Modular integration of a 3 DoF F/T sensor for robotic manipulators

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***Abstract*— Robot assisted surgery and minimally invasive robotic surgery inherently entail that the hands of the surgeon indirectly interact with the patient tissues and organs even if the operator is out of the affected body. Hence, transferring sensor information from the inside of the patient to the outside of the surgeon may certainly improve the perception of the robotic end-user. To this aim – within the EU framework of the STIFF-FLOP project (STIFFness controllable Flexible and Learnable Manipulator for Surgical Operations), we developed a novel design of miniaturized and magnetic resonance compatible sensors for force and torque real-time measurements in robotic surgery. The sensor design has a hollow shape, whose geometry allows its integration and embedding within snake-like surgical robots and modular devices. According to typical requirements and specifications of a surgical procedure, the sensor operates in a range of force and torque of 0-5 N and 0-5 N·cm, respectively. Due to a customized tool and calibration procedure, an error of less than 15% of sensor range can be obtained. This novel transducer may advance force and haptic feedback in robot assisted and minimally invasive surgeries.**

Keywords*—*force sensor; minimally invasive surgery; hollow design; MR compatibility sensin; keyhole surgery.

I. INTRODUCTION

During laparoscopic procedure, robot assisted surgery and minimally invasive robotic surgery (MIS), surgeons are going into the human body of the patient with tools which are remotely interfering with their operating hands [1-3]. Therefore, set of visual instruments are usually employed to make surgeons able to achieve the surgical tasks. Usually, these instruments supply a real-time stream of visual information through local or remote docking stations, providing that external monitors are available and one or more cameras are embedded within the surgical tool. Such an approach means that all information - which are usually transferred into the hands of the surgeon during an open surgical procedure - are implicitly replaced and surrogated by means of a unique senor channel, namely the visual one. Undoubtedly, vision is one of the most relevant sensors in human being. Nevertheless - due to the typical tasks of surgery, which usually requires directpalpation of human tissues, vessels and organs - touch sensitivity fulfills a not negligible role [4]. As a result, even if these concerns are largely discussed within the medical community, supplementary information procured from further sensor modalities may be beneficial while exploiting robotic surgery.

To this aim, within the EU framework of STIFF-FLOP Project - which develops new concepts and class of robotic devices for MIS based on STIFFness controllable Flexible and Learnable Manipulator for Surgical Operations [5] – a novel force and torque (F/T) sensor was conceived. The F/T sensor is easily integrated in a modular fashion within STIFF-FLOP manipulator [6, 7]; thanks to its optimized design, it can be easily adapted and employed within other surgical manipulators having a snake-like and hollow configurations. The sensor contains an interesting sets of peculiarities: small size, reproducible design (due to a 3D printing-base manufacturing process), magnetic resonance compatibility; it also allows cables and other linkages to passing through its structure internally, thanks to its geometry which is built externally and covers the peripheral area of the robot only.

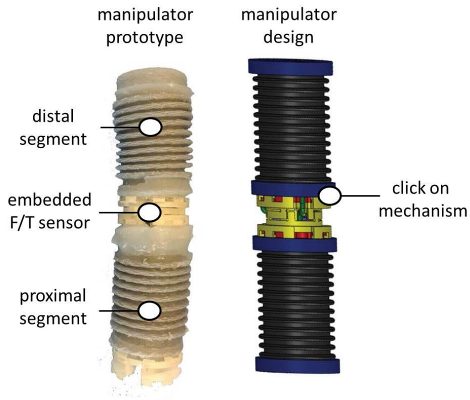

Fig. 1. STIFF-FLOP two segments manipulator with its own modualr strucutre and the embedded 3 d.o.f. F/T sensor.

II. THE 3 D.O.F. F/T SENSOR

A. *Sensor design*

Sensor design and characteristics originate from a set of preliminary and desired specifications and requirements:

Biocompatibility – a device, which has to be fully compatible vs. surgical application is desirable, therefore it has to avoid electric power and wires, as well as to elude the presence of any metal components (in order to pursue whole compatibility with magnetic resonance scans).

Modularity - the sensor structure should inherently allow the structural connection between the modules of the surgical manipulator. Hopefully, it should also leave an internal room (i.e. auxiliary channel) which may be used to accomplish other surgical tasks like the introduction of tools or actuators for a biopsy or other assignments.

Degree of freedom (d.o.f.) – from a sensorial viewpoint, the transducer should be able to measure applied forces as well as torques with a good S/N ratio and precision as it is required by a surgical task.

In line with these specifications, a ring-shape device has been designed as it is shown in Fig. 2. The device was plotted with the Solid Works software environment (by Dassault Systèmes Corp.) and manufactured in PROJET VisiJet® EX200 material (by 3D SYSTEM Co. Ltd) with a 3D printer (ProJet HD3000, by Print It 3D Ltd). The sensor structure is made a 3 d.o.f. plate, which is supported by 3 equally distributed cantilevers at 120° on the circular shape (Fig. 2, left panel). This structure allows measuring longitudinal force, F_z, and two torques in the orthogonal plane (M_x and M_y, Fig. 2, left panel). The principle behind the F/T measurements lays on the displacement estimation of each distal section of the 3 cantilevers. The displacement is transduced into a light intensity modulation, which is obtained by means of 3 couples of optical fibres (one for each cantilever), namely emitting and receiving fibres coupled with a digital amplifier FS-N11MN Fiber Optic Sensor (by Keyence Co., Ltd). Finally, the light modulation is performed through 3 reflective mirrors, which are fixed on each tip of the cantilever (Fig. 2, right panel). The whole sensor restrained within the size of 33x13 mm.

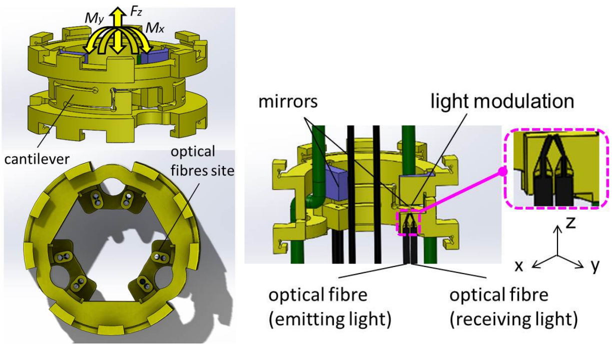

Fig. 2. Sensor design and geomtry (left panel) and its principle of functioning (right panel).

B. Sensor integration

Design of a 2-segmentsSTIFF-FLOP manipulator is shown in Fig. 1: a modular structure contains 3 air chamber actuators within each module plus an auxiliary channel allowing tubes to pass through the manipulator internally. On the periphery of the sensor, a click-on mechanism is embedded, which matches with a similar coupled structure designed in the manipulator (Fig. 1, right panel): the mechanism allows connecting multiple actuated modules by introducing force sensors in between each couple of consecutive segments..

C. Sensor performance

A specific tool and procedure for the calibration of each sensor and release of main characteristics was designed: the tool allows loading different weights on the sensor which stress the cantilever plates with different forces and torques [6]. A Multiple Linear Regression (MLR) method is then applied to sensor data to infer 3x3 calibration matrix (K_{calib}): this latter one establishes the relationship between the F/T output (F_z, M_x, M_y) and input signals (i.e. the 3 measurements of light intensity, as retuned from the FS-N11MN amplifiers, aset of 3 voltage levels, V_1, V_2 and V_3). Therefore it holds:

$$\begin{bmatrix} F_z \\ M_x \\ M_y \end{bmatrix} = \left[K_{calib}\right] \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (1)$$

The final sensor operative range, in terms of force and torque, is from 0 to 5 N and from 0 to 5 N·cm, respectively; proper MLR estimation of K_{calib} entails a maximum absolute error of force and torque of less than 0.3 N and 0.1 N·cm, respectively.

III. Conclusion

A novel bio-compatible and metal free F/T sensor for robotic and minimally invasive surgery has been presented. The sensor was originally designed for a specific family of manipulators within the EU STIFF-FLOP project. Nevertheless, due to its hollow shape, size and performance , the proposed device lends itself to be used and embedded in different surgical robots.

Current sensor performances are constrained within a maximum percentage error of less than 15% of its range . Due to the sensor manufacturing process and material, a deeper analysis of its properties linearity and hysteresis should be performed, as it was already proposed for similar devices and applications [8-10].

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