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# Recent developments in fibre optic shape sensing

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A B S T R A C T

This paper presents a comprehensive critical review of technologies used in the development of fibre optic shape sensors (FOSSs). Their operation is based on multi-dimensional bend measurements using a series of fibre optic sensors. Optical fibre sensors have experienced tremendous growth from simple bend sensors in 1980s to full three-dimensional FOSSs using multicore fibres in recent years. Following a short review of conventional contact-based shape sensor technologies, the evolution trend and sensing principles of FOSSs are presented. This paper identifies the major optical fibre technologies used for shape sensing and provides an account of the challenges and emerging applications of FOSSs in various industries such as medical robotics, industrial robotics, aerospace and mining industry.

## 1. Introduction

Shape sensing has been an area of interest for many researchers and industries in the past few decades. There are two type of shape sensors: conventional shape sensors (CSSs) and fibre optic shape sensors (FOSSs). CSSs include (1) non-contact based shape sensors, and (2) contact based shape sensors, also referred to as self-sensing surfaces. Non-contact CSSs include visual systems such as cameras, radio detection and ranging (RaDAR), and light detection and ranging (LiDAR) sensors. Ambient temperature or contamination can interfere with the performance and integrity of these shape sensors [1,2]. Shape sensing becomes more critical in the applications where non-contact visual systems cannot be used and real-time data of a dynamic object is required [3,4]. In these applications, small size and flexible contact based sensors are required to be attached directly to the objects and move with them, transducing the position to optical/electrical signals to sense shape, curvatures, bends and twists. This paper firstly presents contact based CSSs briefly, then provides a comprehensive critical review of technologies used in the development of FOSSs. The opportunities and challenges of applications of FOSSs in various industries such as medical robotics, industrial robotics, aerospace and mining are discussed.

## 2. Contact based conventional shape sensors

Development of a suitable contact based shape sensing technology has been the topic of many research and development projects over recent years for a wide range of industrial and medical applications [5–8]. In this section common contact based CSSs are reviewed with examples of their applications, together with their advantages and disadvantages. Based on sensing technology used, contact based CSSs are categorised into: (1) electrical resistivity and strain sensors, (2) optoelectronics sensors, and (3) micro electro mechanical systems (MEMS) sensors.

### 2.1. Electrical resistivity and strain sensors

Electrical resistivity and strain sensors have been used on large structures, as well as smaller devices such as gloves to measure change in two-dimensional (2D) or three-dimensional (3D) directions [8–11]. Fig. 1 shows a contact based electrical resistivity glove shape sensor, known as GloveMAP. The system is a low-cost fingertip bending tracking using electrical resistivity and strain sensors. It uses a standard Arduino microcontroller for receiving the electrical signals, calculations and interfacing with a computer. The technology is promising for gaming and wearable devices, but complexity and inaccuracy are the main limiting factors of the technology for wider applications. Electrical resistivity sensors have limitations in terms of complication and weight of wiring, for example in large scale applications where many cables are needed [8]. In small scale applications such surgical tools, conventional electrical sensors are not suitable due to size, complexity and sensitivity to electromagnetic noise and temperature [12]. In addition, electrical sensors have limitations in hazardous and explosive areas.

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**Fig. 1.** Contact based electrical resistivity glove shape sensor, known as GloveMAP [8].

### 2.2. Optoelectronics sensors

Optoelectronics sensors used for shape sensing operate based on a combination of light sensors, a series of conventional microelectronic gyroscopes and tri-axial accelerometers to estimate shape of the object in real-time. Fig. 2 shows an optoelectronics based shape sensing ribbon equipped with a series of sensors, known as SensorTape [7]. The developed technology is a printable electronics and a series of LEDs and detectors to measure time-of-flight (ToF) between different points on the object. The sensor development cost is low, as it uses mass produced, off-the-shelf sensors and can be manufactured with available printable electronic technologies. The maximum length that can be produced is 2.3 m and it is compatible with low-cost Arduino microprocessor for connectivity to computers. SensorTape was developed as a low-cost solution for posture measurement and is not suitable for industrial applications, such as in confined spaces of surgical and drilling tools.

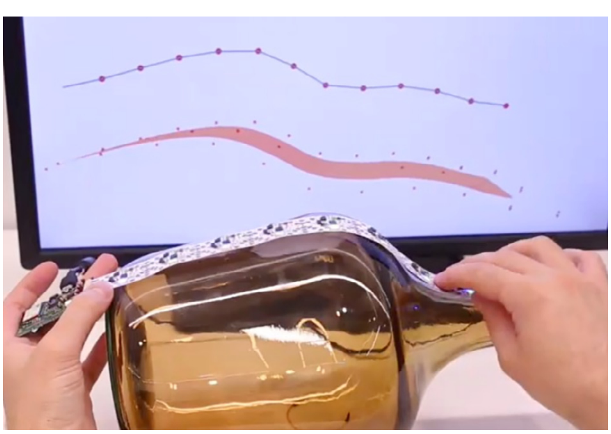

**Fig. 2.** Contact based optoelectronics shape sensor, known as SensorTape [7].

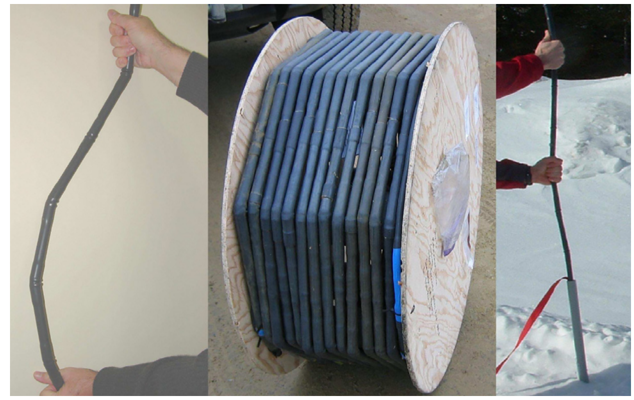

**Fig. 3.** Contact based MEMS shape sensor, known as ShapeAccelArray [13].

### 2.3. Micro electro mechanical systems sensors

MEMS sensors are integrated microscopic devices enabling measurement of various parameters in moving devices, such as directional tilt measurement in connected joints in respect to each other. Fig. 3 shows a commercial product developed based on MEMS sensors for geotechnical applications, known as ShapeAccelArray or SAA [13]. ShapeAccelArray consists of a series of waterproof tubes connected with flexible joints. Each section/tube is around 0.3 m long and is equipped with MEMS based tri-axial accelerometers and gyroscopes. Using data fusion and correction techniques an estimated 2D/3D shape of the ShapeAccelArray is calculated by the software. ShapeAccelArray is commonly used in boreholes, drill positioning, pipes, wall movement or embedded in structures for deformation monitoring [13–17].

The selection of an appropriate shape sensing technology depends on several factors such as cost, installation constraints, applications and environmental considerations. Table 1 presents a summary of conventional contact based shape sensors (non-fibre optic technologies) and presents a comparison of their performances.

## 3. Why fibre optic sensing?

Fibre optic sensing provides a promising opportunity to determine the shape status of an object in real-time. FOSSs utilise fibre optic sensors (FOSs) to realise the orientation and position of the optical fibre relative to its starting point or realising the shape of an object with embedded FOSs. The FOSSs are mainly designed based on directional strain measurements. As an example, a FOSS can consist of tri-core fibre Bragg gratings (FBGs) sensor planes measuring strain for multi-dimensional bend direction calculation of an object, which is consequently used in a computer model to reconstruct the 2D/3D shape of the object (Fig. 4).

In general, FOSSs hold many distinct practical advantages over their conventional counterparts, such as:

- FOSSs can be monitored simply by a single remote interrogator unit, without complexity of wiring and connecting many sensors;
- There is no electricity required at the position of the sensor therefore they can be placed and the strain/bend can be measured in otherwise inaccessible places;
- Small dimensions of optical fibres (diameters between 100 µm and 2 mm) allow them to be embedded into very thin materials, surfaces/structures, or in the centre of a rod or small devices, which transforms the object into a self-sensing surface; and
- Fibre optic sensors are immune to external electromagnetic fields.