A Novel Force Sensor Integrated into the da Vinci Trocar for Minimally Invasive Robotic Surgery

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INTRODUCTION

Minimally invasive robotic surgery (MIRS) has revolutionized surgical and therapeutic procedures by changing their effect on patients and significantly reducing collateral damages. On the other hand, the loss of tactile sensation can potentially lead to tissues damage and bad execution of particular surgical tasks, such as suturing and operational decisions that would require feeling the tissue deformation. One of the most challenging problem regards the force sensing in the surgical scenario. On this purpose many prototypes of sensorized surgical instruments have been developed by integrating force sensors in the instrument shaft or wrist, or even in the gripper fingers and clamp faces. For instance, in [1] a prototype of 6-axis FBG-based force sensor located between the wrist and the gripper of the surgical instrument is developed; in [2] a solution that uses FBG sensors integrated in the instrument shaft to measure the forces on the orthogonal plane of the surgical instruments is presented; on the other hand solutions for sensing the forces directly on the surgical gripper are evaluated in [3] and [4], using capacitive and piezoelectric effect. All the above-mentioned works have in common the fact that they require the modification of the instrument structure to integrate the force sensor. This entails higher costs, problems related to the tendon-driven actuation, greater likelihood of instrument breakage, the need of sensorize properly instruments with different characteristics. In this work, a new solution for a force sensor collocated at the end-tip of the trocar is evaluated. With respect to the state of the art, this solution allows measuring the interaction forces between the surgical instrument and the environment without any changes to the instrument structure and with full adaptability to different robot platforms and surgical tools. The sensor would be capable of measuring the forces in the orthogonal plane of the surgical instruments along the axis x_S and y_S in Fig. 1. As a matter of fact, the concerned two components are difficult to be reconstructed using the robot dynamical model. On the other hand, the force exerted along the axis of the instrument shaft is easier to be reconstructed due to the prismatic joint actuation.

MATERIALS AND METHODS

The innovation of the proposed approach consists on conceiving the structure, hosting the sensor element, to be allocated at the end-tip of the trocar. This permits the indirect measurement of the interaction forces between the instrument end-effector and the patient body by means of non-allocated forces generated by the displacement of the instrument shaft with respect to the fixed trocar pipe. Our first prototype is designed to guarantees a resolution of 0.1 N in a range of $[-10, 10]$ N that are common values in robotic surgical procedure.

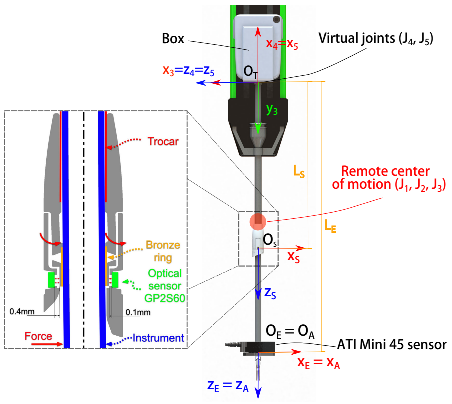

Fig. 1. The Da Vinci PSM arm front view and the sensor static characterization setup.

Working principle

A detailed explanation of the inherent operating principle follows. A little gap between the instrument shaft and the trocar exists to guarantee the reciprocal sliding. When the forces are exerted on the instruments end-effector, the component acting in the plane orthogonal to the instrument axis causes a dis-alignment between the instrument and the trocar axes (Fig. 1). This leads to contacts between the trocar, where it is placed the sensor, and the instrument. In those contact points the forces are discharged causing deformation of elastic frames that compose the sensor. The main idea is to measure the dis-alignment between the instrument shaft and the fixed trocar using four proximity optical sensors mounted in appropriate way. This solution have some advantages with respect to the state of the art: (i) the measure is not influenced by the tendon driven mechanism, as happens for the sensors solutions located in the instrument shaft or wrist; (ii) the connection cables and the data acquisition system are fixed and far away from the surgical site; (iii) the sensor (structure and acquisition system) is cheap and could be disposable.

Mathematical model

In this section a brief description of the sensor model is reported, for the sake of brevity, only the static model is considered. The dynamical model of the instrument shaft must be taken into account to reduce the effects of its dynamics on the measure. However, we found experimentally that the dynamic effects of the robot motion on the sensor measurements are negligible when instruments with low mass and inertia are used. For further information refer to [5]. In order to estimate the forces on the robot end-effector the prismatic joint position must be explicitly considered. The force on the sensor is related to the force on the instrument end-effector by means of simple geometrical consideration. In particular, we consider two virtual joints in the $\boldsymbol{O_T}$ point, J_4 and J_5 represented in Fig. 1, where the instrument shaft is connected to the instrument's box that slides in the prismatic joint guide. We consider the tube as rigid, thus the static model can be obtained simply considering a frame fixed to the box and centered in $\boldsymbol{O_T}$. The two jacobian matrices $\boldsymbol{J}_S(\boldsymbol{q}) \in \mathbb{R}^{2\times 2}$ and $\boldsymbol{J}_E \in \mathbb{R}^{3\times 2}$ in (1) map, on the virtual joints, the forces acting on the sensor and on the end-effector.

$$\boldsymbol{J_S}(\boldsymbol{q}) = diag(L_S, L_S) \qquad \boldsymbol{J_E} = \begin{bmatrix} diag(L_E, L_E) \\ \mathbf{0} \end{bmatrix} \tag{1}$$

where $L_S = (0.43 - q_3)$, $L_E = 0.389$ and q_3 is the position of the robot prismatic joint.

For the static equilibrium of the forces, results that

$$\begin{cases} \boldsymbol{\tau_G} = \boldsymbol{J}_{\boldsymbol{E}}^T \boldsymbol{f_E} \\ \\ \boldsymbol{\tau_G} = \boldsymbol{J}_{\boldsymbol{S}}^T(\boldsymbol{q}) \boldsymbol{f_S} \end{cases} \Longrightarrow \boldsymbol{f_E} = (\boldsymbol{J}_{\boldsymbol{E}}^T)^{\dagger}\, \boldsymbol{J}_{\boldsymbol{S}}^T(\boldsymbol{q})\, \boldsymbol{f_S} \tag{2}$$

where $\boldsymbol{\tau_G} \in \mathbb{R}^2$ is the torque vector of the two virtual joints, $\boldsymbol{f_S} \in \mathbb{R}^2$ and $\boldsymbol{f_E} \in \mathbb{R}^3$ represent the two vectors of the forces in the sensor frame and in the end-effector frame, respectively.

RESULTS

The validation of the sensor performances is obtained by two experiment: (*i*) comparison between our solution and a commercial torque-force sensor (ATI Mini45); (*ii*) estimation of the interaction forces between the needle and the tissues during a complete suturing procedure. In both the experiment the da Vinci research kit in telemanipulation mode was used to control the instruments in real-time. More in detail, in the first experiment the ATI sensor was fixed in correspondence to the end effector frame of the surgical instrument (see Fig. 1); a force to the ATI sensor was applied while the surgical instrument was in motion along the J_3 axis with the linear law reported in Fig. 2 bottom. The force measured by the ATI sensor, the force measured by the trocar sensor projected in the end-effector frame using the equation 2, and the relative error have been reported in Fig. 2. The results show that the sensor has a good response close to that of the commercial sensor ATI mini 45 with an error less then 12% for both the axis. In the second experiment the high resolution of the proposed sensing system was proved during a complete suturing procedure. In Fig. 3 is possible to evaluate the ability of the sensor to sense forces with very low intensity (less then 0.5 N) during the interaction between the suturing needle and the tissues.

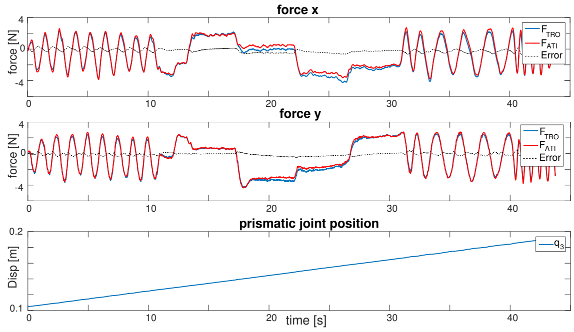

Fig. 2. Comparison between the force measured by a commercial ATI Mini 45 force/torque sensor and by the proposed solution while the instrument is in motion along the PSM prismatic joint J_3

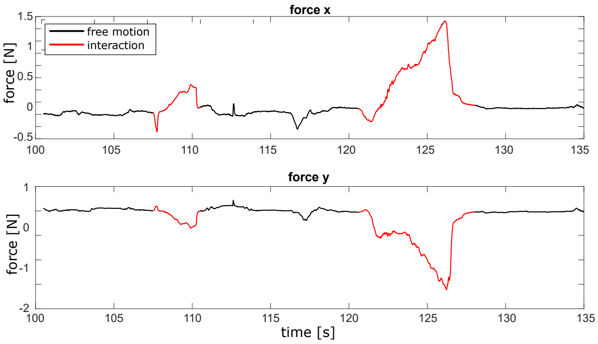

Fig. 3. Needle-tissues interaction force estimation during a suturing procedure (in red is highlighted the interaction between the needle and the tissue).

CONCLUSION AND DISCUSSION

In this work a new concept of force sensing for MIRS is evaluated. The proposed solution differs from the force sensors presented in the literature since does not require the modification of the surgical instruments, but exploits the possibility of placing the force sensor on the trocar. This opens the way for new disposable, low cost and simple force sensors that allowing the haptic feedback on different set-up even on clinical robotic surgical systems currently used in operating rooms. The prototype presented in the paper is printed using 3D printing technology only for proof of concept. In future works a prototype suitable to be used in a real surgical scenario will be developed.

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