sensor in sensing twisting [86,152]. A theoretical approach, based on Saint-Venant's Torsion Theory, was proposed to determine the twisting in the MCF from the strain sensed in the cores, as illustrated in Fig. 16. On the basis of this approach, the mathematical relationship between twisting sensitivity and core spacing and twisting rotation were defined. A twisted FOSS was produced by inscribing four FBGs in a commercial spun MCF with a spin pitch of 15.4 mm manufactured by Fibercore [108,112], and the validity of the theoretical approach was experimentally demonstrated with a series of twisting tests. An enhanced method of shape reconstruction was proposed to take into account and compensating the twisting.

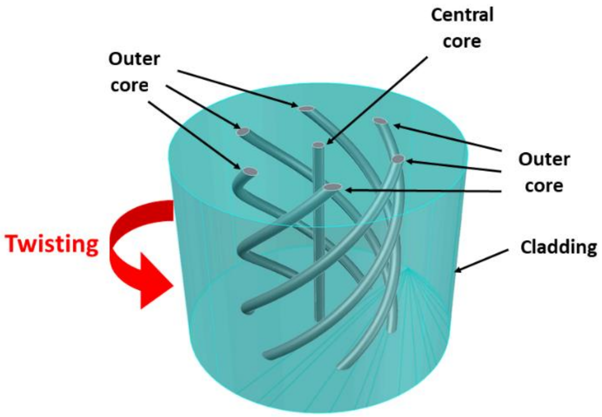


Fig. 16. Twisted multicore seven-core fiber [86].

In conclusion, several numerical studies were undertaken to simultaneously investigate and evaluate the influence of different variables on the accuracy of fiber optic shape sensors.
Henken et al. performed an error analysis to quantify the accuracy of FBG-based shape sensors with a three-core configuration and to assess their suitability for robotic medical needle steering [164]. Several parameters that influence shape reconstruction accuracy were considered in the simulations, including: measured wavelength inaccuracy, photoelastic coefficient, sensor geometry inaccuracies (errors in core spacing and angular spacing), and the measured curvature inaccuracies. It was found that the accuracy of FBG-based shape sensors implemented in needles can be in the order of 10% of the deflection at the tip, depending on the configuration. Nevertheless, when tip deflection is smaller than approximately 1 mm it cannot be detected accurately.
Floris et al. conducted two numerical studies to analyze the effects of core position errors and strain measurement uncertainty on the performance of fiber optic shape sensors used to sense three-dimensional curvature, which is a fundamental step in the process of shape reconstruction [84,85,200]. The studies, applicable to shape sensors based on both MCF and multiple single-core fibers equipped with distributed or quasi-distributed strain-sensors, determined the law of uncertainty propagation by simulating the measurement process through the Monte Carlo Method (MCM) and showed the crucial role played by different parameters, including core spacing, curvature measured and number of cores. Ultimately, a series of predictive models were proposed, described by simple equations and capable of predicting the achievable FOSS performance in diverse conditions.

8. Conclusions and future research

An enormous research effort has been devoted to the development of a new generation of shape sensors based on optical fiber sensing technology. The reasons behind the interest in this innovative technology are its ground-breaking advantages that make it extremely competitive against existing shape tracking methods. This paper has presented a comprehensive review of the state-of-the-art of fiber optic shape sensing from its historical evolution to its application.
This review will help scientists and industries in the field to have a panoramic and concise overview of the subject, raise awareness to the potential and criticalities of this novel technology and provide inspiration for future investigations. On the basis of this review, the following observations and conclusions can be drawn:

- FOSSs provide a valid alternative to traditional shape sensing methods, thanks to a combination of exceptional advantages, including capability of tracking shape directly, continuously, dynamically and in real-time, no necessity for visual contact, embedding capability, ease of installation, compactness, small size, flexibility, immunity to electromagnetic interference, intrinsic safety, resistance to corrosion and harsh environments;
- FOSSs can be primarily divided into two main categories: MCF-based and multi-fiber-based. The first category is characterized by monolithicity, compactness, small size, high-precision manufacturing and ease of assembly. Such characteristics make it particularly suitable for the implementation in medical instruments, such as needles, catheters and endoscopes and in small instruments in general. The second, instead, in virtue of its larger core spacing, achieves higher accuracy in shape reconstruction in equal conditions and finds applications in the medical tracking devices as well as in geotechnical and structural health monitoring, for instance to reconstruct the deformed shape of structures and components – characterized by limited deformability –, common in civil, aerospace and mechanical engineering;
- Another possible FOSS category is based on the technology used to sense strain; the most commonly employed are: quasi-distributed (fiber Bragg grating) and distributed (Rayleigh and Brillouin backscattering). FBG-based FOSSs are the most widely used thanks to the vastly lower cost of their interrogation systems and to higher speed data acquisition (~ kHz), which make this technology suitable for dynamic sensing. Distributed strain sensing systems can enhance sensing length and achieve higher accuracy in shape sensing. This last case occurs when the spatial resolution is particularly high (spatial resolution lower than center-to-center distance of the gratings in FBG-based shape sensors);
- The average accuracy of FOSSs in position and shape measurements is ~1 mm [98,149,158,159,161,165,195,196], although, in some cases, submillimetric accuracy was demonstrated [83,90,197]. Unfortunately, a comparison of the performance among the large number of FOSSs reported until now is not possible, since their accuracy was assessed in non-standardized conditions and with widely varying length and complexity of the shape measured, parameters that greatly influence sensor performance.
- In spite of the large amount of research dedicated to the development of fiber optic shape sensing and its great potential, the overwhelming majority of studies on its applications belong to the medical or geotechnical fields. An in-depth study on the employment of FOSSs in a number of other possible applications (see Section 6) including structural health monitoring of buildings, bridges, tunnels and mechanical components, and the tracking of human posture and robot movements, is still missing. Future research directed to bridging this gap would substantially contribute to the diffusion of this technology.

Acknowledgments

This work was carried out within the ITN-FINESSE framework, funded by the European Union's Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Action Grant Agreement N° 722509. It was also supported by the Ministry of Economy and Competitiveness of Spain under DIMENSION TEC2017-88029-R.

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