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A Review of Current Research on Human Sensing for Minimally Invasive Surgical Machines based on Fiber Optic Gratings

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Abstract

Force sensing feedback is an important basis for the surgeon's judgment when performing surgery and reducing damage to the patient's body tissues. Minimally invasive surgical instruments bring convenience to surgeons while losing the interactive feedback of direct contact between surgeons and patients' body tissues, so timely and accurate force sensing of minimally invasive surgical instruments is a very important part of minimally invasive surgical machine systems. Researchers have learned that fiber optic gratings, with their advantages of electromagnetic interference resistance, small size, simple structure, and bio-compatibility, are well suited for integration in the ends of delicate surgical instruments to provide timely force feedback information. The central wavelength of the fiber grating force sensing system is shifted to indirectly reflect the magnitude of the external force. This paper summarizes the current status of research on fiber grating-based force sensing systems for minimally invasive surgical instruments at home and abroad and provides an outlook on this technology.

Keywords

Minimally Invasive Surgical Instruments; Force Sensing; Fiber Optic Grating.

1. Introduction

Fiber grating force sensing technology is an emerging technology that has been widely known and utilized in recent years. Fiber grating force sensing technology generally uses the offset of the center wavelength of the fiber grating caused by external forces to calculate the magnitude of external forces such as pressure. In recent years, this technology has been widely used in minimally invasive medical procedures. To achieve the requirements of low trauma, high accuracy, and rapid post-operative recovery and aesthetics, doctors have demanded high accuracy of end force detection and control for minimally invasive surgical robots.

Fiber grating with light as the signal has the advantages of avoiding electromagnetic interference, high-temperature resistance, small size, simple structure, variable shape adapted to the environment, an optical fiber can be connected in series with multiple gratings, and other advantages [1,2,3]. Since the end of the last century, fiber grating sensing technology in the sensing side of the design and production of packaging technology, and information processing has rapidly become a research hot spot at home and abroad [4]. Current domestic and international research focuses on fiber grating tactile sensing, of which force sensing is a very important part. Therefore, there is a need to organize the current state of development of this sensing technology at home and abroad to show the characteristics and advantages of each technology research.

This paper briefly describes the basic principles of fiber grating force sensing detection, focuses on the research results of fiber grating force sensing technology in the biomedical field, especially in the

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field of minimally invasive surgery at home and abroad, and finally outlines the main problems and development trends faced at present.

2. Fiber Bragg Grating Sensing Principle

2.1 Section Headings

2.1.1 Sub-section Headings

A fiber Bragg grating is essentially a narrow-band filter or reflector[5] formed within a section of optical fiber of about 10 mm to change the transmission path of light of different wavelengths through the fiber.

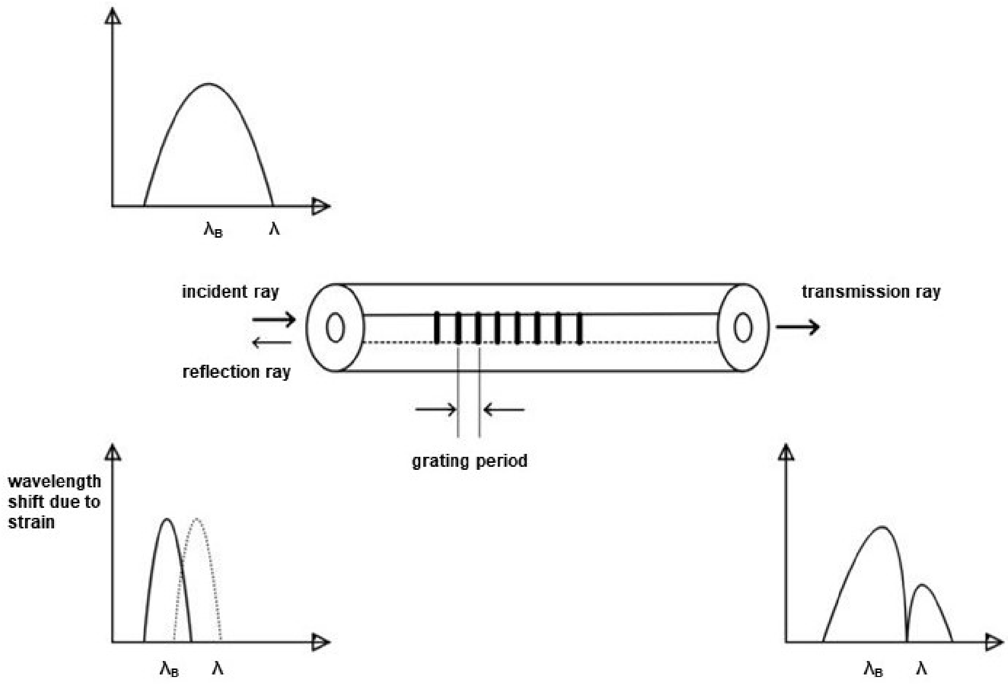

Fig. 1 Fiber grating sensing diagram

As shown in Fig 1, when the fiber Bragg grating sensor enters a beam of light provided by a broadband light source, the narrow-band light of a specific frequency is reflected, and the light of other frequencies continues to transmit. According to the coupled mode theory, the peak wavelength of the reflection spectrum of the fiber grating is related to its grating period and the effective refractive index of the fiber core material, that is, the reflection wavelength of the fiber grating satisfies the relationship [6]:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where neff is the effective refractive index of the fiber, Λ is the grid period, that is, the distance between two adjacent refractive index changing points. From equation (1), it can be known that the reflection center wavelength of FBG changes with the changes of neff and Λ.In the formula, the refractive index of neff fiber is affected by temperature, and Λ is affected by pressure and decreases with the increase of pressure. If the change value of reflected wavelength is demodulated, the external physical quantity can be obtained by theoretical formulae, such as changes in pressure. The value of the change in reflected wavelength can be expressed by the following equation:

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$$\Delta\lambda_B = 2n_{eff}\triangle\Lambda + 2\Delta n_{eff}\Lambda \tag{2}$$

Therefore, changes in parameters such as temperature, pressure, and strain will lead to changes in neff and Λ, which in turn will affect the central wavelength [7]. Divide equation (1) by equation (2) to get:

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{eff}}{n_{eff}} \tag{3}$$

It can be seen from formula (3) that the change in the center wavelength of the fiber grating is mainly caused by the grating period and the effective refractive index of the fiber. By reading the change value of the center wavelength by the instrument, the change of external physical quantities such as pressure can be obtained value.

3. Research on Force Sensing Measurement Technology based on Fiber Bragg Grating

In the treatment process of modern medicine, the premise of cure, people prefer minimally invasive surgery with less intraoperative trauma, less pain, simple postoperative recovery, and at the same time aesthetic, and minimally invasive surgery has become a big part of the surgery. The advent of minimally invasive surgical robots has helped doctors to achieve efficient and precise minimally invasive stereotactic surgery. The front-end surgical instruments are controlled by the surgeon's console to mimic the dexterity of the surgeon's arm and wrist, thus requiring a higher level of design for the surgical instruments used in minimally invasive surgical robots. Minimally invasive surgical instruments have some significant differences compared to traditional surgical instruments, and to ensure the effectiveness of the surgical task, they should have precise and real-time contact force detection to be controlled. In minimally invasive surgery, for example, the distal force of surgical instruments is important for the safety of soft tissue manipulation and the accuracy of instrument deformation control. Force perception can also be used to determine the tension of sutures, for example, during suture tying, to avoid damage to organ tissues by over-tightening the sutures[8].

In recent years, the measurement technology with fiber optic grating as a carrier has been developed rapidly in recent years, which is mainly due to the outstanding advantages of the optical fiber itself, including light as a sensing signal has no electrical detection, is not subject to electromagnetic interference, can withstand high and low temperatures, no zero drift, high accuracy, tiny size can be integrated with tiny probes, extremely stable physical properties, good bio-compatibility, good sterilization performance.[9,10,11,12,13]These advantages are very meet the demanding requirements of minimally invasive surgical robots for measurement components. In short-distance and high-precision occasions, the currently reported fiber-optic grating force sensing measurements mainly focus on the end force measurement of surgical robots, and because of the precision requirement of minimally invasive surgery, the error requirement for the end force measurement of surgical robots is very high, generally below 0.1 mN.

End-operating force measurement of surgical robots is the key to achieving precise control of the robot and is essential to ensure the safety of surgical operations. For this reason, interactive force measurement of surgical robotic instruments has become a hot topic of technological research for researchers at home and abroad [14]. Among the many surgical procedures, the most needed and suitable for the use of minimally invasive surgical robotic systems are mainly for the treatment of lesions in the eye, heart, or small vessels in the human body.

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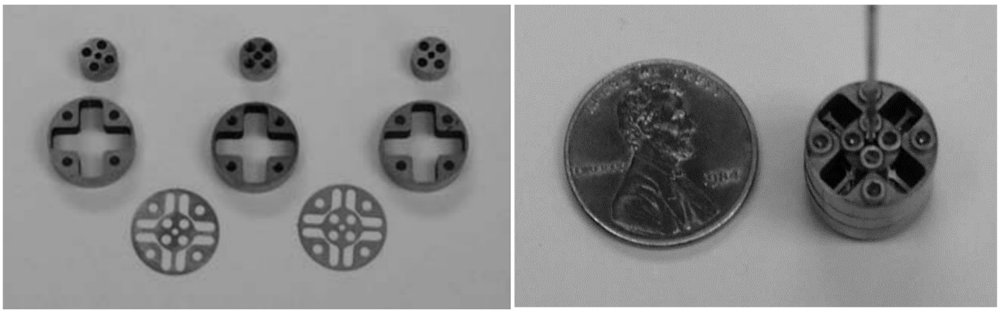
3.1 Force-aware Design for Minimally Invasive Surgery Robots Facing the Eye

Among domestic and international research teams investigating ophthalmic surgical robots and corresponding force sensing systems, the Computer-Assisted Surgery Research Center at Johns Hopkins University in the U.S. is at the forefront of the world. in 2000, Peter J. Berkelman et al. of this team proposed a small-size force sensing system using silicon strain gauges as sensors [15]. As shown in Fig 2, this sensing system uses two force-sensing steel sheets containing cross elastic beams to form a force-measuring mechanism that can adjust the relationship between the magnitude of axial and lateral stiffness by changing the vertical distance between the two elastic measuring sheets, thus achieving the coordination of sensitivity between axial and lateral forces.



a.Force sensor components b.Sensor assembly

Fig. 2 PS-mall size force sensing system designed by eter J. Berkelman et al.

As mentioned at the end of Peter J. Berkelman's article, a tiny force sensing system using silicon strain gauges as sensors suffers from sensitivity to temperature changes, electromagnetic noise effects, and bio-compatibility issues [16]. In 2009, Iulian Iordachita et al. of the team published a landmark study in the direction of human sensing for ophthalmic surgical machines, as shown in Fig 3[17], in which the new force sensing system described The new force sensing system measures the deformation of the instrument end by three FBG sensors arranged on titanium alloy, whose mechanical dimensions basically match those of conventional ophthalmic surgical instruments; not only that, Iulian Iordachita et al. established a temperature compensation algorithm in order to minimize the calculation error caused by the wavelength change due to the external ambient temperature change, introducing the The concept of "relative sensor reading S", the algorithm eliminates the common modulus of temperature variation and axial strain in the data measured by FBG with the help of symmetry of the sensor arrangement, and thus the wavelength variation of the three FBG sensors independently of the external temperature variation can be obtained separately. The force sensing system is capable of measuring forces in the transverse two degrees of freedom direction with a diameter of only 0.5 mm, but with a resolution of 0.25 mN.

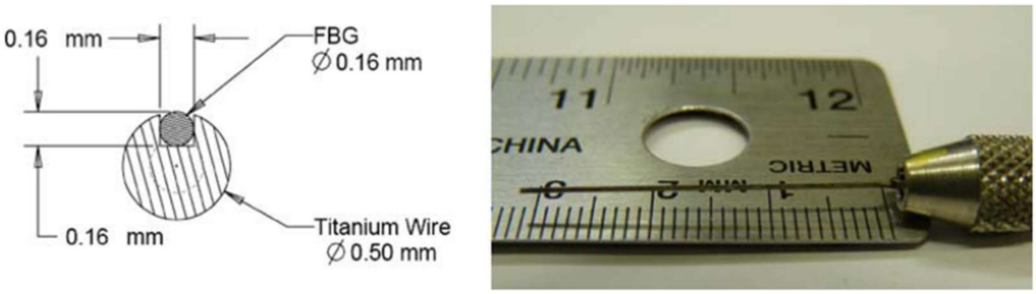


Fig. 3 1-DOF end force perception tool designed by Iulian Iordachita et al.

However, as pointed out by Iulian Iordachita et al. in the concluding section of the paper, this force sensing system had an obvious shortcoming: namely, it could only sense the two-dimensional radial force and could not obtain the three-dimensional force vector acting on the end of the instrument. By around 2012 [18,19,20], as shown in Fig 4, the team changed the carrier of the force sensing system and used a super-elastic medical nickel-titanium alloy as the carrier to improve the force sensing accuracy. Meanwhile, to solve the problem that the axial force could not be measured, the team proposed a new type of transmission mechanism to realize the end forceps clamping action, but the final result was still bad and did not reach the expected vision.

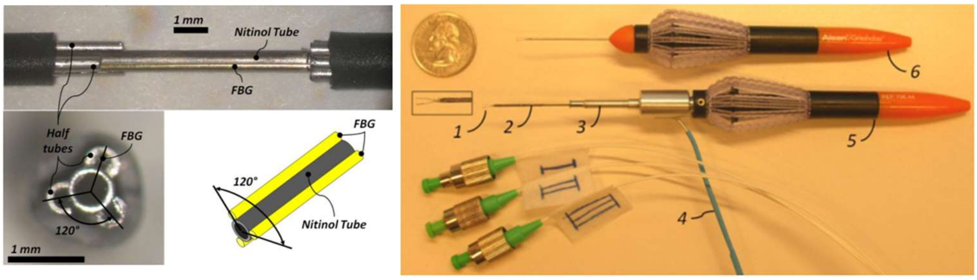


Fig. 4 New clamping structure designed by the JHU team

Around 2014, the JHU team led by Xingchi He published a series of papers reporting the results of their work on an FBG-based 3D force sensing system [21,22,23], which determined the parameters of the sensor based on a report published by Puneet K. Gupta et al on contact forces in ophthalmic surgery. As shown in Fig 5 [24], a feature that clearly distinguishes this force sensing system from the previous team is the addition of a fourth FBG sensor at the axial position of the surgical instrument to obtain information about the axial force at the end of the instrument. The team used four fiber-optic grating sensors to maximize the decoupling of axial and lateral forces, thus successfully expanding the two-degree-of-freedom force sensor to three degrees of freedom with an increase in diameter of only 0.3 mm, achieving a resolution of 1 mN for axial forces and 0.25 mN for lateral forces [23].

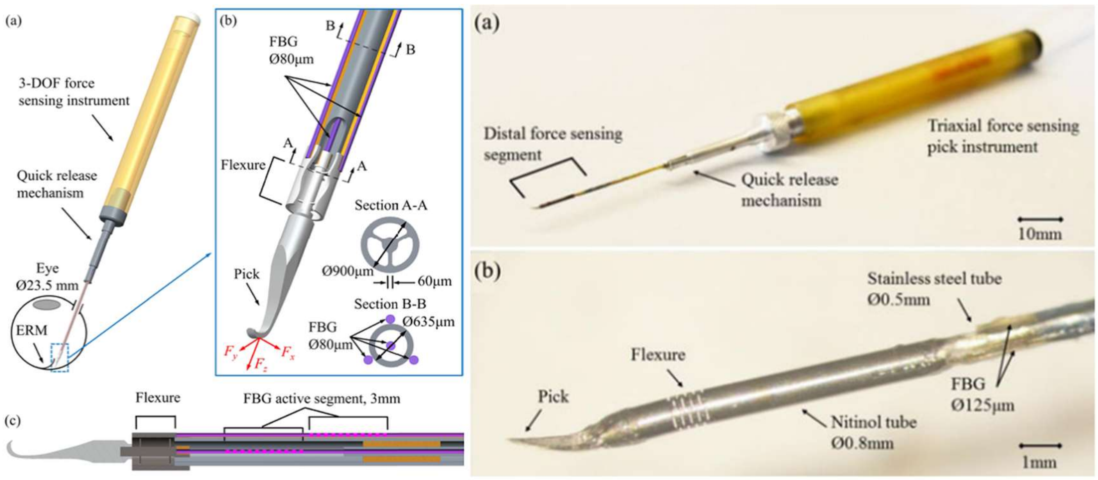


Fig. 5 Surgical instrument with four FBG sensors 3D force sensing system designed by He et al.

During the fifteen years from 2005-2014, the Johns Hopkins team has contributed its great efforts in the field of ophthalmic surgical robots and corresponding force sensing systems, from single-dimensional force detection to 3D force detection, from silicon strain gauge sensors to four fiber grating sensors, from simple embedded sensors to optimized sensor carriers, it is clear that the team has been at the forefront of the world, but the team has always completed its experiments on the

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surgical instrument models proposed by other teams, and has not tried to complete the optimization of corresponding surgical instruments based on its force sensing system, so there is still some room for the team's work.

In 2014, Piers et al [25] from KU Leuven, Belgium used a similar force sensing method to embed three fiber optic gratings into the end of a retinal surgical probe, as shown in Fig 6[26], adding a series of micro-machined holes at the tip that increased sensitivity to axial force changes with no significant reduction for stiffness and strength. The enhanced sensitivity at the tip is particularly noticeable when there is significant friction along the needle sheath. The force sensing system achieves a 2D force measurement and a measurement resolution of 0.25 mN for an axial load of 10 mN, with a smooth response detectable in the 0-200 Hz range[25].

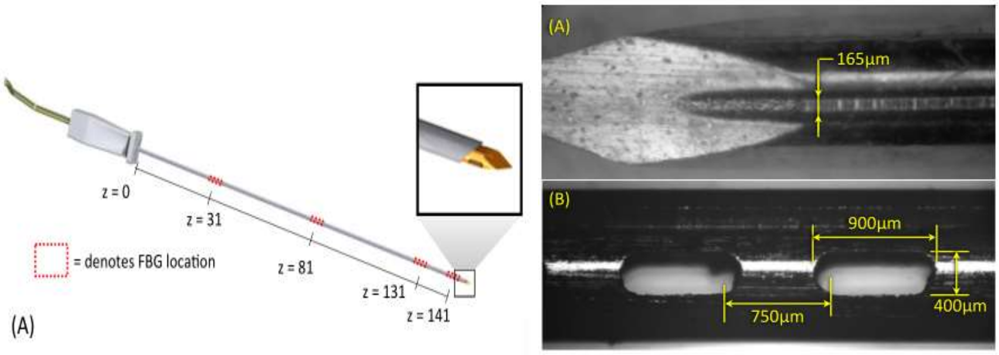
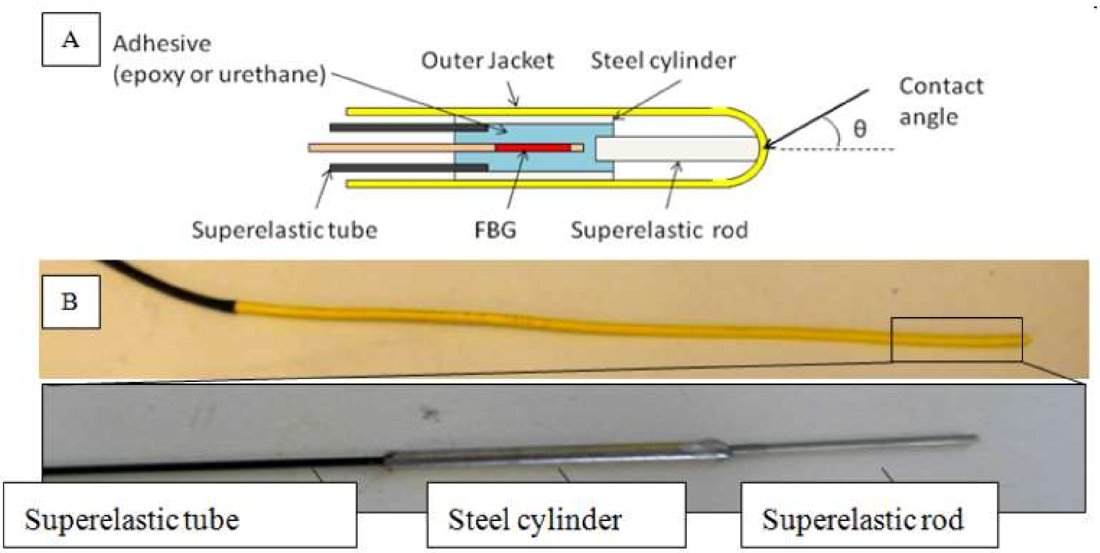


Fig. 6 The force sensing system integrated with the end of the surgical probe by Piers et al.

3.2 Force-aware Design for Minimally Invasive Cardiac Surgery Robots

A research team from the National University of Singapore first [27] applied fiber-optic grating multidimensional force measurement technology to the distal end of a cardiac ablation catheter for 3D force measurement and a tissue palpator for haptic feedback, respectively. Simulated surgical experiments were performed in silicone aorta and simulated tumors, and the results showed that the fiber grating sensing device can effectively achieve 3D force measurement at the distal end of the catheter, as well as accurately identify tumor regions and detect stiffness differences between regions.



a.Schematic diagram of the sensor head b.Exterior and interior photos of the sensor

Fig. 7 Single sensor structure based on fiber Bragg grating designed by Ho et al.

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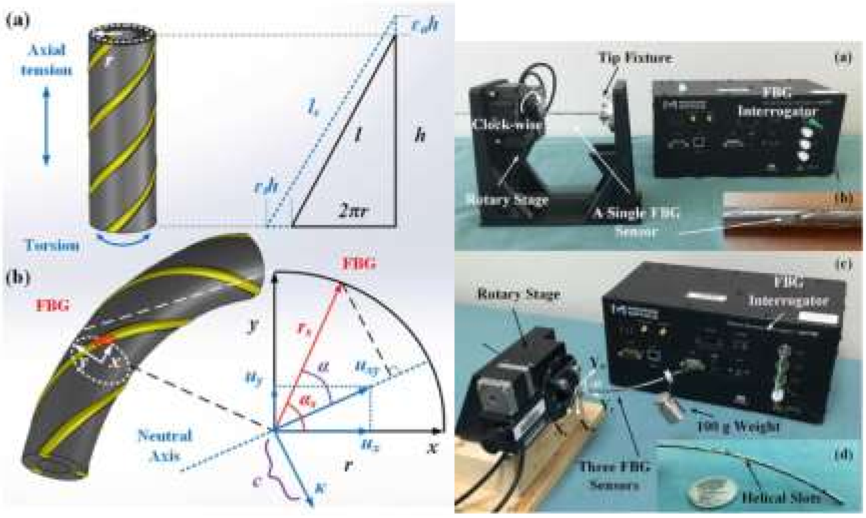
In 2012, Ho et al, at the University of Houston developed two prototypes of a single sensor based on a fiber Bragg grating to sense axial forces, as shown in Fig 7[28], to help predict possible cardiac perforation during surgery to treat atrial fibrillation. When the sensor is in firm contact with the endocarditis wall, the peaks appear in synchrony with the heart rate, with multiple periodic peaks visible in the signal when contact is made and rapidly diminishing when no contact is made. Pre-perforation signals,which for one of the epoxy-based sensors, in the form of a slight signal inversion (12-26% of the loaded phase size) were observed before the onset of the shot hole [29].

In 2016, Ran Xu et al from the Canadian Institute for Surgical Technology and Advanced Robotics took advantage of the FBG's tiny size and flexibility to be integrated with small robots. The team designed and fabricated a spiral-wound FBG haptic sensor and developed a corresponding force-curvature-strain model based on this sensor structure to provide simultaneous curvature, torsion, and force measurements. Timely and accurate curvature, torsion, and force measurements can be obtained at a sampling frequency of 100hz, as shown in Fig 8[30] , for use in concentric tube medical robotics.



a.Demonstration of curvature-strain model for spiral wound FBG sensor b. Experimental setup for straight tube torsion verification

Fig 8. Spiral-wound FBG haptic sensor designed by Ran Xu et al.

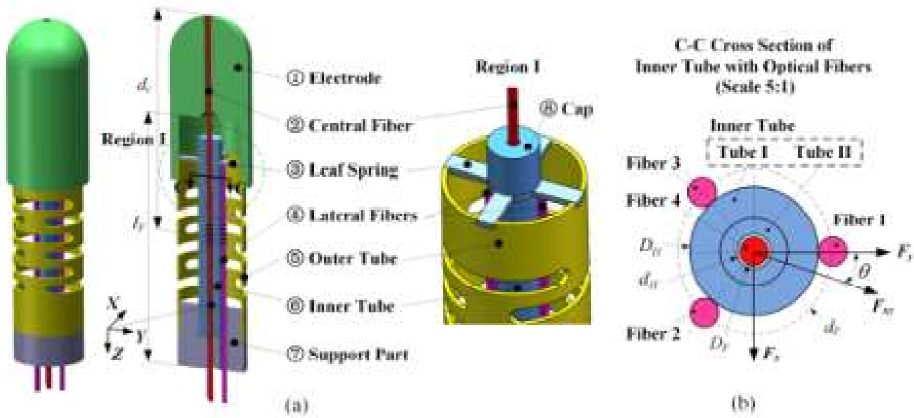


Fig. 9 Three-axis force sensor structure with a parallel flexible hinge and four optical fibers designed by Gao et al.

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In 2018, Gao et al [31] from Shenyang Institute of Automation, Chinese Academy of Sciences, designed and implemented a fiber grating three-axis force sensor for cardiac catheter ablation, as shown in Fig. 9[32], which achieves the estimation of three-axis tip force, which integrates a parallel flexible hinge to achieve a good transverse and axial stiffness balance with <1 g resolution in both transverse and axial directions. The force sensor achieves a measurement range of [-100 g, 0100 g] for lateral forces and [0 g, 100 g] for axial compression forces.

3.3 Force-aware Design in the Face of Minimally Invasive Surgery-related Instruments

In 2011, Song Ho et al. of the Korea Institute of Science and Technology [33,35] took advantage of the small size of fiber optic gratings for easy integration with surgical instruments and integrated fiber optic gratings into surgical forceps, as shown in Fig 10[34]. The sensing technology was applied to a three-dimensional force measurement system for surgical forceps, which is a 3D force measurement system consisting of four fiber-optic gratings that are glued to a specially designed quadrature beam structure. The sensor is connected in parallel with the surgical forceps in series to measure the axial force information of Fz, Mx, and My of the surgical arm with a force resolution of 0.05 N and a maximum error of 0.1 N. The surgeon can distinguish abnormal parts or vessels from the target tissue during surgery based on the feedback force information.

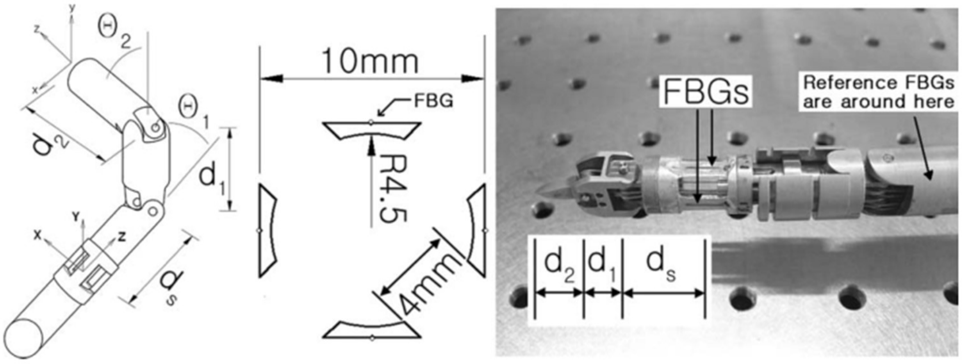

Fig. 10 Surgical instrument with a 3D force measurement system designed by Song Ho et al.

In 2013 Haslinger et al from DLR designed a 6-DOF fiber optic force-torque sensor for integration in a minimally invasive robotic surgical instrument, as shown in Fig 11[36] . The six fiber optic gratings of this sensor are embedded into the six connecting rods of the parallel mechanism, with an additional temperature complementary grating. The whole sensor is very precise and compact and has shown good multidimensional force measurement capability after testing with various loads applied to the sensor by a calibration device. Further load tests have shown that the structure can be robust under design loads of up to 20 N and 15 N·cm.

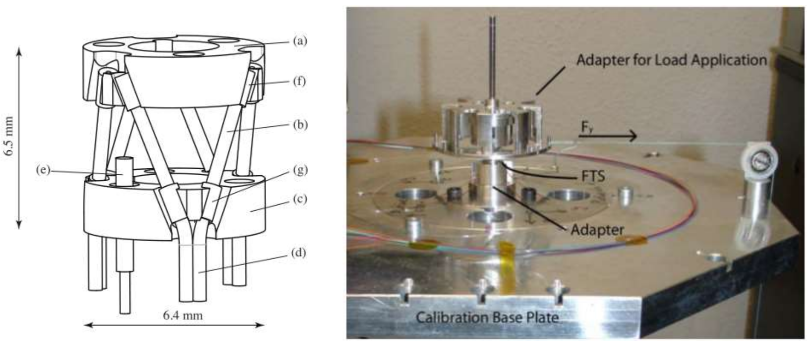

Fig. 11 6-DOF fiber optic force-torque sensor designed by Haslinger et al.

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In 2010, Park Y et al from Harvard University arranged fiber grating measurement points at two locations inside the medical inspection probe, as shown in Fig 12 [37] , while three strings of fiber gratings were arranged at 120°intervals from each fiber grating measurement point. These two sets of sensors, not only provide the measurement of tip deflection, but also estimate the bending profile, present the 3D bending shape of the probe in real-time, and provide temperature compensation. It is very important to track the trajectory state of the probe in real time and grasp the action of the probe with human tissue, which is very helpful for the precise manipulation of robotic surgery.

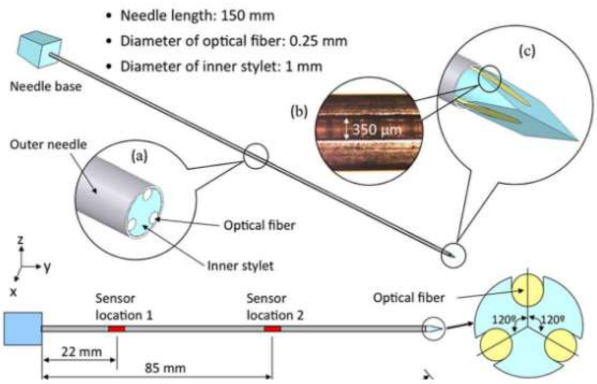

Fig. 12 Medical detection end-probe with 3D force measurement designed by Park Y et al.

In 2021, Chen Tang et al. of the Beijing University of Information Science and Technology, proposed a fiber-optic grating-based method for measuring the three-dimensional force at the end of a minimally invasive soft robot for minimally invasive surgery, as shown in Fig 13 [38]. The fiber grating is implanted into the soft robot at an interval of 120°. A least-squares linear calibration-based and Bernstein polynomial non-linear compensation-based decoupling model of the end force of the soft robot is established to study the relationship between the wavelength drift of the fiber grating center and the end 3D force of the soft robot. The results show that the repeatability of fiber grating sensing is 1.5 pm on average, the accuracy error of end force measurement in XYZ directions is less than 5% of the full range, and the residual distribution is mostly concentrated in the reliable interval, which has good repeatability.

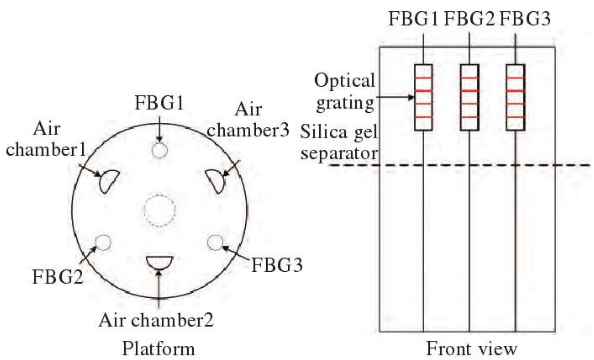

Fig. 13 A force sensing system with 3D force measurement designed by Tang Chen et al.

3.4 Force-aware Design for Minimally Invasive Surgery in the Face of Other Fields

In 2019, Bixuan Luo et al. designed and implemented a miniature axial force sensor for the ureteral flexible mirror, as shown in Fig 14 [39] , and to eliminate the cross-effects caused by force and temperature on the fiber grating sensor, the sensor was designed to achieve temperature compensation utilizing hardware compensation. After testing, the sensor's package structure was able to withstand lateral forces from -10 N to 10 N. The sensor achieved a soft mirror end-action force signal measurement with a resolution of 0.01 N and an accuracy of 0.27 N [40].

Fig. 14 Miniature uniaxial force sensor designed by Bixuan Luo et al. for flexible spectroscopy

4. Conclusion

Fiber grating components in the field of multidimensional force measurement are not easily disturbed by electromagnetic forces, have high-temperature resistance, good bio-compatibility, and small size, and are easy to integrate with the robot other significant advantages have been widely valued and recognized by researchers at home and abroad. Especially in the field of minimally invasive surgery, in recent years, the research reports of Harvard University, Johns Hopkins University, National University of Singapore, Tianjin University, Shenyang Institute of Automation of Chinese Academy of Sciences, and other famous institutions in the field of multidimensional force measurement of surgical robots have been continuously presented, showing a high degree of cross-fertilization of optical, mechanical, control, material, biological, medical and other disciplines, and these research works have significantly promoted the fiber optic force measurement of surgical robots. These research efforts have significantly advanced the technical progress of fiber optic multidimensional force measurement for surgical robots, but there is still some effort to be made before they can move toward surgical applications, not only to make a single sensing system match the surgical instruments, but both should work together to find a harmonious unity. On the other hand, out of the laboratory, there are still many problems and challenges in the application of many practical scenarios, which will be the direction of further research and development of fiber-optic grating force sensing technology.

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