Multi-Component FBG-Based Force Sensing Systems by Comparison With Other Sensing Technologies: A Review

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***Abstract*— A multi-component force sensing system, capable of monitoring multiple components of force terms along x-, y-, and z-axis (F_x, F_y, and F_z) and the moments terms about x-, y-, and z-axis (M_x, M_y, and M_z) simultaneously, has been utilized in a huge variety of automation systems since 1970s. Fiber Bragg grating (FBG)-based sensing systems offer a significant viable with numerous competitive advantages over traditional force sensing systems such as immunity to electromagnetic interference, high sensitivity, larger sensing range, light weight, small size, intrinsically safe in the explosive environments, and multiplexing capabilities. Recently, a number of applications, such as robotic manipulation and robot-assisted surgery, have benefited from the developments in FBG-based force sensing systems. This paper presents a comprehensive review of different force transduction principles, state-of-the-art designs, and development methods, as well as their significances and limitations. Meanwhile, some of the significant developments in an FBG-based force sensing technology during the last few decades are surveyed, and current challenges in implementing the FBG-based force sensing technology is highlighted.**

***Index Terms*— Force and moment sensing, opto-electric detecting technology, robotic sensory system, review of technology.**

I. INTRODUCTION

FORCE and moment information can be used as feedback to form an automatic control system to accomplish efficient manipulation. The origins of force measurement and control can be traced back to the late 1970s [1]– [4]. Since then, multi-component F/M (force/moment) sensing systems have been widely known and intensively studied. In the past few years, force measurement practices have been significantly affected by new tools (such as digital force gauges, virtual instrumentation, high speed data acquisition system, etc.) as well as sophisticated measurement methods such as mechano-magnetic, mechano-optical, etc. [5] and [6]. A large number of force and moment sensing technologies with numerous innovative signal analysis techniques and processing methods (for example, perceptually-motivated methods, statistical methods, and unsupervised learning methods) have been designed for practical applications, including minimally invasive surgery and therapy, hybrid position/force control of manipulators, resistive touch-pads, and cutting force dynamometer all can be found in recent literature [7], [8]. Additionally, many commercially available force sensing systems capable of detecting multi-component force and moment signals in different applications (such as minimally invasive surgery [9], robotic assembly [10], haptics [11], machining process monitoring and control [12], etc.) have been developed by numerous companies such as ATI Industrial Automation, Kistler, Interface, OMEGA Engineering, TLC (Technische Lehrmittel Construktion), and LORD Sensing-Stellar Technology, etc.

The force measurement methods that are most commonly studied and widely adopted in force sensing systems originate from the exploitation of various measurement principles such as piezo-resistive, capacitive, piezoelectric, magnetic, inductive, and optical methods [13], [14]. Generally, the essential principles associated with these methods have unique benefits and drawbacks, as illustrated in [15] and [16].

Fiber-optic sensors have appeared as an excellent measurement method from the early 1980's [17]. Optical force sensors have been believed to show a great deal of promise, and they have been very successful in physical sensing systems because of some of their key advantages, such as electromagnetic immunity and higher resolution [18], [19]. Some

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TABLE I

TYPICAL MULTI-COMPONENT FBG FORCE SENSING SYSTEM COMPARISON

Year & developer	Modulation type	Characterization method	Size (mm)	No. of component	Performance index	Measurement range	Application area
2012 & Puangmali [25]	Light intensity	Standard F/T (Force/Torque) sensor (ATI Mini 40)	<20mm (in diameter)	3	0.02 N (resolution)	±1.5 N in *z*-axis, ±3 N in *x*- and *y*-axis	Minimally invasive surgical palpation
2016 & Guo [26]	Wavelength shift of FBG	Standard weights	Φ 20 × 35.5	3	44.116 *p*m/N (maximum sensitivity)	10 N in *z*-axis, ±25 N in *x*- and *y*-axis	Robotic manipulation
2015 & Liu [27]	Wavelength shift of FBG	Analog Force Gauge, NK-500	Φ 56 × 7	3	0.5136 $\mu\varepsilon$/N (maximum sensitivity)	5000 N	Milling force measurement
2014 & Roesthuis [28]	Wavelength shift of FBG	CCD cameras	Φ 1 × 172	2	0.74 mm (maximum reconstruction error)	n. a.	Shape reconstruction
2017 & Li [29]	Wavelength shift of FBG	Commercial tacho-torquemeter (JN338-500A, Range: -500~500 Nm)	n. a.	2	7.02 *p*m/N·m (sensitivity)	±20 N·m	Online Torque Detection
2005 & Zhang [30]	Wavelength shift of FBG	A jack with a stress gauge	Φ 50 × 35	1	210 N (resolution)	0 to 3000 N	Heavy load measurement

NOTE: Φ = diameter; F.S. = Full Scale; n. a. = not applicable; $p=10^{-12}$; $\mu=10^{-6}$.

commonly explored optical force sensing techniques are based on modulation of intensity, phase, polarization, wavelength or transit time of light in the fiber. Generally, fiber optic force sensing systems can be categorized into intrinsic, extrinsic, or hybrid measurement technologies. Specifically, the optical fibers are used as the force-sensing element and are responsible for delivering the measurement (light) in the intrinsic approach. On the other hand, the extrinsic approach employs an external transducer to detect the applied force; it also uses a multimode optical fiber cable to transmit modulated light. Hybrid methods can adopt the optical fiber to carry light in and out of the system.

A number of multi-component opto-electric force sensing systems have been implemented in various applications. These are typically developed in order to reinforce the exploitation of more intelligent and automatic systems. Comprehensive reviews of opto-electric sensing systems have been presented in literature [20]–[24]. However, few surveys regarding multi-component FBG based force sensing systems were carried out. Therefore, this paper extends previous surveys with particular attention to multi-component FBG based force sensing systems. The main features and performance comparisons of multi-dimensional FBG based force sensing systems are summarized in Table I.

Numerical papers about FBG based force sensing systems have been published in the past decades, and many results have been collected. Table II shows a summary of search results for research using the search term “Fiber Bragg Gratings and force sensor” in databases such as IEEE (Institute of Electrical and Electronics Engineers) library, Web of science, ASME (American Society of Mechanical Engineers) digital collection, SPIE (The International Society for Optical Engineering) digital library, and Springer-link. An impressive and steadily increasing growth in development of FBG based force sensing system can be apparently noticed in academic research during the past decades. The order of magnitude growth over FBG based force sensing systems reflects the maturity of FBG based force sensing systems.

TABLE II

COUNT OF PAPERS FROM 1980 BY USING THE SEARCH TERMS “FBG AND FORCE SENSOR”

Year	**IEEE library**	**Web of Science**	**ASME Digital Collection**	**SPIE Digital library**	**Springer-link**
1980-1989	1	0	0	0	0
1990-1999	3	2	0	0	3
2000-2009	53	49	9	13	17
2010-present	115	95	25	50	34

II. FORCE SENSING SYSTEMS BASED ON DIFFERENT DETECTION TECHNIQUES

A wide variety of design and implementation alternatives in force sensing systems have originated from several different types of detection techniques such as mechano-electric, mechano-magnetic and mechano-optical transductions [31], [32]. Generally, resistive, capacitive, inductive, piezoelectric, optical (such as FBG based systems) F/M sensing systems provide certain specific known performances

TABLE III
ADVANTAGES OF FBG BASED FORCE DETECTION TECHNOLOGY BY COMPARING TO CONVENTIONAL SYSTEM

Detection technique	Technique description	Pros	Cons
FBG based system	refractive index/light intensity/ spectrum variation due to a mechanical force or moment	• good reliability and high sensitivity • wide measurement range • noncontact and high-temperature performance • nonelectrical and immunity to electromagnetic interference • light weight and small size • intrinsically safe in the explosive environments • distributed measurement	• hard to construct dense arrays • more costly • complex Information processing system
Resistive	semiconductors conductivity/resistance variation due to a mechanical force or moment	• simple construction and low cost • high and adjustable resolution • high reliability and maintenance-free • compatibility with VLSI	• higher power consumption • rigid and fragile • scarce reproducibility • electromagnetic compatibility • narrow frequency bandwidth • contradictions between flexibility and sensitivity
Capacitive	capacitance variation due to a mechanical force or moment	• high sensitivity and resolution • large bandwidth • robustness • long-time stability • drift-free • durability • Adaptability to Environment	• complex with the compulsory electronic circuits • stray capacitance • edge effect • temperature sensitivity
Inductive	magnetic coupling variation due to a mechanical force or moment	• linear output • high power output • wide dynamic range	• lower frequency response • poor reliability • massive size
Piezoelectric	generation of a surface charge due to a mechanical force or moment	• high frequency response • higher accuracy and finer resolution • high sensitivity and superior stiffness • high dynamic range	• charge leakages • require to be embedded into the machining structure • deteriorations of voltages or drifts in the presence of static forces • poor spatial resolution

(as shown in Table III), and thus have been widely applied in applications requiring force feedback. Also, the advantages and disadvantages of these detection techniques are illustrated in Table III.

A. Resistive Force Sensing Systems

The most commonly used force sensing system relies on the resistive transduction technique due to its simple construction, cost effectiveness, compatibility with VLSI (Very Large-Scale Integration), and convenient availability of the output signal [32]. Generally, a resistive force sensing system achieves its function through a sensing element, which can be roughly categorized into either a piezo-resistive or a strain gauge based element [33]. The piezo-resistive sensing element changes its electrical resistance in a predictable manner following the applied force and moment.

Resistive force sensing systems have been utilized commonly in the manufacture of force and moment sensors due to their advantages such as simple construction, high reliability, as well as high and adjustable resolution [34]. However, in most situations, they exhibit high EMI induced errors, and temperature sensitivity [35]. Additionally, the system is rigid and fragile due to its mechanical structure and strain gauge adhesive bonding process.

B. Capacitive Force Sensing Systems

Another force sensing technique that has received considerable attention is the capacitive approach [36]. Capacitive force sensing systems are capable of measuring forces with *m*N even *p*N resolutions in wide measurement ranges [37], [38]. Parallel-flat configurations are often adopted by capacitive force sensing systems. In particular, the variable capacitance changes due to the variation of changeable distance between the flats caused by the applied force or moment can be obtained through switched-capacitor circuits, capacitive AC-bridges, and capacitance to frequency converters [16], [39].

Capacitive force sensing systems generally show high resolution, wide frequency bandwidth, and excellent durability. Estimation shows that more than 30% of modern force sensing systems are based on capacitive measurement technology. However, in general, they suffer from drawbacks such as parasitic capacitance, and require dummy elements and differential measurements to filter out noise and edge effect.

C. Inductive Force Sensing Systems

By detecting changes of self-inductance and mutual inductance of the inductive loop, the inductive force sensing systems employ Faraday's law of induction to measure the applied force and moment. Specifically, inductive force sensing systems consist of an induction loop with variable inductance; these systems can be categorized into differential transformer, reluctance, impedance and mutual inductance systems.

Inductive force sensing systems usually exhibit wide dynamic range and high linear output [40], [41]. However, these sensors generally have a lower spatial resolution, poor repeatability, complex mechanical construction and complicated electronic circuit. Moreover, they drift significantly, and need automatic compensation.

D. Piezoelectric Force Sensing Systems

Piezoelectric force sensing systems employ the piezoelectric effect of quartz crystal or ceramic elements to detect the applied force and moment by converting them to an electrical charge [42]. The amount of the produced charge is proportional to the applied force or moment according to the longitudinal effect of piezoelectric sensing material.

High elasticity modulus of piezoelectric materials ensures the piezoelectric force sensing system's wide dynamic ranges. Additionally, a piezoelectric force sensing system also exhibits a high natural frequency, high stability, excellent reproducibility, and superior linearity over a wider measurement range [43], [44]. Compared to other types of force detecting approaches, the main disadvantage of piezoelectric force sensing system lies in their leakage current behavior, which raises doubts as to their precision when detecting static force over a longer period of time.

A piezoelectric force sensing system with the electric charge output produced by piezoelectric material behaves like a capacitor giving an output signal without any external electric excitation. Therefore, leakage current behavior is a special and inevitable characteristic of piezoelectric force sensing systems.

Further disadvantages of this type of force sensing system include inflexibility and the requirement of frequent recalibration after long-time monitoring.

E. FBG Versus Other Electric Sensors

Among the various force measurement methods, opto-electric force sensing systems have been widely investigated [45]. Generally, opto-electric force sensing systems can be ranked based on the physical quantity being analyzed, among which the most regularly examined measurands are intensity, wavelength, phase and polarization [17]. FBGs offer significant potential for force measurement applications [46]. The importance of opto-electric force sensing systems stems from the following performance advantages over conventional electrical force sensors [47], [48]:

- Opto-electric force sensing systems exhibit excellent environmental resistance. Since no electric current flows through the optical fiber cable and with the absence of electrical connections, opto-electric force sensing systems are undisturbed by electrical noise and are immune from electromagnetic, lighting and electrostatic interferences.
- A particularly useful feature of an opto-electric force sensing system is that it can, if required, provide an advantage in sensitivity. A FBG sensing element is capable of detecting slight strain changes less than 1 $\mu\varepsilon$ (10^{-6}mm/mm). With sensitivity enhancement methods, opto-electric force sensing systems can measure force and moment with more excellent sensitivity.
- Other attractive features of an opto-electric force sensing system are the small size and light weight of its sensing element (the profile of FBG sensing element ranges from a few tens to hundreds of micro-meters with a typical core diameter value around Φ 60 – 200 μm), which enables the compactness and miniaturization of the system [49], [50].
- An individual FBG only reflects a particular wavelength of light and transmits all others. FBGs (more than 100 FBGs with a sophisticated interrogation instrument) can therefore be multiplexed on a single optical fiber, and even into arrays, by using several input and output optical fibers and choosing different Bragg wavelengths. Multi-component force sensing systems need several sensing elements for each component to turn into differential measurement and obtain automatic temperature compensation. Therefore, the multiplexing capability of FBGs enables the multi-component force measurement along a single optical fiber with a compact elastic element.

With other inherent features such as high accuracy, long term accuracy, zero drift, wide frequency response, and excellent high-temperature performance, opto-electric force sensing systems have obtained significant interest among practicing engineers and scientists. A synoptic illustration of an opto-electric force sensing system is given in Table III by comparing it to other conventional systems.

III. FBG BASED OPTICAL FORCE SENSING SYSTEMS

Among the optical force sensors, FBG based optical force sensors are becoming increasingly popular due to their small profile with light weight, high accuracy, remote sensing, multiplexing capabilities, inherent safety with high resistance to hostile environments, immunity to electro-magnetic interference and radio frequency. Therefore, they are widely employed in civil structural health and seismology monitoring, mechanical equipment, spacecraft monitoring in aerospace engineering, and biomedicine. This paper describes scientific research in the area of multi-component FBG based force sensing systems. FBG based force sensing systems use optical fiber with constructed distributed Bragg reflectors as force sensing elements. They acquire force and moment information through the change in the FBG reflection spectrum, which is affected by the applied load to be measured. A multi-component FBG based force sensing system could be used for measuring several components of tangential force terms along x-, y-, and z-axis (F_x, F_y and F_z) as well as moments terms about x-, y-, and z-axis (M_x, M_y and M_z) simultaneously.

A. Sensing Principle of the FBG Based Optical Force Sensing Systems

FBGs are distributed Bragg reflectors which can be constructed into fibers and represent one of the most significant devices in decades. FBGs can reflect specific wavelengths

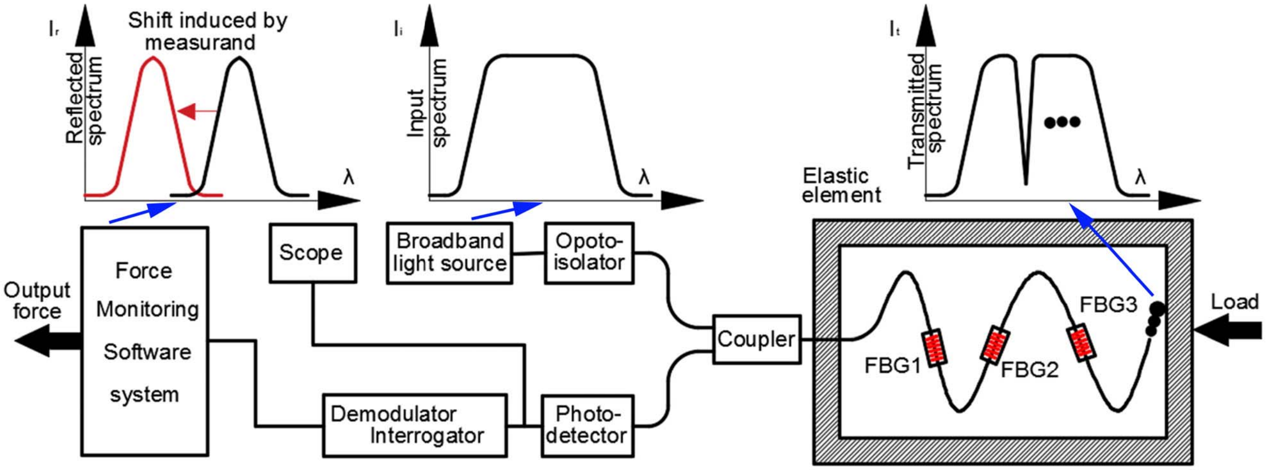

Fig. 1. Functional diagram of FBG based force sensing system.

of the input light, and become a critical potential of the optical sensing element of multi-component force sensing systems. The measurement principle of the FBG based optical force sensing system is illustrated in Fig. 1. In order to detect multi-component force and moment, several FBGs are multiplexed along the length of a fiber and bonded onto the elastic element of the force sensing system. The specific narrow optical reflection-band range at the Bragg-wavelength λ_{b} of the broadband light source is reflected by each single FBG. Particularly, the wavelength of this reflection band is dependent on the strain that induced by the applied load. Therefore, the measurand (force and moment) can be detected by monitoring the shift in wavelength of the reflection light.

The central Bragg wavelength of the reflected signal (λ_{b}) is related to the effective refractive index of the grating in the fiber core (n_e) and the periodicity of the grating pitch (Λ_f) [51],

$$\lambda_b = 2n_e\Lambda_f \tag{1}$$

Since the periodicity of the grating pitch and the effective refractive index are impacted by variations of mechanical strain (longitudinal and radial strain) and temperature, the shift in the central Bragg wavelength of the reflected signal for a FBG based optical force sensing system can be expressed as

$$\Delta\lambda_b/\lambda_b = (1 - p_c)\varepsilon_a + (\zeta_\Lambda + \zeta_n)\Delta T \tag{2}$$

where ΔT is the temperature change in the optical fiber, and ε_{a} is the axial strain of the optical fiber. ζ_Λ and ζ_{n} are the thermal expansion coefficient and the thermo-optic coefficient of the fiber, respectively. p_c is the photo-elastic constant of the Bragg grating (strain applied along fiber axis),

$$p_c = \left(\frac{n_e^2}{2}\right)\left[\tau_2 - \nu\left(\tau_1 + \tau_2\right)\right] \tag{3}$$

where υ is the Poisson's ratio (0.17), τ_1 and τ_2 are Pockels coefficients of silica (respectively 0.11 and 0.25), respectively.

In Eq. (2), the Bragg wavelength is varied in accordance with the changes of the environment temperature and axial strain. Specifically, a typical FBG with a $\lambda_b$of 1550 nm is capable of perceiving strain and temperature with sensitivities of 1.2 pm/$\mu\varepsilon$ and 10 pm/°C, respectively. Therefore, a FBG based optical force sensing system responds to both strain and temperature, requiring the temperature cross-interference effect to be eliminated in order to ensure the validity and reliability of the measurement of axial strain, which represents applied force with linear relationship. Considerable efforts have been focused on the cross-interference topic, and various solutions have been presented [52]. Conveniently, temperature cross-interference compensation techniques could be separated into at least two groups consisting of active and passive approaches [53], [54]. An active compensation approach refers to automatically eliminating the cross-interference effect in the force detection process with a sophisticated elastic element structure, while a passive compensation approach relies on an additional reference grating [55]. A reference grating can be on the same or different fiber and embedded onto the specific position of elastic element. Hence, it is isolated from strain signal. Additionally, another passive compensation approach with FBGs written on different-diameter fibers has been explored. These FBGs provide different strain responses with the same temperature response, allowing the temperature cross-interference effect to be eliminated [56]. A demodulator or interrogator is used to recover the force information from the the wavelength-encoded measurand information, a unique characteristic of FBGs. Specifically, the optical interrogator or demodulator is an optoelectronic instrument that evaluates the wavelength shift in the reflected spectrum of FBG sensors.

B. 1D FBG-Based Force Sensor

FBGs have been well established in many sensing applications with longitudinal strain measurement technology. The FBG-based force sensor is capable of detecting single dimensional force with a single FBG as well as proprietary hardware and software [57], [58].

Based on the measurement of the transverse strain-introduced birefringence, a novel fiber optic load sensor with LPFGs (Long-Period Fiber Gratings) produced in non-high-birefringence fiber was reported [59]. Additionally, high transverse strain sensitivity of 500 nm/kg/mm was achieved. The LPFGs devices offer the prospect of further development of multi-component strain measuring due to their high transverse strain sensitivity. Lim *et al.* [60] reported on force sensitive forceps with two FBGs in order to detect the grasping force for haptic feedback. Experimental results showed that the force sensing system could measure the grasping force with high sensitivity and resolution (11 *m*N). Liu *et al.* [61] demonstrated a 1D FBG-based force sensor with a simple fiber-optic sensor to measure the transverse force. A resolution of less than 0.49 N/mm and sensitivity of 30.7 *p*s / (N/mm) were achieved. Jin *et al.* [62] described an approach for measuring cutting force with an optical fiber sensor. The calibration experiment and manufacturing test results demonstrated that the described approach possessed competitive advantages. The natural frequency, sensitivity and linearity of the system were 950 Hz, 2.51 *m*V/N and 1.2% F.S., respectively.

For dynamic force measurements, Bartow *et al.* [63] presented an optoelectronic micro machine tool motion sensing system based on FBGs. The FBG sensors were mounted to the tool surface, and the precise evaluation of tool tip motion was performed by comparison with a piezoelectric accelerometer. Cutting test results demonstrated the feasibility of the proposed system.

C. 2D FBG-Based Force Sensor

Most 1D FBG-based force sensors were developed with longitudinal strain measurement method. However, fiber grating sensors can detect transverse and longitudinal strain simultaneously [64]. The possibility of transverse strain measurement of FBGs enables the FBG-based sensing systems to measure 2-axis forces [65]–[67].

Gonenc and Iordachita [68] proposed a method for predicting transverse and axial forces for retinal microsurgery with integrated fiber Bragg grating strain sensors. Specifically, three lateral FBGs were fixed evenly around the guide tube to measure the transverse forces, while the fourth FBG was located inside the guide tube to predict the axial forces. The results of calibration and validation experiments showed that the proposed approach could measure both the transverse and axial forces with RMS (Root Mean Square) errors of 0.15 *m*N and 1.69 *m*N, respectively.

A novel approach to detect two independent components of transverse strain by a single Bragg grating written into high-birefringent, polarization maintaining optical fiber was described by Lawrence et al. [69].

D. 3D FBG-Based Force Sensor

With the advantage of distributed measurement, a multi-parameter fiber grating system is capable of monitoring forces along multiple axes [70], [71].

Xiong *et al.* [72] described a 3D force sensor based on FBG technology for a robot foot with Maltese-cross beam. Five FBGs with wavelength interval of 3 nm were used to sense forces along three axes F_x, F_y, and F_z with measurement ranges of ± 50N, ± 50N, and 0-60N, respectively. Experimental results under different conditions demonstrated that the system repeatability and coupling errors were less than 2.87 N and 4.045 N, respectively. However, practical force measurement experiments on an actual robot foot is missing.

Recently, Choi *et al.* [73] designed and developed a 3D FBG-based force sensor to measure three directional forces with a flexible titanium structure and three FBGs. The developed sensor was experimentally verified to have a measurement range from -12 N to 12 N. Benefitting from artificial neural network based calibration and compensation method, the system estimated the multi-axis force with a maximum error and sensitivity of 0.12 N and 0.06 N, respectively.

Müller *et al.* [74] described an approach for measuring multi-axis force and torque with a fiber that contained six FBGs of 3 mm length. The calibration experiment and test results demonstrated that the approach possessed competitive advantages. The maximum force resolution and the condition number of the normalized compliance matrix were around 100 *m*N and 28.9, respectively.

Liu *et al.* [27], [75] published research in which they investigated three perpendicular force measurement with a sensing range of 400 N for milling operations based on FBGs. An elastic element with four rings in annulus shape was designed, and the Fiber Bragg grating sensors was fixed on the elastic body. Verification experiments were performed and the results showed the maximum detection error was around 15.6 N, which verified that the proposed approach could be adopted in milling and turning operations.

IV. TARGET APPLICATIONS

The optical force sensing technology has been approaching maturity in the past 30 years [76]–[79]. Early investigators and scientists such as Kane noticed enormous potential of the fiber optical sensing technique in areas of military and industrial applications [80]. Among the pioneers of the applications, Hirose and Yoneda developed a compact optical multi-component force sensing system based on light intensity detection technology [77]. At the same time, other researchers applied the optical force sensing technology into abroad and practical applications such as medical applications [81]–[82], robotic control [83]– [85], special measurement applications in harsh environments such as smeary working conditions, and strong Electro-Magnetic Interference (EMI) environments [86]. Much research has also been conducted on FBG based optical force sensing systems and many of which have already reached commercialization phases [87]–[91]. However, potential to continuously improve performance and reliability is still pursued by developers and engineers, while special efforts are made towards achieving more cost-effective approaches and exploring new applications.

A. Robotic Applications

Accurate measurement of force and moment information is becoming more and more significant and has received considerable attention in numerous robotic applications [92]. Despite this awareness, force sensors still fail to be widely equipped when industrial automation systems perform reliable and non-destructive manipulations.

A great number of research teams proposed their significant work on force and moment measurement for robotic applications. Recently, a three-component force sensor based on FBG for a robot fingertip has been proposed by Guo *et al.* [26]. The sensor enabled the three-component force detection based on FBG technology for robot fingers. The sensing system consisted of an elastic force-sensing element bonded with six FBGs, a fingertip, a cover, and a FBG interrogator based on a CCD (Charge-Coupled Device) spectrometer. The variation of FBGs wavelength data due to the applied force was recorded by the interrogator. The calibration experiment was performed and the results showed that the sensor possessed high performances with the minimum precision of 0.061 N, 0.059 N, and 0.045 N for F_x, F_y and F_z, respectively.

Similarly, Melchiorri *et al.* proposed a compact and reliable three-component F/M sensor based on optoelectronic components for robotic systems such as robotic fingers [93]. The applied external force could be measured by photodetectors through detecting the scattered energy density variation. Static and dynamic calibration experiments were performed, and the results showed that the developed sensor could measure the applied force/torque and determine the contact point position with satisfactory performance. More recently, the team took their efforts one step further and extended the proposed optical-based approach to detect six-component force/torque information for robotic applications such as robotic hand fingertip and industrial grippers [94]. The maximum measurement range of the sensor was up to [−50, 50] N and [−1, 1] Nm for force and torque components, respectively. A calibration experiment was conducted with a reference sensor of ATI F/T sensor (SI-130-10), and the results indicated that the maximum relative error over the measurement range was about 10%.

Su *et al.* [95] from Worcester Polytechnic Institute used their efforts to develop a MRI (Magnetic Resonance Imaging)-guided needle placement robot for real-time in situ needle steering applications. A high-resolution force sensing system based on a Fabry-Perot interferometer and fiber optic detection approach with a 16-bit data acquisition system was integrated into the robot. The sensing ability of this force sensing system with a gauge factor of 47.48 $m\text{v}/\mu\varepsilon$ was confirmed via a MRI compatibility test and calibration experiments.

B. Measurement Under Special Environments

More recently, an impressive development was reported by Tan et al. [96]. In an attempt to develop a MRI-compatible force sensor for continuous MR imaging, a multi-component force sensor based on an optical method was proposed with a novel sensing element in shape of elastic frame structures, which were fabricated with polymer materials. Specifically, topology optimization techniques were used in order to obtain maximum resolution and bandwidth performance. Meanwhile, Prandtl-Ishlinskii (PI) play operator was proposed to account for the hysteretic behavior of the polymer materials. Calibration experiments and MRI compatibility tests were conducted, and the results showed that the feasibility of the sensor with a resolution of 3 mV and a maximum RMS error of 0.525 N.

A sophisticated temperature-independent optical force sensor with a wide measurement range of 0 to 3 kN was presented by Zhang *et al.* [30]. The sensor was characterized by a novel elastic element with a spoke-type structure and two FBGs with different wavelengths. The theoretical and experimental results showed that the sensor could detect the applied load with a high resolution of 0.21 kN. The presented system could automatically compensate the temperature cross-interference effect between −20 °C and 75 °C with differential detection technologies.

C. Biomedical and Medical Applications

Minimally Invasive Surgery (MIS) has been recently revolutionized by the development and upgrade of a number of innovations in instrumentation and specific technology because of its notable advantages over the traditional open surgery, while its wider applications are restricted by the lack of force and tactile perception. Numerous studies aiming to support force and tactile feedback for biomedical and medical applications have been proposed [97], [98]. However, the research and development results were usually not utilized in practical devices or systems due to the regulation of clinical implementation.

A sophisticated intensity-modulated optical fiber force sensor with three force components for minimally invasive surgical palpation procedures was presented by Puangmali *et al.* [25]. The three-component force information provided by the sensor was used to identify tissue stiffness variation, and thus locate tissue lesions, such as tumors. The hysteresis error and RMS (Root Mean Square) error of the proposed sensor were 3.5% and 0.68% F.S. respectively. To identify the effectiveness of the sensor, the developed sensor and a standard F/T (ATI Mini 40) were equipped to a 6-DOF robotic platform. The results of the experiment on a porcine kidney showed that the proposed sensor could detect and localize the invisible tumor.

To achieve multi-component force/torque measurement in minimally invasive robotic surgery, Haslinger *et al.* [99] from German Aerospace Center (DLR), Germany, developed a novel force sensing system based on a fiberoptic approach. With an elastic element of Stewart Platform, the authors proposed the smallest 6-component FBG based force/torque sensing system (Φ 6.4 mm × 6.5 mm). The calibration experiment was conducted and the results demonstrated that the maximum crosstalk error among components and the maximum hysteresis error were 6.5657 Nmm and 0.5320 N for component M_y(moment about the y-axis) and F_z (force along the z-axis), respectively.

For application in MRI-guided cardiac catheterization procedures, the FBG based sensing method was investigated by Polygerinos *et al.* [100], [101] with a specially designed catheter tip based on the light-intensity modulation technology. In order to detect the load, three plastic optical fibers were integrated into a catheter tip in a circular pattern, and a reflector was bonded to the catheter tip through an elastic material. The optical fiber light intensity was modulated by the distance changes between the reflective surface of the reflector and the optical fibers in alignment. The calibration experiment was carried out with a commercial force sensor from ATI Industrial Automation, Nano 17, and a linear micrometer calibration tool. Additionally, experiments under lab conditions and in real-time MRI in vivo conditions were conducted, and the results demonstrated that the proposed system could measure the three-component force in the range around 0 – 0.85 N with a 0.0478 N resolution and relatively small hysteresis.

Gonenc *et al.* [102] have designed and constructed a multi-component force sensing system based on an opto-electric approach for robot-assisted vitreoretinal surgery. With four strategically embedded FBG sensors and a linear regression as well as a nonlinear fitting based on second-order Bernstern polynomials, the system was capable of accurately capturing a tensile force component along the tool axis as well as the tangential force components with a measurement range of 0 – 25 mN. The results of calibration and validation experiments showed that the proposed system could predict 3-component forces with an RMS error under 0.15 mN, 2 mN for transverse components and axial component, respectively.

D. Dynamic Measurements

FBG based force sensing systems have demonstrated significant advantages in the dynamic measurement of force, torque, vibration, bending, pressure, etc. [103].

A novel real-time torque detection approach based on the FBG strain sensing system was recently investigated by Li *et al.* [29]. Two FBG strain sensors were bonded onto a rotating shaft in opposite positions to obtain the bending and torsion information. Results of dynamic experiments conducted to evaluate the proposed online detection approach verified that the system could be applied to the online vibration measurement of large rotating machinery with a calibrated sensitivity of 7.02 pm/Nm. Additionally, results of rotating experiments at different revolution speeds showed that the proposed system could measure the applied torque at the 400 RPM (Revolutions per Minute) with higher accuracy than a commercial tacho-torquemeter. The advantages associated with the system enabled the practical vibration measurement applications of rotating machinery.

A haptic interaction system has been described by Park *et al.* [104] based on miniaturized fiber-optic-based force measurement technology. In order to realize real-time estimation of the needle tip position and deflection, three optical fibers with FBG sensors were adhered inside the grooves in the inner stylet of the needle. The real-time strain and temperature of the needle could be detected by the gratings with different orientations and positions. The calibration experiment was performed with two high resolution digital cameras. The calibration and experimental results showed that the system could estimate the deflection and bend shape with 0.6 mm error for two-point bending deflection of 6.8 mm.

E. Other Measurement Applications

Roesthuis *et al.* [28] reported a shape and force sensing system based on FBG sensors for steering multi-segment continuum manipulators. Twelve FBG sensors were integrated into 3 optical fibers, which were introduced into the hollow backbone of the continuum manipulator via a nitinol wire. A Deminsys Python FBG interrogator was utilized to connect the optical fibers and detect the strain-induced change in the reflected wavelength from FBG sensors. The possibility of detecting axial tip interaction forces as well as bending was demonstrated.

Malla *et al.* [105] presented a novel fiber optic force sensing system for detecting wheel loads of moving vehicles on highways. By using an optic fiber that was featured with two concentric light guiding regions as the sensing element and the Forward Time Division Multiplexing (FTDM) approach, the system could be used to estimate the magnitudes and locations of the applied forces with the measurement range of 3781 N (850 lbs). Experiments under a commercial universal test loading machine (SATEC^{TM}Series) and car wheel load tests were carried out. Results showed that the system could detect the wheel loads with a sensitivity of 2.1×10^{-3} mV/N for Weigh-in-Motion (WIM) systems. The proposed system was economically feasible for measurement tasks on busy roads due to its advantages such as weighing vehicles while they are in motion rather than at rest.

Park *et al.* [106] paid special attention to the exoskeletal force sensing approach by using fiber optical technology for composite end-effectors. The shape deposition manufacturing technology was used to fabricate a miniaturized polyurethane finger with a hollow shell exoskeletal structure (with a size of 15 mm). Five FBG sensors were embedded in the fingertip and shell for strain measurement and temperature compensation. Experiments were conducted to verify the system capability of estimating the contact location as well as detecting multi-component force. The working range of the force sensing system was around 5 N with a 0.15 N resolution.

V. DISCUSSION AND CONCLUSIONS

Optical fiber sensing systems have drawn a great deal of attention from many researchers and engineers, leading to a significant amount of research conducted in the last few decades [5]. Accordingly, numerous types of optical fiber sensing methods are presently realized and commercialized in areas including strain measuring, pressure sensing, rotation observing, underwater acoustic sensing, temperature monitoring, certain chemical and biomedical species sensing, etc. It is impossible to survey every approach in the area due to the limits on length of this paper; moreover many brilliant surveys on specific topics have previously been presented. In this review, we tried to focus on the primary concepts of optical fiber force sensing systems and review some results published more recently with emphasis on FBG based force sensing systems.

Over the last 12 years, the authors have designed and developed several multi-component force sensing systems aimed at high-performance monitoring of force and moment information. Based on this wide field of experience and the main aspects of the survey presented herein, the following observations and conclusions can be reached for the new generation of the opto-electric multi-component force sensing system:

- Multi-component force sensing systems capable of estimating several force and moment components simultaneously can benefit from the multiplexing capability of the FBG based measurement system.

- Several of the most notable successes in the fiber optic sensor technology have been realized. However, FBG based force sensing systems have always confronted the difficulty of competing with relatively conventional force measurement approaches, which proffer decent performance criteria with excellent reliability and cost-effectiveness.
- Though opto-electric force sensing systems can provide outstanding performance, some important issues should be considered in the design of the FBG based force sensing system into real-world applications, such as sterilizability for medical applications.
- The best approach to estimate operating force information in medical applications, considering MRI-compatibility and compactness in space, is the optical force measurement method especially the FBG-based one.
- The success of a force sensing system is also related to the post-processing of the acquired force and moment data. Specifically, the vast majority of the existing multi-component force sensing systems with a single elastic element are confronted by fatal coupled interference errors among their components. Correspondingly, the efficient data post-processing procedures including nonlinear and dynamic decoupling, segmented linearization and temperature compensation, offset correction, modeling and compensation of asymmetric hysteresis nonlinearity, etc. may also be implemented.
- The bare FBG can only resist deformation with micro strain around 3000. This depends on the FBG photowriting technique (laser fluence), fiber recoating (polymer, carbon, metal), application (or not) of a proof-test, environmental parameters (temperature, relative humidity) and duration of use under the maximum strain level. Therefore, the maximum allowed strain for a given MTTF (mean time to failure) may significantly change according to FBG manufacturing and test conditions. Consequently, it is necessary to enhance its resistance to enlarge the measurement range of the sensing system. At the same time, overload protection against excessively large forces should be addressed when designing practical force sensing systems.
- Because the minimum detectable strain signal increment of FBG sensors is about 1 or 2 micro strain, FBG based force sensing systems for high-precision monitoring applications must be designed and validated with sensitization treatment.

As demonstrated in the previous sections, significant improvements have been achieved in addressing numerous aspects of designing and developing multi-component opto-electric force sensing systems. However, some concerns have not yet been addressed and numerous technical challenges must still be overcome to implement multi-component opto-electric force sensing systems.

- Regarding the sophisticated structure and material of elastic elements of the multi-component force sensing systems: the structure and material of elastic elements, which serves as the reaction mechanisms to the applied loads, are critical to the performance of the system. Developers should consider several design criteria such as global sensitivity, minimum stiffness, overall dimensions, measurement isotropy, coupling effect, hysteresis, and repeatability simultaneously when designing the particular structure and selecting the material of the elastic element.

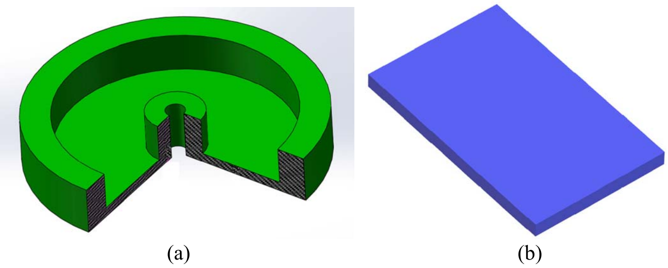

Fig. 2. A Modular design of force sensing system with circular diaphragm (a) and cantilever beam (b).

- Modular design and development methodology: Generally, multi-component force sensing systems with special requirements of measurement range, sensitivity and other performance criteria need to be designed and developed individually. This is an efficient way to design and develop multi-component force sensing systems with identical Elastic Elements (EEs) of different dimensions for different robotic applications. For example, circular diaphragms and cantilever beams (as shown in Fig. 2) [107], typically used and validated by researches, are available as modular EEs. With Simulation-Driven Design and Optimization (SDDO), the appropriate geometry dimensions of modular EEs can be efficiently determined. Therefore, an important goal of the new force sensing system is to design and develop modular architectures for multi-component force sensing devices, which can reduce the complexity and increase strength.
- Low cost force/moment sensing systems or instruments. To extract the original force information-bearing signal from the light signals obtained from the opto-electric sensors, optical spectrum monitoring systems are required. Demodulators, interrogators, tunable lasers, and optical spectrum analyzers are typically used to observe the wavelength shift of FBGs and collect the measured data. In order to pursue higher performance, essential elements such as holographic diffraction gratings, CCD detectors, radio-frequency modulation and spectrometer detection system, etc. may increase the cost of the system. Therefore, inexpensive optical spectrum monitoring systems with high wavelength scanning speed, wide dynamic range, high measurement resolution, and robust stabilization will make it possible to detect force with higher performance in a cost-effective manner.
- Compact design with all complementary optical system: Though the sensing element of the opto-electric force sensing system is small in size, the complementary optical systems are always large in size (in comparison with

traditional force sensing systems). The limitation in size may be the result of the requirements of the associated optical-interrogation and opto-electronic integration instruments. Opto-electronic integration technology enables that various accompanying optical components of opto-electric force sensing systems (such as high-power fiber amplified spontaneous emission sources, optical circulators, photonic processing subsystem, photoelectric detection chip, demodulators, interrogators, optical spectrum analyzers, and etc.) can be integrated onto a single specific package with the rest of the applied systems. This strategy is essential to decrease the cost and size of the system, and will then bring opto-electric force sensing systems into more extensive usage.

- MEMS Opto-electric force sensing systems: MEMS (Micro-Electromechanical Systems) technology is critical to reductions in cost and size of opto-electric force sensing systems, which can lead to more widespread usage. Specifically, the cross-sectional dimensions of the FBG sensor can be reduced with the MEMS approach and high refractive index contrast materials. Therefore, MEMS opto-electric force sensing systems are benefit from miniaturization [108], higher performance, low cost and power consumption [109], and may be employed in a wider range of applications.
- Combination with other transduction methods: In addition to the design and development of innovative force sensing technologies and devices, integration and implementation of the force sensing system with the other measurement systems (or the rest of the automatic system) have also drawn an increasing amount of attention over the last few years [110], [111]. Along with force sensing systems, the idea of using multiple transducers for different or identical functions all in one package will emerge soon. This configuration also boasts lower power consumption and effective integration, as well as the ability to overcome the limitations of individual sensors.

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