PART II

Creation and Integration of Multiple Sensing Modalities

6

Optical Force and Torque Sensor for Flexible Robotic Manipulators

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Abstract

Robot-assisted Minimally Invasive Surgery (RMIS) typically uses a master–slave surgical configuration allowing surgeons to carry out surgical tasks remotely. In typical RMIS scenarios, the surgeons use visual information provided by a three-dimensional (3D) camera to interact with patients' internal body organs via haptic interface devices. However, visual occlusion is one of the major drawbacks of the surgical approaches relying on visual information indicating the need for physical or virtual presence of the sense of touch during the operation. A multiaxis force sensor was developed to be integrated into the structure of surgical robots to enable continuous monitoring of external forces applied to the robot's body, thereby assisting the surgeon in undertaking precise control actions using more accurate sensory information. In this chapter, we report on the STIFF-FLOP approach in design and implementation of a three-axis force sensor based on fiber optics. The sensing system has a hollow geometry, is immune to electrical noises and

low cost, and hence, is suitable for integration into a wide range of medical and industrial manipulation devices.

6.1 Introduction

Control of articulated surgical instruments and robots [1], e.g., the STIFF-FLOP, requires precise sensing of the robots' shape and end-effector position [2–4], as well as applied external forces [5–9]. In general, the 3D camera embedded in the surgical instrument can provide visual feedback during surgery [1], but it does not completely eliminate the need for haptic perception attained by feeling the touch. The sensation of the patient's organs provides valuable information to the surgeon such as the consistency and health of the tissue and organs. In addition, in the robot-assisted surgery, the sense of touch could assist the surgeon in controlling the amount of the exerted force on the delicate tissue, in order to prevent any damage to the tissue. In summary,

- Haptic feedback is important since it can enhance the patient's safety and prevent dangerous after-effects following the surgical procedure.
- Additional information retrieved from further sensor modalities may assist the surgeon when using robots for surgical procedures.

In the EU STIFF-FLOP project, it was essential to integrate force and torque sensors into the proposed robots in order to provide sensory feedback on the external forces. Here we presented the development of three-axis force and torque sensors based on a fiber optic Light Intensity Modulation (LIM) approach [5–10]. The sensing mechanism enables embedded measurement of force and torque values via low-power low-noise electrical and optical components encased into a flexible structure that can safely interact with human body.

The sensor makes use of optoelectronics and fiber optic technologies. It was designed, calibrated, tested, and fully integrated within the soft continuum STIFF-FLOP robot arm. The design of the sensor was optimized in order to work in a range of values of the applied forces, which are comparable with typical values in surgical scenarios, according to medical requirement and specifications provided by medical specialists involved in the project. Although we report only on the integration of the two sensor systems into the STIFF-FLOP arm, the design, geometry, and structure of the sensor allow integration into a wider range of robotic manipulation systems.

6.2 Materials and Methods

6.2.1 Sensor Design Rational

The proposed F/T sensing systems should satisfy a number of key technological and medical requirements to be applicable in medical and surgical procedures. These include its ability in multiaxial measurement of the force and torque values ($\mathrm{F_{range}}$: ±5.0 [N]; $\mathrm{T_{range}}$: ±3.5 N*cm, respectively), consistent operation with low hysteresis, satisfying manipulator's size restrictions (maximum sensor's external diameter is 32 mm), and compatibility with intraoperative Magnetic Resonance Imaging (MRI), and similar diagnosis techniques which can be used during the surgical procedure. Considering the above restrictions and the technical capacity required for a surgical robot, the STIFF-FLOP F/T sensors were developed with the following specifications:

- The sensor should be embedded between two mutually tangent segments of the STIFF-FLOP manipulator.
- It should have a ring-like hollow structure to allow for actuation pipes and electrical wires to be passed through the arm.
- The device should be capable of simultaneous measurement of three components of external forces and moments, namely, the longitudinal force (F_z) and the two torque components (M_x, and M_y – see Figure 6.3).

Such measurement abilities are important for estimating the external forces applied on the arm. Note that a two-segment STIFF-FLOP arm can undergo two three-directional bending in each segment that can also be combined with elongation of the arm.

6.2.2 Sensor Configurations

The three-axis force sensing can be conceived by adopting two classes of light intensity-based approaches: optoelectronic and optical fiber-based techniques. These technologies allow compact design and modular integration between successive segments of the STIFF-FLOP arm and reduce concerns on possible interferences with intraoperative diagnosis techniques.

In the first approach, three optoelectronic sensors, model QRE1113 (Fairchild Semiconductor Corp., USA), were used in combination with three reflectors, i.e., the mirrors (Figures 6.1 and 6.2a); in the second approach, three pairs of optical fibers were employed, and again, in combination with three reflecting surfaces (Figures 6.1 and 6.2b). Those sensing elements are integrated into a flexible ring-like structure made from ABS plastic

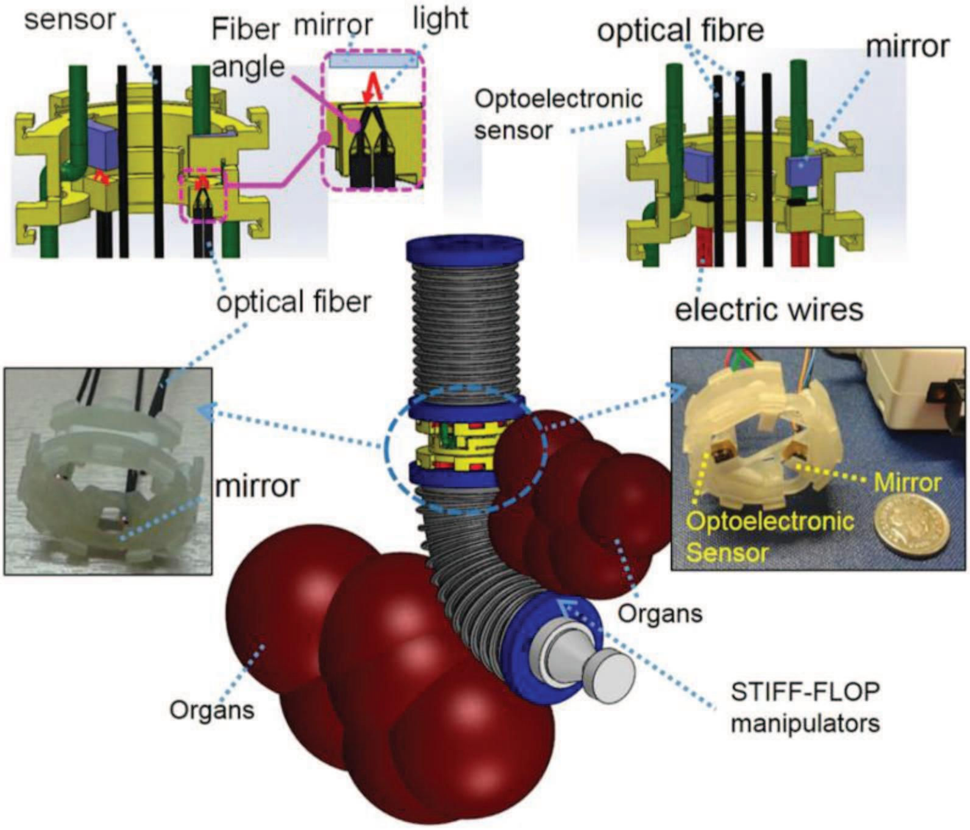

Figure 6.1 Force and torque sensors integrated into the STIFF-FLOP soft manipulator: fiber optic and optoelectronic technologies are shown on the left and right panels, respectively [5–9].

(copolymer of acrylonitrile, butadiene, and styrene) fabricated via a Projet$^{\mathrm{TM}}$ HD 3000 3D prototyping machine (3D Systems, Inc., USA) [5–9].

The optoelectronic type sensor consists of light-emitting diodes (LEDs) and phototransistors for emitting and receiving light, respectively (Figure 6.2a). The fiber optic type uses a pair of the two optical fibers connected to FS-N11MN fiber optic sensors (Keyence$^{\mathrm{TM}}$, Japan), which is a similar LED-phototransistor arrangement integrated into a commercial product (Figure 6.2b).

In both cases, the three flexible cantilever beams were used as LIM mechanism to create the displacement of the element: they are equally distributed with an angular spacing of 120° (between any two) in the periphery of the sensor structure (Figures 6.1 and 6.3). The displacements of these cantilevers occur as soon as the sensor is stressed by a longitudinal load or lateral torques: the arrangement allows the measurements of the force component F_z and the two moment components, M_x and M_y.

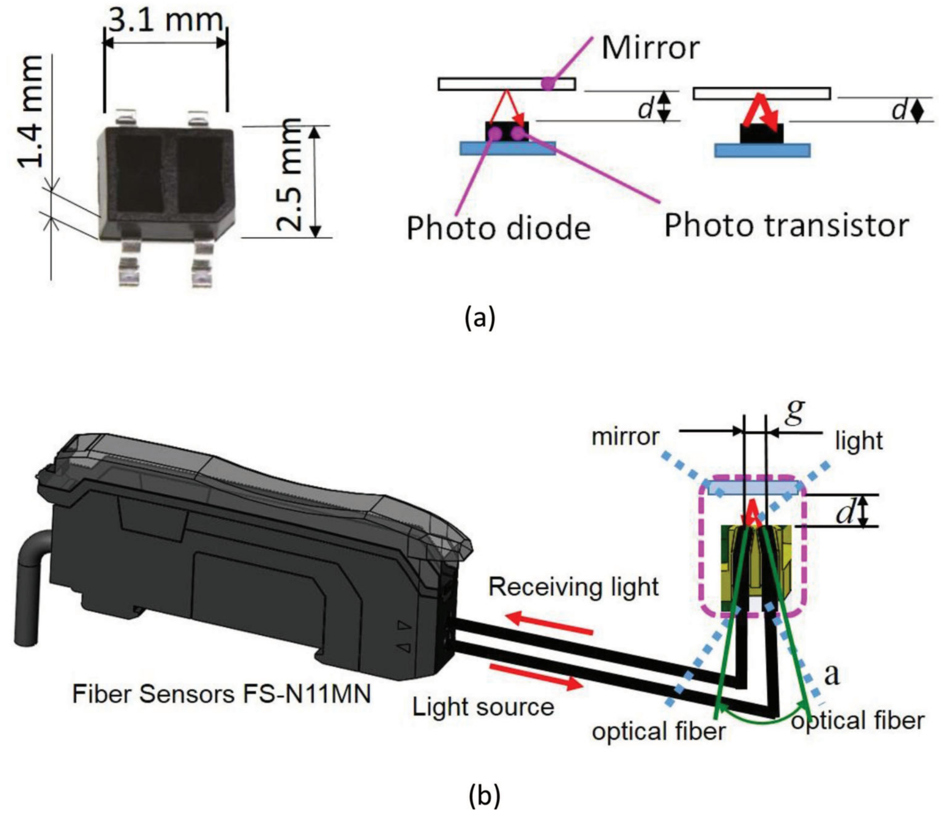

Figure 6.2 The two sensing approaches: the optoelectronic and fiber optic-based F/T sensors on the top (a) and bottom (b) panels, respectively [5–9].

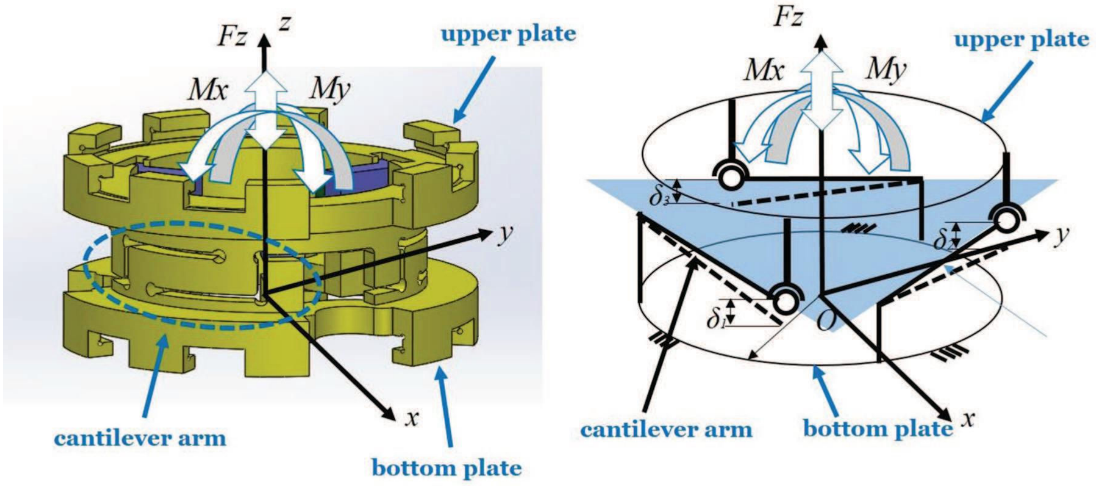

Figure 6.3 The F/T sensing principle based on three equally spaced flexible cantilever beams [5–9].

In the optoelectronic type sensor case, the light emitted from the LED is reflected by the mirror. The reflected light is transmitted to the phototransistor which can convert light intensity to voltage values. In the same way,

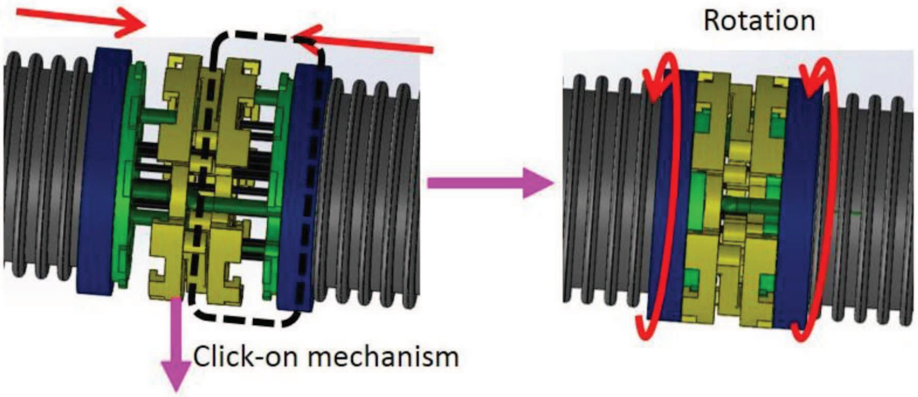

Figure 6.4 The integration into the STIFF-FLOP arm. The design allows insertion and removal of the sensor via a simple click-on mechanism [5–9].

in the fiber optic type case, emitting light and receiving light are transmitted via two fibers using KEYENCE fiber optic sensors (FS-N11MN) (Figure 6.2). The closer the distance between the reflector and the optoelectronic sensor or the distal end of the two fibers is, the higher is the amount of received light and its respective sensor output voltage. The experimental results show the reflected light intensity (converted to voltage values) changes linearly with respect to the distance changes between the optoelectronic sensor (or a pair of fibers) and the reflector [5–9].

It is worth noting that as some amounts of external force F_z and moments M_x and M_y are applied to the upper plate, the three associated cantilever beams are deflected. The three corresponding photo-interrupters, or three pairs of the optical fibers, measure the resultant cantilever beam deflections (δ_1, δ_2, and δ_3) between the upper and bottom plates of the sensor (Figure 6.3). From the three deflections, the external force F_z and moments M_x and M_y can be inferred by multiplying a calibration matrix [5–9].

In order to integrate the force sensor to the structure of the STIFF-FLOP manipulator, a locking and unlocking mechanism has also been integrated within the sensor design (Figure 6.4). Such a mechanism allows the integration of multiple sensors in between multiple modules of the robots.

6.3 Results and Discussion

In order to evaluate and test the performance of two types of developed sensors, external known forces and moments have been applied to the sensors using a custom characterization system [5, 8], in both optoelectronic and fiber optic configurations. The errors between the real values of the loads and the estimated ones using proposed sensors are shown in Tables 6.1 and 6.2.

Table 6.1 Sensor error property – optoeletronic technology

Force/Moment	Range	Maximum Error	Percentage Error [%]
F_z	±5.0 [N]	0.65 [N]	6.5
M_x	±3.5 [N.cm]	0.71 [N.cm]	10
M_y	±3.5 [N.cm]	0.45 [N.cm]	6.4

Table 6.2 Sensor error property – fiber optic technology

Force/Moment	Range	Maximum Error	Percentage Error [%]
F_z	± 3.0 [N]	0.32 [N]	10.7
M_x	±3.15 [N.cm]	0.38 [N.cm]	12.2
M_y	±3.15 [N.cm]	0.59 [N.cm]	18.2

The difference in the maximum error values for the two types of sensors is mainly due to different calibrations' complexities associated with the optoelectronic sensor (QRE1113) and the fiber force convertor (FS-N11MN). The optoelectronic sensor performance and its response can be tuned by changing d (the distance reported in Figure 6.2a), whereas the fiber optic sensor can be optimized by changing three different parameters g, a, and d (Figure 6.2b). Due to these inherent degrees of freedom of the mechanical design, each sensor prototype presents different values of these parameters and therefore requires its own specific calibration [5–9].

Both the optoelectronics and the fiber optic-based techniques have their advantages and drawbacks and, depending on the surgical application and required level of miniaturization within the surgical tool, they can be preferred one each other. One of the main advantages of the optoelectronic solution is its straightforward integration within the sensor structure and, consequently, into the robot. In case of the arm being damaged, the force/torque sensor can be removed and easily reinstalled again, and typically the calibration procedure does not need to be performed again. The main advantage of the fiber optic approach is the MRI compatibility and immunity from magnetic and electrical disturbances. In contrast, once the optical fiber is removed and reattached to the FS-N11MN convertor, typically, a recalibration of the sensor is required.

6.4 Conclusions

A novel force/torque sensor based on optoelectronic and fiber optic technologies for robotic and MIS has been presented. The sensor is particularly suited for integration into the articulated manipulation devices requiring pipes or tendons passing through the inner part of the sensor. The arm's proximal and distal segments can be equally connected to the base electrically and pneumatically, thanks to the sensor's hollow structure.

The results of experiments show maximum errors of around 18% and 6% in estimating external forces using fiber optics and optoelectronic configurations, respectively. Due to the variability of the geometry of the sensor prototype, the fiber optic configuration presents a quite large percentage error, which may be strongly reduced by standardizing the position and orientation of the fibers within the sensor framework. The proposed system can help in enhancing the haptic feedback in robot-assisted surgical procedures and palpation devices. Improvements on the sensor manufacturing process, material, and structure should be investigated to reduce the error and hysteresis, and enhance the sensor linearity.

Since the STIFF-FLOP project has ended, the team has been developing similar technologies for tactile and force/torque sensing for applications such as palpation tasks, automatic localization of tumors, flexible manipulators, and robotic hand fingertips for dexterous manipulation and grasping of objects [11–16].

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