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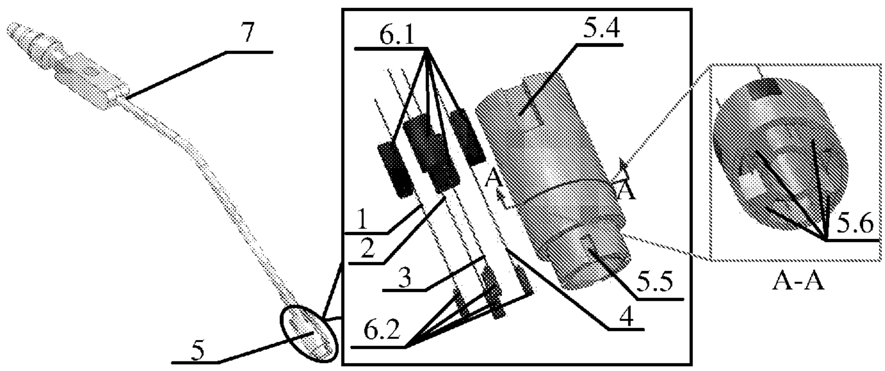

Figure 1

(57) Abstract: A fiber grating sensor for a surgical instrument includes a base body which includes a front end, a rear end and a middle part for connecting the front end and the rear end, and a plurality of optical fibers. A fiber grating is inscribed on each of the plurality of optical fibers. Each of the plurality of optical fibers is fixed to the front end and the rear end respectively so that each fiber grating can be suspended on each optical fiber. When configured in the surgical instrument with a tubular end for force detection, the fiber grating sensor may eliminate temperature coupling interferences, and meanwhile can be integrated at a distal part of a tubular catheter conveniently.

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FIBER GRATING SENSOR FOR SURGICAL INSTRUMENT

FIELD OF THE INVENTION

The present invention relates broadly to a fiber grating sensor, and more particularly but not exclusively, to a fiber grating multi-dimensional force/torque sensor for a surgical operating instrument.

BACKGROUND OF THE INVENTION

In a surgery, an aspirator is a common and important general surgical instrument. The aspirator plays a plurality of roles in the operation. For example, the aspirator is not only configured to aspirate bloody water, clean up a field of view of a surgical region, and meanwhile remove focus tissue (a tumor, necrotic tissue, a hematoma or a cyst), but also configured as a retractor and a separator. Some pieces of tissue (for example, brain tissue) are extremely delicate, but a rear end of the surgical instrument may contact with the brain tissue, and when performing the surgery in the absence of force feedback, an attending doctor is required to have rich experience and a series of subtle and careful operations.

A cardiovascular surgery also requires assistance of force feedback of a distal end of a catheter, for which purpose there are also many medical instances at present. Interventional electrocardiographic radio frequency ablation is a common minimally invasive surgery for treating arrhythmia in clinic. During the surgical procedure, the catheter is required to be punctured through the femoral artery of a patient, enters the heart through the aorta, approaches a focus point, and then releases a radio frequency current for local heating, which in turn causes coagulative necrosis of the endocardium of the focus point. Necrotic endocardium tissue cannot transmit an electrocardiosignal which is transmitted by normal tissue to return to normal, thereby restoring a normal rhythm of the heart. During the surgical procedure, an electrode at the rear end of the ablation catheter is required to maintain a large constant force contact with diseased tissue in the heart, so as to guarantee necrosis of the diseased tissue, increase the success rate of the surgery, and reduce a complication, such as postoperative myocardial perforation, pericardial tamponade, thrombosis, or the like, caused by a large force operation.

For a common cardio-cerebral vascular disease, such as a cerebral arterial disease or coronary atherosclerosis, the minimally invasive interventional surgery requires penetration of a guide wire through the arterial network and implantation of a stent from the distal end of the catheter at the focus point. The catheter may be required to pass through a blocked area, but the distal end of the catheter is not easy to control. Since the distal end is difficult to control when using the catheter, a fault tends to occur, which increases the risk of a surgical failure. If a force at the rear end of the catheter can be measured in real time, the doctor may perceive the contact force between the catheter and the tissue in real time, which facilitates a safe operation, reduces a harm to the patient, and reduces the risk of the surgical failure.

At the same time, the measurement of the force at the distal end of the catheter is crucial for a minimally invasive surgery robot to realize a force sense feedback function and a force control function of an operating system. Furthermore, these pieces of information may also be used to evaluate a skill of the doctor and provide an optimized standard for training the doctor.

Currently, for the above-mentioned needs, several technologies have been developed to perceive the contact force between the catheter and the tissue. One technology is a silicone force sensor used at a distal end of a suction tube, in which a camera or an endoscope is configured to sense a polar deformation of a silicone structure to detect traction, but such a design is difficult to be used in a miniaturized interventional neurosurgery since it leads to a complicated structure and a large volume due to an inclusion of an external vision unit. Another technology is a strain gauge-based sensing device which is widely configured for force feedback in the surgery due to a low cost, a simple structure and an easy operation. However, such a strain gauge-based sensing device tends to be damaged during disinfection and sterilization operations, and similarly, a strain gauge is also difficult to be provided in a miniaturized instrument or sensing structure.

In order to overcome the defects of these traditional force sensors, an optical fiber sensor has been adopted. Due to its small size, light weight, electromagnetic interference resistance, biocompatibility, non-toxicity and corrosion resistance, the optical fiber sensor can be integrated at a tip of the catheter of the surgical instrument to measure the contact force. For example, the optical fiber-based force sensor at the tip of the catheter can measure the force in the axial direction by detecting a change in the intensity of light reflected in a cardiac surgery, but each sensing unit is provided with two separate optical fibers to transmit and receive a light signal, which tends to result in a large-volume output end of the multi-dimensional force sensor. In addition, since the sensor has a non-hollow structure while integrated at the tip of the suction tube, the suction tube loses a suction function.

A 2-D fiber Bragg grating (FBG) force sensor based on wavelength demodulation can avoid the above-mentioned influence of a disturbance of the input light intensity. However, an FBG reflection spectrum stuck to a surface of a perception body is prone to present the risk of a chirp failure due to uneven strain on the surface of the perception body. Further, the problem of how to integrate the sensor at a distal end of the suction tube has not been solved.

SUMMARY OF THE INVENTION

Thus, there exists a need to provide an FBG-based multi-dimensional force/torque sensor for a surgical operating instrument, with an improved measurement accuracy, which may be integrated at a distal end of a tubular catheter conveniently.

In one embodiment, the present invention relates to a fiber grating sensor including a base body which includes a front end, a rear end and a middle part for connecting the front end and the rear end, and a plurality of optical fibers, wherein a fiber grating is inscribed on a distal part of each of the plurality of optical fibers, characterized in that the distal part of each of the plurality of optical fibers is fixed to the front end and the rear end respectively so that each fiber grating can be suspended on the distal part of each optical fiber.

Preferably, the plurality of optical fibers include four optical fibers, the base body is tubular, and the distal parts of the four optical fibers are arranged evenly along a circumferential direction of the base body with an angular interval of 90°.

Preferably, the base body is printed by a 3-D printer as a whole.

Preferably, the fiber grating is a fiber Bragg grating.

Preferably, the base body includes a hollow elastomer and the middle part is an annular diaphragm so that a diameter of the rear end is greater than that of the front end and each fiber grating on the distal part of each optical fiber is suspended within the rear end at the position of the rear end.

Preferably, the fiber grating sensor can detect a force in an axial direction of the base body, 2-D torques on a cross section perpendicular to the axial direction and an increment of ambient temperature.

Preferably, the hollow elastomer includes four stiffeners that are arranged evenly along a circumferential direction of the hollow elastomer to eliminate interferences of transverse forces, so that each fiber grating on the distal part of each optical fiber goes through between each adjacent two stiffeners.

Preferably, the middle part is a flexible hinge, and each fiber grating on the distal part of each optical fiber can be suspended outside the flexible hinge at the position of the flexible hinge.

Preferably, the fiber grating sensor can detect 2-D forces on a cross section perpendicular to an axial direction of the base body and an increment of ambient temperature.

In the multi-dimensional force/torque sensor according to embodiments of the present invention, each optical fiber inscribed with a separate FBG element processes a sensed signal by means of wavelength demodulation. Compared with the way of light intensity demodulation in a prior art, such a configuration can overcome the interferences caused by light intensity fluctuations effectively. The distal part of each optical fiber is mounted at two ends of the elastomer along a longitudinal direction of the elastomer with a part inscribed with the fiber grating suspended. Under this configuration, the FBG in each suspended optical fiber section may be compressed or stretched directly in the axial direction. Compared with a traditional FBG-based force sensor, the technique according to embodiments of the present invention can avoid an FBG chirp failure advantageously, thus improving the measurement accuracy.

Furthermore, information of a contact force between an instrument and tissue is fed back in real time by integrating the multi-dimensional force-torque sensor at the tubular end of the surgical instrument, which may reduce effectively the risk of an iatrogenic injury of the brain tissue caused by a mis-operation, and meanwhile improve a safety of a surgery greatly. At the same time, the surgical instrument integrating the force sensor may also evaluate and improve a skill of a doctor by monitoring the force during the operation, and provide an operation standard for training the doctor.

BRIEF DESCRIPTION OF THE DRAWINGS

The technical solution of the present invention may be better understood with accompanying drawings and the following description, in which:

Figure 1 shows a perspective view of a sensor integrated at a tubular end of a surgical instrument, an exploded view of an assembly and an A-A sectional view according to an example embodiment;

Figure 2 shows a structural sectional view of the sensor according to an example embodiment;

Figure 3 shows a side view of the sensor according to an example embodiment;

Figure 4 shows a schematic diagram of an axial deformation of an annular diaphragm of the sensor according to an example embodiment under the action of an axial force F_z;

Figure 5 shows a schematic diagram of an axial deformation of the annular diaphragm of the sensor according to an example embodiment under the action of a concentrated torque M_x (M_y);

Figure 6 shows a perspective view of a 2-D force sensor based on a flexible hinge and the fiber grating sensor according to an example embodiment;

Figure 7 shows a perspective view of a base body of the 2-D force sensor according to an example embodiment; and

Figure 8 shows a sectional view of the base body of the 2-D force sensor according to an example embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

In terms used in the present disclosure, “a distal part” refers to an end of an interventional surgical instrument and components therein, such as an optical fiber, a catheter, or the like, inserted into tissue of a patient, i.e., an end apart from an operator of the medical instrument. The “distal part” itself has a certain length and “two ends”.

First Embodiment

As shown in Figures 1 and 2, the first embodiment of the present invention provides a fiber grating triaxial force/torque sensor which has a low cost and is convenient to mount, so as to detect a contact force between a tubular end of the surgical operating instrument and the tissue in real time. A base body of the sensor is configured as a tubular hollow elastomer 5 including a rear end 5.1, an annular diaphragm 5.2 and a front end 5.3. The rear end 5.1 is integrated at a rear end of the surgical instrument 7 by interference fit to be mounted conveniently, the front end 5.3 is configured to contact with the tissue in a surgery, and the annular diaphragm 5.2 is configured to connect the rear end 5.1 with the front end 5.3 and enable a diameter of the rear end 5.1 to be greater than that of the front end 5.3. An axial force F_z in a z direction as well as torques M_x and M_y in x and y directions are obtained in real time by means of a deformation of the annular diaphragm 5.2 generated when the tubular end of the surgical instrument contacts with the tissue in a surgical operation. The elastomer 5 may be printed by a low-cost 3-D printer (for example, Stratasys Objet260 Connex3 manufactured by Stratasys Direct Manufacturing) and made of a biocompatible polymer material with high flexibility and moderate rigidity, for example, VeroClear RGD810. Furthermore, a plurality of stiffeners are evenly disposed along a circumferential direction of the elastomer. For example, four internal stiffeners 5.6 are arranged in the elastomer 5 along a circumferential direction of the elastomer with an angular interval of 90° to eliminate interferences of transverse forces. Distal parts 1, 2, 3, 4 of a plurality of optical fibers, e.g. four optical fibers, are arranged evenly on the elastomer 5 successively, e.g. with an annular angular interval of 90°. A fiber Bragg grating (FBG) element is inscribed on the distal part of each optical fiber, wherein parts of the distal part of each optical fiber on two sides of the FBG element are fixed to the rear end 5.1 and the front end 5.3 by viscose at a rear end viscose groove 5.4 and a front end viscose groove 5.5 respectively, and each fiber grating on the distal part of each optical fiber can be suspended inside the rear end 5.1 at a position of the rear end 5.1. An inner cavity 8 is formed between each two stiffeners, and furthermore, a relatively small annular cavity 9 is formed between the annular diaphragm 5.2 and tops of the four stiffeners 5.6. Thus, the four inner cavities 8 are connected by the annular cavity 9, so that they share almost the same ambient temperature. Each of the distal parts 1, 2, 3, 4 of the four optical fibers goes through the corresponding inner cavity.

During assembly, the optical fiber 1 is passed through the corresponding rear end viscose groove 5.4 and front end viscose groove 5.5 firstly, and then coated with rear end viscose 6.1 and front end viscose 6.2 at the rear end viscose groove 5.4 and front end viscose groove 5.5 respectively, so as to fix two ends of the optical fiber 1 in the rear end viscose groove 5.4 and front end viscose groove 5.5 and to ensure that the first fiber grating 1.1 of the first optical fiber 1 is suspended in the rear end 5.1. The viscose 6.1, 6.2 may be adhesives suitable for bonding the optical fiber and the elastomer, for example, AB adhesives. The optical fibers 2, 3, 4 are configured and mounted in the same way respectively, so that the second fiber grating 2.1, third fiber grating 3.1and fourth fiber grating 4.1 inscribed into the optical fibers 2, 3, 4 respectively are suspended in the rear end 5.1. Figure 3 shows a side view after the optical fibers 1, 2, 3, 4 are mounted, in which P_1, P_2, P_3 and P_4 correspond to mounting positions of the optical fibers 1, 2, 3, 4 respectively, 2r represents a diameter of a dotted circle passing through centers of the distal parts of the four optical fibers in the drawing, and $2R_1$ represents a diameter of the tubular front end 5.3. As a variant, the distal parts of the optical fibers 1, 2, 3, 4 may also be fixed at the rear end 5.1 and the front end 5.3 respectively in other suitable ways.

As shown in Figure 4, in a surgical operation, when the tubular end of the surgical instrument contacts with the tissue, the measured force F_z acts on the rear end of the sensor in the z direction, and at this point, the four fiber gratings will bear consistent axial deformations. When the concentrated torque M_x acts on the front end 5.3, as shown in Figure 5, at this point, the annular diaphragm 5.2 will be deformed, so that the fiber grating 1.1 and the fiber grating 3.1 generate same-value deformations in the z direction respectively. Since the fiber grating 2.1 and the fiber grating 4.1 are overlapped with a neutral axis of the elastomer 5, axial deformations thereof are close to zero.

To this end, according to a principle of mechanics of materials, axial stain of the fiber gratings in different states may be described as a formula (1):

$$\begin{cases} \varepsilon_{iz} = \dfrac{\Delta_z}{L} F_z & (1\text{-}1) \\ \varepsilon_{1M_x} = -\varepsilon_{3M_x} = -\dfrac{r\Delta_x}{R_1 L} M_x;\ \varepsilon_{2M_x} = \varepsilon_{4M_x} = 0 & (1\text{-}2) \\ \varepsilon_{2M_y} = -\varepsilon_{4M_y} = -\dfrac{r\Delta_y}{R_1 L} M_y;\ \varepsilon_{1M_x} = \varepsilon_{3M_x} = 0 & (1\text{-}3) \end{cases} \quad (1),$$

in which Δ_z, Δ_x and Δ_y represent the axial deformations at a middle position of the annular diaphragm in the z axis under the action of the unit axial force F_z as well as the unit torques M_x and M_y. ε_{iz} is the axial strain of the ith fiber grating under the action of F_z, and ε_{iMj} is the axial strain of the ith fiber grating under the action of M_j (j=x or y). L is a working length of the optical fiber. To this end, in conjunction with a working principle of the fiber grating, a center wavelength shift amount of the fiber grating has the following relationship with the strain and temperature:

$$\Delta\lambda_i / \lambda_i = (1-\rho_e)\varepsilon_i + (\alpha_f + \xi_f)\Delta T \quad (2),$$

in which ε_i is a sum of the axial deformations of the ith fiber grating caused by F_x and M_x/M_y. $\Delta\lambda_i$ is the wavelength shift amount of the ith fiber grating, λ_i is a center wavelength of the ith fiber grating, and the four fiber gratings configured in the sensor have the similar center wavelengths denoted as λ_0. ρ_e is an effective photoelastic effect of the optical fiber, α_f is a coefficient of thermal expansion of the optical fiber, ξ_f is a thermo-optical coefficient of the optical fiber, and ΔT is an increment of ambient temperature of a measured object. For this purpose, formula (1) is substituted into formula (2) to obtain:

$$\begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \\ \Delta\lambda_3 \\ \Delta\lambda_4 \end{bmatrix} = \lambda_0 \begin{bmatrix} \Delta_z/L & -r\Delta_x/LR_1 & 0 & \alpha_f+\xi_f \\ \Delta_z/L & 0 & -r\Delta_y/LR_1 & \alpha_f+\xi_f \\ \Delta_z/L & r\Delta_x/LR_1 & 0 & \alpha_f+\xi_f \\ \Delta_z/L & 0 & r\Delta_y/LR_1 & \alpha_f+\xi_f \end{bmatrix} \begin{bmatrix} F_z \\ M_x \\ M_y \\ \Delta T \end{bmatrix} = [S]_{4\times4} \begin{bmatrix} F_z \\ M_x \\ M_y \\ \Delta T \end{bmatrix} \qquad (3).$$

Thus, according to formula (3), the tri-axial force/torques F_z, M_x, M_y may be detected in real time from center wavelength shifts of the four fiber gratings, and the increment ΔT of the corresponding ambient temperature may be obtained.

In the present embodiment, each optical fiber inscribed with the separate FBG element processes a sensed signal by means of wavelength demodulation. Compared with the way of light intensity demodulation in a prior art, such a configuration can overcome the interferences caused by light intensity fluctuations effectively. The distal part of each optical fiber is mounted at two ends of the elastomer along a longitudinal direction of the elastomer with a part inscribed with the fiber grating suspended. Under this configuration, the FBG in each suspended optical fiber section may be compressed or stretched directly in the axial direction under the action of the force F_z and the torques (M_x, M_y). Compared with a traditional FBG-based force sensor, the present technique can avoid an FBG chirp failure advantageously and eliminate temperature coupling interferences, thus improving the measurement accuracy.

Furthermore, the detected torques M_x, M_y may also be configured to evaluate and reflect a type and a direction of the contact force between the instrument and the tissue quantitatively, and a contact surface based on the two torque components can help a doctor to obtain quantitative direction information of the contact force. In addition, the force/torque sensing way may further be applied to various types of tubular medical apparatuses, for example, an endoscope or tubular robot, so as to help the apparatuses to obtain information of the contact force and the temperature.

Second Embodiment

Figures 6 and 7 show a perspective view of a 2-D force sensor based on a flexible hinge and the fiber grating sensor according to the second embodiment of the present invention. Different from the first embodiment, the hollow elastomer in the sensor is replaced with a flexible base body 10 including a catheter connecting end 10.1, a tubular rear end 10.2, a tubular front end 10.4, a flexible hinge 10.3 and a hemispherical contact head 10.5, wherein the catheter connecting end 10.1 is connected with a distal end of the catheter in the surgical operation, and the flexible hinge 10.3 connects the rear end 10.2 with the front end 10.4. Two ends of the distal parts 1, 2, 3, 4 of a plurality of optical fibers, e.g. four optical fibers, are fixed at the rear end 10.2 and the front end 10.4 respectively. The first, second, third and fourth fiber gratings 1.1, 2.1, 3.1, 4.1 are inscribed on the optical fibers 1, 2, 3, 4 respectively, and the fiber grating on the distal part of each optical fiber can be suspended outside the flexible hinge 10.3 at a position of the flexible hinge 10.3.

As shown in Figure 8, the tubular rear end 10.2 and the tubular front end 10.3 have the same diameter d. The flexible hinge 10.3 has a diameter less than d, and has chamfers with a diameter R at joints with the rear end 10.2 and the front end 10.3, so that the fiber Gragg gratings 1.1, 2.1, 3.1, 4.1 suspended outside the flexible hinge 10.3 are at a distance h from the flexible hinge 10.3, and the optical fiber has a working length L. Those skilled in the art may design values of the above-mentioned diameter d, the diameter R, the distance h and the length L according to a size of a tube of the connected instrument and the accuracy of the force required to be measured.

Similar to the first embodiment, the flexible base body 10 may also be printed by the low-cost 3-D printer and made of the biocompatible polymer material with the moderate flexibility. During assembly, the two ends of the optical fiber 1 are fixed at the front end 10.4 and the rear end 10.2 respectively with viscose 1.2, 1.3, each fiber grating at the distal part of each optical fiber can be suspended outside the flexible hinge 10.3 at the position of the flexible hinge, and then the optical fibers 2, 3, 4 are fixed on the flexible base body 5 successively in the same way.

In conjunction with the working principle of the fiber Gragg grating, when the sensor is subjected to the forces in the x and y directions, the first and third fiber gratings 1.1, 3.1 decouple the force in the x direction, and the second and fourth fiber gratings 2.1, 4.1 decouple the force in the y direction. Under the action of the force in the x direction, the center wavelength shift amounts of the first and third fiber gratings have the following relationship with the strain:

$$\begin{cases} \dfrac{\Delta\lambda_1}{\lambda_1} = (1-\rho_e)\dfrac{\delta_x}{L} + (\alpha_f + \xi_f)\Delta T \\ \dfrac{\Delta\lambda_3}{\lambda_3} = (1-\rho_e)\dfrac{-\delta_x}{L} + (\alpha_f + \xi_f)\Delta T \end{cases} \qquad (4),$$

in which δ_x is the axial deformation of the corresponding fiber grating caused by F_x. $\Delta\lambda_i$ is the wavelength shift amount of the ith fiber grating, λ_i is the center wavelength of the ith fiber grating, and the four fiber gratings configured in the sensor have the similar center wavelengths denoted as λ_0. ρ_e is the effective photoelastic effect of the optical fiber, α_f is the coefficient of thermal expansion of the optical fiber, ξ_f is the thermo-optical coefficient of the optical fiber, and ΔT is the increment of the ambient temperature of the measured object.

Two formulas in formula (4) are subtracted and collated into:

$$\frac{\Delta\lambda_1}{\lambda_1} - \frac{\Delta\lambda_3}{\lambda_3} = (1-\rho_e)\frac{2\delta_x}{L} \qquad (5).$$

Similarly, for the second and fourth fiber gratings 2.1, 4.1, detection of the force in the y direction may be implemented according to the formula (4) and denoted as:

$$\frac{\Delta\lambda_2}{\lambda_2} - \frac{\Delta\lambda_4}{\lambda_4} = (1-\rho_e)\frac{2\delta_y}{L} \qquad (6),$$

in which δ_y is the axial deformation of the corresponding fiber grating caused by F_y. Thus, δ_x and δ_y in the x and y directions may be obtained according to corresponding wavelength shift differences $\Delta\lambda_i$ of the four fiber gratings in formulas (5) and (6), and then the forces F_x and F_y subjected by the 2-D force sensor in the x and y directions may be obtained according to the following formula (7).

$$\begin{Bmatrix} \delta_x \\ \delta_y \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} \qquad (7),$$

in which $\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$ represents a flexibility matrix of the flexible base body 5 in the x and y directions. Then, the increment ΔT of the ambient temperature may be decoupled by substituting the calculated F_x and F_y into formula (4).

Similarly, in the present embodiment, each optical fiber inscribed with the separate FBG element processes the sensed signal by means of wavelength demodulation. Compared with the way of light intensity demodulation in the prior art, such a configuration can overcome the interferences caused by light intensity fluctuations effectively. The distal part of each optical fiber is mounted at the two ends of the elastomer along the longitudinal direction of the flexible base body in a state of suspension at the position of the fiber grating, and the forces F_x, F_y in the x and y directions as well as the increment ΔT of the ambient temperature may be decoupled in real time by the deformations of the flexible base body in the x and y directions, which eliminates the temperature coupling interferences, thus improving the measurement accuracy.

Such a force/torque sensing way may further be applied to various types of tubular medical apparatuses, for example, the endoscope or tubular robot, so as to help the apparatuses to obtain the information of the contact force and the temperature.

Although the present invention has been described above with reference to the embodiments of the fiber grating sensor for the surgical instrument, certainly, it is conceivable that those skilled in the art can derive many variations, and thus, the variations easily conceived by those skilled in the art are recognized as a part of present invention. The scope of the present invention is defined in the attached claims.

CLAIMS

1. A fiber grating sensor comprising a base body, which comprises a front end, a rear end and a middle part for connecting the front end and the rear end, and a plurality of optical fibers, wherein a fiber grating is inscribed on a distal part of each of the plurality of optical fibers, characterized in that the distal part of each of the plurality of optical fibers is fixed to the front end and the rear end respectively so that each fiber grating can be suspended on the distal part of each optical fiber.

2. The fiber grating sensor according to claim 1, wherein the plurality of optical fibers comprise four optical fibers, the base body is tubular, and the distal parts of the four optical fibers are arranged evenly along a circumferential direction of the base body with an angular interval of 90°.

3. The fiber grating sensor according to claim 1, wherein the base body is printed by a 3-D printer as a whole.

4. The fiber grating sensor according to claim 1, wherein the fiber grating is a fiber Bragg grating.

5. The fiber grating sensor according to any of claims 1 to 4, wherein the base body comprises a hollow elastomer and the middle part is an annular diaphragm so that a diameter of the rear end is greater than that of the front end and each fiber grating on the distal part of each optical fiber is suspended within the rear end at the position of the rear end.

6. The fiber grating sensor according to claim 5, wherein the fiber grating sensor is configured to detect a force in an axial direction of the base body, 2-D torques on a cross section perpendicular to the axial direction and an increment of ambient temperature.

7. The fiber grating sensor according to claim 6, wherein the hollow elastomer comprises four stiffeners that are arranged evenly along a circumferential direction of the hollow elastomer to eliminate interferences of transverse forces, so that each fiber grating on the distal part of each optical fiber goes through between each adjacent two stiffeners.

8. The fiber grating sensor according to any of claims 1 to 4, wherein the middle part is a flexible hinge, and each fiber grating on the distal part of each optical fiber can be suspended outside the flexible hinge at the position of the flexible hinge.

9. The fiber grating sensor according to claim 8, wherein the fiber grating sensor is configured to detect 2-D forces on a cross section perpendicular to an axial direction of the base body and an increment of ambient temperature.

10. The fiber grating sensor according to any of claims 1 to 4, wherein the fiber grating sensor can be mounted at a tubular end of a surgical operating instrument.

11. A method for sensing multi-dimensional forces or torques of an instrument having a tubular end, the method comprising:

(1) providing a fiber grating sensor according to any of claims 1 to 10;

(2) connecting the fiber grating sensor to the tubular end of the instrument;

(3) measuring a center wavelength shift amount of the fiber grating on the distal part of each of the plurality of optical fibers when the front end of the fiber grating sensor contacts with a measured object; and

(4) calculating the multi-dimensional forces or torques of the tubular end based on the measured center wavelength shift amount.

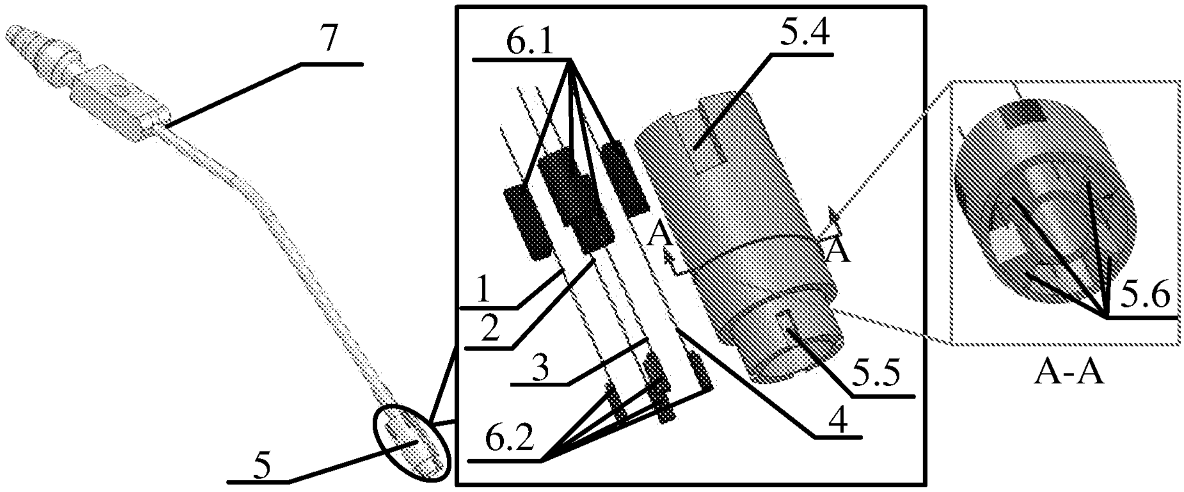

Figure 1

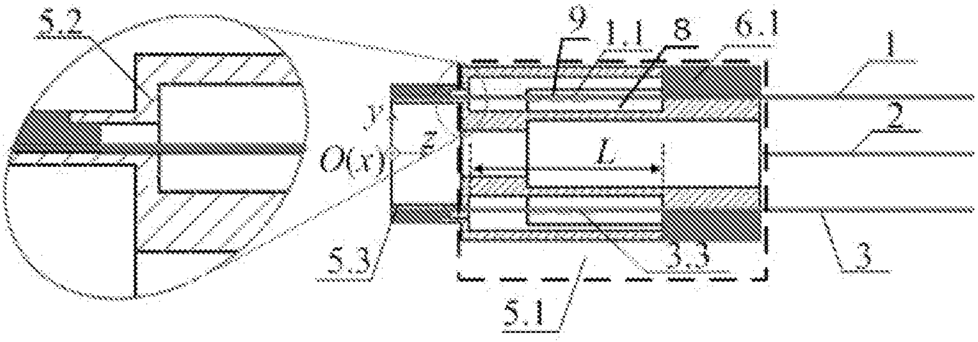

Figure 2

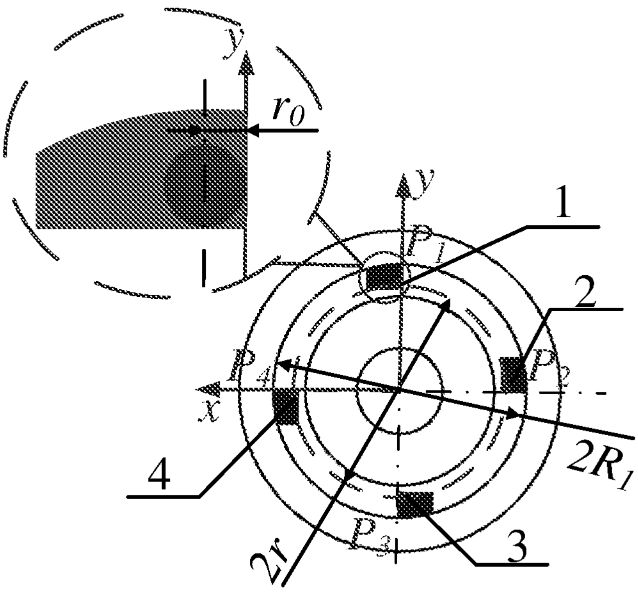

Figure 3

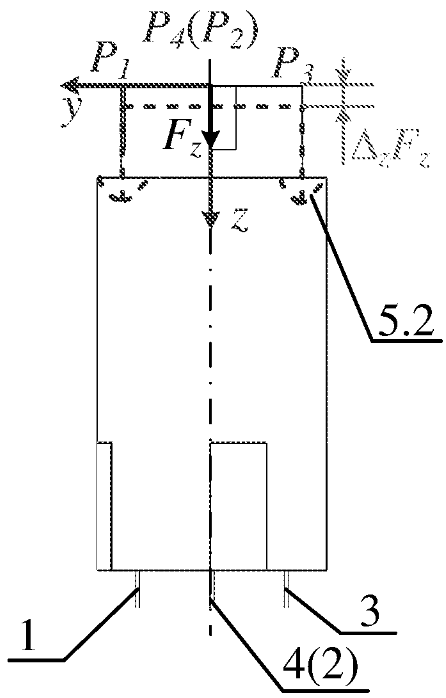

Figure 4

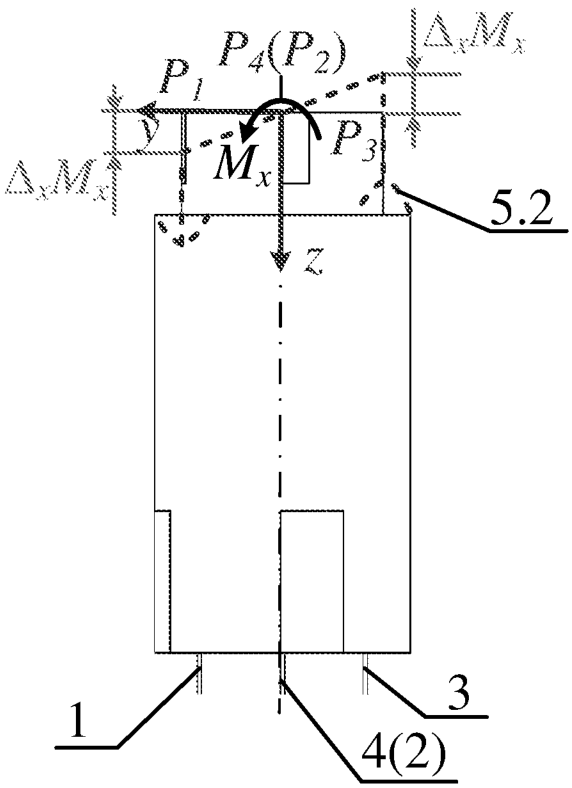

Figure 5

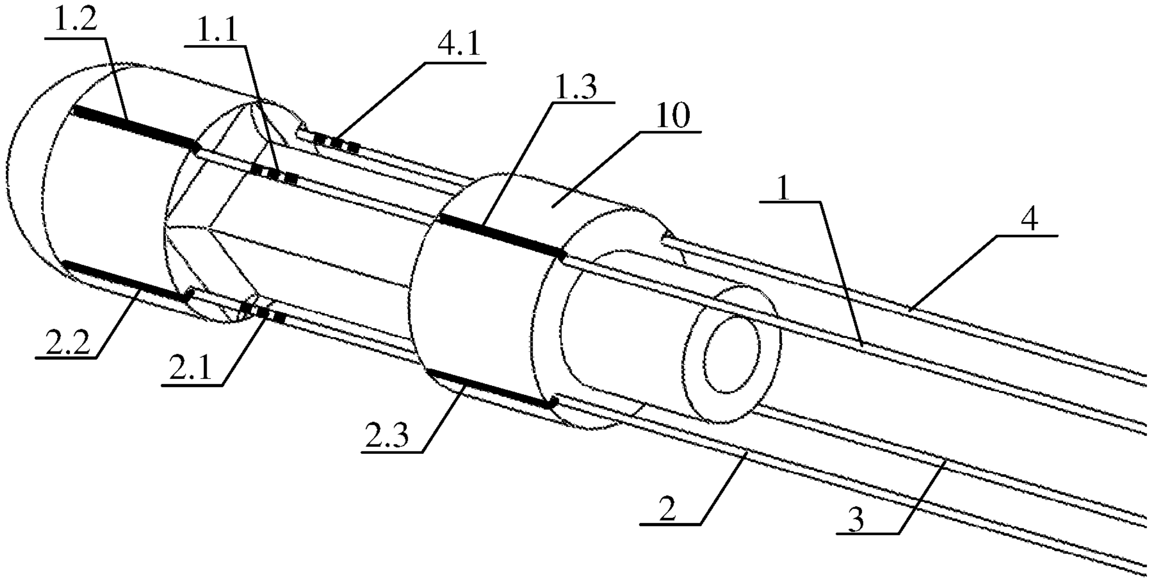

Figure 6

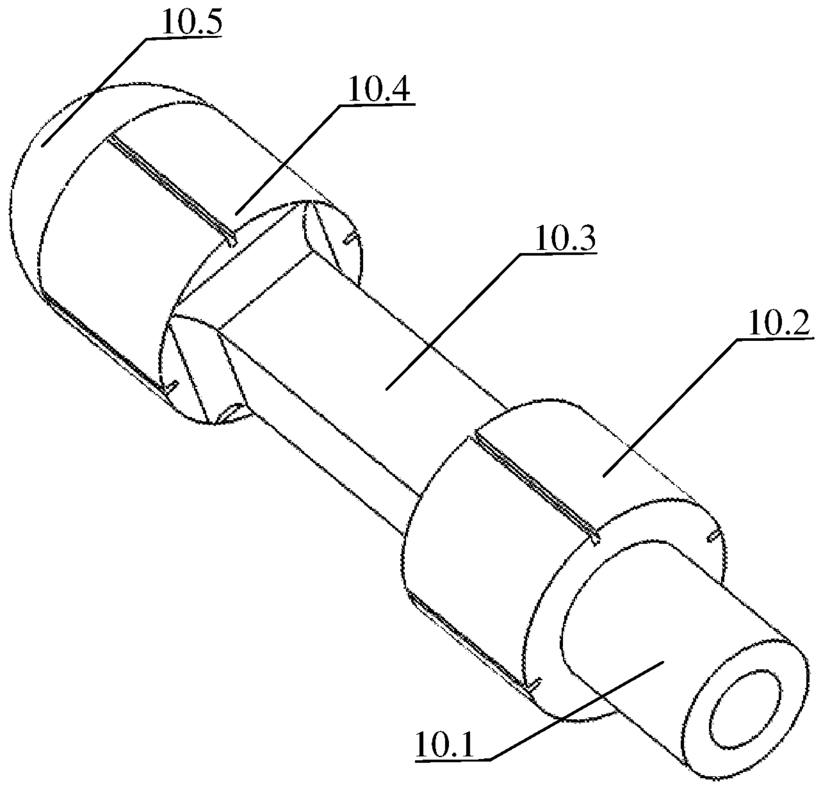

Figure 7

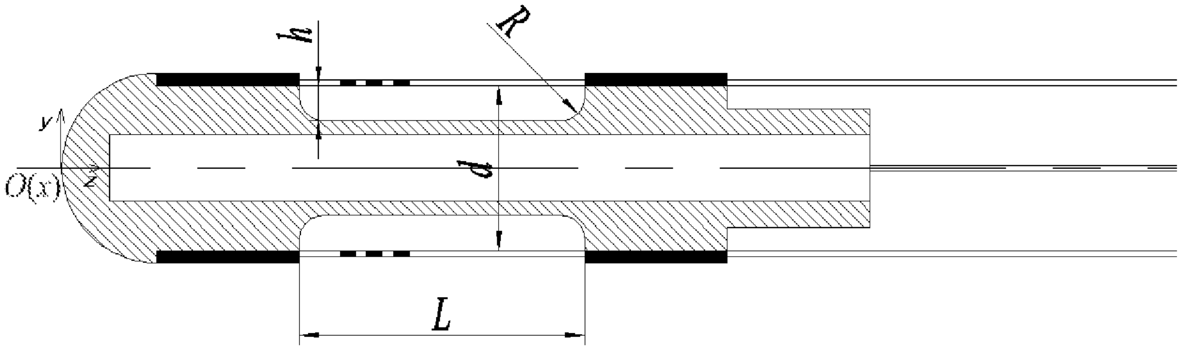

Figure 8

INTERNATIONAL SEARCH REPORT

International application No. **PCT/SG2020/050119**

A. CLASSIFICATION OF SUBJECT MATTER

See Supplemental Box

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01L, G01D, A61B, G01K, G01B, G02B, B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT/IEEE Xplore/CNKI: optical fiber, 光纤, 光导纤维, 光学纤维, fiber (optic, optical) grating, 光纤光栅, fiber Bragg grating, FBG, 光纤布拉格光栅, 布拉格光纤光栅, suspend, suspension, 悬浮, 悬挂, bridge, bridging, 横跨, 桥接, (axial, longitudinal) force, 轴向力, 轴力, 纵向力, torque, moment, 扭矩, 转矩, temperature, 温度, 气温, surgical, surgery, 外科, 手术, catheter, 导管, suction tube, 吸管, center (central) wavelength, 中心波长, and other relevant terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	SHI C. ET AL., A Millinewton Resolution Fiber Bragg Grating-Based Catheter Two-Dimensional Distal Force Sensor for Cardiac Catheterization. *IEEE SENSORS JOURNAL*, 4 December 2017, Vol. 18, No. 4, pages 1539 - 1546 [Retrieved on 2020-06-09] <DOI: 10.1109/JSEN.2017.2779153> Whole document	1-4, 8-11 5-7
X	LI T. ET AL., Three-Dimensional Catheter Distal Force Sensing for Cardiac Ablation Based on Fiber Bragg Grating. *IEEE/ASME Transactions on Mechatronics* , 28 August 2018, Vol. 23, No. 5, pages 2316 - 2327 [Retrieved on 2020-06-09] <DOI: 10.1109/TMECH.2018.2867472> Whole document	1-4, 8-11
X	WO 2018/163622 A1 (SONY CORPORATION) 13 September 2018 & US 2020/0008894 A1 Whole document, especially Paragraphs [0084]-[0091] and [0100]-[0114]; Figures 5-6, 8 and 10 of the patent family member	1-2, 4, 10-11

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

*Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09/06/2020 *(day/month/year)*	*10/06/2020* *(day/month/year)*

Name and mailing address of the ISA/SG	Authorized officer
IPOS INTELLECTUAL PROPERTY OFFICE OF SINGAPORE **Intellectual Property Office of Singapore** 1 Paya Lebar Link, #11-03 PLQ 1, Paya Lebar Quarter Singapore 408533 Email: pct@ipos.gov.sg	Wang Jiayi (Dr) IPOS Customer Service Tel. No.: (+65) 6339 8616

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2020/050119

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016/0022373 A1 (VALSAMIS J.-B. ET AL.) 28 January 2016 Whole document, especially Paragraphs [0059]-[0062] and [0070]-[0075]; Figures 1, 3 and 9	1, 4, 8, 10-11
X	CN 108663110 A (WUHAN UNIVERSITY OF TECHNOLOGY) 16 October 2018 Whole document, especially Paragraphs [0018]-[0060]; Figures 1-3 of the original non-English language document (a machine translation is enclosed **only** for your reference)	1, 4, 8
A	SONG H. ET AL., Development of FBG sensor system for Force-feedback in Minimally Invasive Robotic Surgery. *2011 Fifth International Conference on Sensing Technology*, 1 December 2011, pages 16-20 [Retrieved on 2020-06-09] <DOI: 10.1109/ICSENST.2011.6136956> Whole document	

Supplemental Box
(Classification of Subject Matter)

Int. Cl.

G01L 1/24 (2006.01)

G01D 5/353 (2006.01)

A61B 90/00 (2016.01)

G01K 11/32 (2006.01)

G01D 5/26 (2006.01)

A61M 1/00 (2006.01)

A61M 25/00 (2006.01)

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2018/163622 A1	13/09/2018	US 2020/0008894 A1 DE 112018001260 T5	09/01/2020 19/12/2019
US 2016/0022373 A1	28/01/2016	CN 104244808 A EP 2833781 A1 WO 2013/150019 A1	24/12/2014 11/02/2015 10/10/2013
CN 108663110 A	16/10/2018	NONE	