A Continuum Body Force Sensor Designed for Flexible Surgical Robotics Devices

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Abstract—This paper presents a novel three-axis force sensor based on optical photo interrupters and integrated with the robot arm STIFF-FLOP (STIFFness controllable Flexible and Learnable Manipulator for Surgical Operations) to measure external interacting forces and torques. The ring-shape bio-compatible sensor presented here embeds the distributed actuation and sensing system of the STIFF-FLOP manipulator and is applicable to the geometry of its structure as well to the structure of any other similar soft robotic manipulator. Design and calibration procedures of the device are introduced: experimental results allow defining a stiffness sensor matrix for real-time estimation of force and torque components and confirm the usefulness of the proposed optical sensing approach.

I. INTRODUCTION

During surgical operation, robotic technology can provide valuable assistance for surgical procedures. For example, the da Vinci Surgical System (http://www.davincisurgery.com/) is a popular surgical robot for MIS (Minimally Invasive Surgery). The robot arm of the da Vinci has multiple degrees of freedom (DoF), which makes it easier to carry out surgical operations in a restricted environment. The 3D camera of the da Vinci provides enlarged detail visual information on the surgical site. However, its robot arm has the following shortcomings: 1) the small workspace of its robot arm is constrained by mechanical rigid links; and 2) information describing the interaction between the robot's arms and the patient's organs is not provided during a surgical procedure.

In order to overcome the shortcomings of conventional medical devices, as well as those of surgical robots—particularly of those that are composed of rigid links—the scientific community has started developing a new class of flexible manipulators. In 2009, Simaan et al., Alexander et al., and Taylor et al. presented dexterous, flexible snake-like manipulators that can provide relatively high dexterity and mobility in narrow anatomical areas not easily accessible by traditional robotic instruments [1-3]. Rucker et al. developed active cannula manipulators, which are a new class of thin, dexterous and continuum robots, capable of accessing narrow openings, such as the throat and lung [4]. More recently, Cheng et al., Jiang et al., and Breedveld et al. developed flexible manipulators, which can even change their stiffness and are capable of dexterous precise motion control by cables [5-7]. Nevertheless, in most of these surgical robotic devices the incorporation of sensors able to provide information about the effective pose of the robot and the physical interactions with the surrounding environment has been neglected.

For these reasons, the EU-funded project STIFF-FLOP was proposed in 2012 [8]. The STIFF-FLOP arm (Figure 1) is a soft robotic arm which can squeeze through standard Trocar ports and can then be controlled, achieving omni-elongation and bending of the arm by using air pressure for actuation. Integrated sensors are used for perception of mechanical interaction with the environment and providing feedback. An important aspect of this sensor system is its capability to measure the force and torque information through integrated

Figure 1. Overview of the STIFF-FLOP manipulator and three axis force sensor based on photo interrupters

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takes advantage of the use of optoelectronic components (Figure 2). Thus, it is immune to electromagnetic fields, has low power consumption, low-level noise and no need for any electronic filtering [12].

In this paper, we focus on the development of a multi-DoF force sensor for the STIFF-FLOP manipulator and show how to design, calibrate, and calculate a stiffness matrix by considering integration of the sensor with its manipulator.

II. METHODS

A. Design Concept

The design concept of the multi-axial force sensor should satisfy several conditions, which are as follows:

1) The sensor device has to serve as a medium between mutually tangent segments of the STIFF-FLOP manipulator and, hence, should have a ring-like structure to allow pipes for fluidic chambers to pass through proximal segments and reach distal ones.

2) The sensor should be capable of measuring at least three components of external force and moment, namely the longitudinal force, $F_z$, and the two torques, $M_x$ and $M_y$ (Figure 3). Note that the STIFF-FLOP manipulator has 3 DoF, including two omni-directional bending motions and one elongation motion.

B. Configuration of Three-Axis Force Sensor

The three-axis force sensor contains three photo interrupters (model SG-105 from KODENSHI CORP.) which are coupled with three mirrors made of write-reflective plastic and a flexible ring-like structure with two plates of ABS plastic (a copolymer of Acrylonitrile, Butadiene, and Styrene) which is designed with a 3D rapid prototyping machine (Figs. 2 and 3). The structure design is based on three flexible cantilever beams measuring the force component $F_z$ (+/- 5N) and two moment components, $M_x$ (+/- 3.5 Ncm) and $M_y$ (+/- 3.5 Ncm).

The photo interrupter consists of a photo diode and a phototransistor, emitting and receiving light, respectively. The amount of light emitted from the photodiode is reflected by the mirror and is received by the photo transistor. The closer the distance between the mirror and the photo interrupter is, the higher the intensity of the reflected light that the phototransistor receives [13]. The amount of reflected light is proportional to the output voltage of the photo interrupter. From the output voltage of the photo interrupter, the distance between the mirror and the photo interrupter can be measured, as shown in Fig. 2 (bottom panels). When an external force $F_z$ and moments $M_x$ and $M_y$ are applied to the upper plate, the three associated cantilever arms are deflected. The three corresponding photo interrupters measure the resultant cantilever arm deflections ($\delta_1$, $\delta_2$, and $\delta_3$) between the upper and bottom plates of the sensor (Fig. 3). In order to anchor the force sensor to the structure of the STIFF-FLOP manipulator, a clocking mechanism is also integrated in the sensor design (Fig. 4). The hollow structure of the whole design and clocking mechanism allows the conveyance of
optical fibers, electrical wires and air tubes between the different segments of the manipulator with a stable connection of the sensor in between.

### III. SENSOR CALIBRATION

#### A. Setup for Calibration Experiments

In order to use the sensor, a calibration procedure is required. A proper calibration should convert the output voltage of the three photo interrupters into the effective values of the force and torques applied to the sensor. To this aim, a calibration device has been designed, and a stiffness matrix has been calculated, as described below.

1) Calibration device

The device aims at calibrating the normal force $F_z$ and the two moments $M_x$ and $M_y$. It consists of a sensor base where the three-axis sensor and the static loads are mounted (Fig. 5).

#### Calculation of stiffness matrix by multiple linear regression

The calibration data is used to generate a 3x3 calibration or stiffness matrix, which converts the three output voltages to three physical values of force and torque. Therefore the matrix can be later on multiplied by any three-element voltage vector (column)—see Eq. (1) and (2), below—to obtain the sensor output.

Multiple Linear Regression (MLR) finds the relationship between two or more independent variables and a dependent variable by fitting a linear equation to the observed data. In
Finally, we have validated the sensor range through the experimental measurements.

In future work, sensor characteristics such as error, nonlinearity, crosstalk, repeatability, and hysteresis will be evaluated and improved. Additionally, the force sensor will be integrated within the STIFF-FLOP manipulator to measure external force and momentum components in experimental surgical scenarios. Since the hysteresis level of ABS plastic is likely consequential, metallic components such as titanium or aluminium may be used in future versions of the sensor.

### REFERENCES


