Collaborative Camera-Holder Robotic System for Minimally Invasive Surgery

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***Abstract*—An innovative collaborative robotic system for camera holding assistance during minimally invasive surgery (MIS) is presented in this paper. The proposed system uses a 7-DoF collaborative robot as the camera-holder, which autonomously focus the endoscopic camera towards the surgical instruments inside the patient's body. A collaborative setup procedure has been implemented, firstly, allowing a member of the medical staff to manually teach the robot where the incision has been made and, secondly, defining a constrained null-space compliance range, where the limits are manually defined by the members of the medical staff, according to the workspace constraints. In order to preserve the patient safety, the Remote Center of Motion (RCM) constraint generated by the trocar placed at the incision is guaranteed by the control approach. Moreover, a compliance control law is implemented to smooth the robot movements as well as to reduce the efforts generated by the human-robot interactions. Although several solutions have been considered for the online tracking of the surgical instruments, the use of a motion capture system is depicted in this paper.**

Keywords—Collaborative robot, Robot-assisted minimally-invasive surgery, compliance control.

I. INTRODUCTION

The use of robotized assistant systems for medical applications is growing rapidly in recent years [1]. In the context of minimally invasive surgery (MIS), researchers and companies are developing new robotic systems to join in the supply market, among others, the well-known Da Vinci surgical system [2].

Besides the functionalities provided by a fully teleoperated system, such as the Da Vinci system, other different needs are evidenced by surgeons, where a robotic assistant could also provide a solution. For instance, in classical minimally invasive surgical procedures, the surgeon usually uses both hands to manipulate the surgical instruments (scissors, forceps, needle holders, etc.) during the task execution. These instruments are inserted into the patient's body through trocar devices placed at the desired incision points. In order to obtain a visual feedback of the surgical gestures, an endoscopy camera is also inserted into the patient's body, held by a medical staff assistant or a medical student [3]. During the procedure, the surgeon continuously gives orders to the assistant to correctly move the camera so that it correctly follows the surgical tips instruments. However, this method doesn't filter assistant hand's tremor, it generates a lack of precision, time delays in the surgical task execution as well as an increase of the stress suffered by the surgeon. Moreover, these difficulties can be significantly aggravated due to the lack of the assistant expertise. To overcome this problem, robotic solutions have been proposed over the past years: The discontinued AESOP [4] and EndoAssist [5] systems, the lightweight FreeHand robot [6], or the recently produced robot ViKY [7]. A recent research work also proposed to use a 7-DoF commercial robot, where gaze gestures of the surgeon were used to control the camera movements [8].

Although the solutions presented above replace the human assistant, surgeon is always requested to continuously send commands to the robot according to the desired camera movements. Moreover, the effects of undesired contacts between the robot assistant and the medical staff is neglected. To cope with, a collaborative robot-assistant camera holder system for MIS is proposed in this paper, using a 7-DoF collaborative robot. The robot assistant continuously focuses the camera towards the instruments, considering their movements, and guaranteeing minimal forces at the incision, where the trocar device generates a Remote Center of Motion (RCM) constraint [9]. The presented work proposes to use a Motion Capture (MoCap) system composed of a set of 8 high resolution cameras, i.e. Qualisys system, for the online tracking of the instruments.

In order to provide smooth robot movements, avoiding sudden changes of velocity, and to reduce the contact forces generated along the trocar, a cartesian compliance control approach has been implemented [10]. Moreover, a collaborative setup procedure has been proposed, exploiting the interactive features of a torque-controlled robot. Thus, the incision position is manually set up by moving the robot until the trocar. The available elbow's range motion can also be manually set up, according to the workspace needs. A null-space compliance strategy is implemented to guarantee the specified range limits.

This paper is organized as follows. The description of the robot-assistant platform is presented in Section 2. Then, the collaborative setup procedure is presented in Section 3. The overall control approach allowing to determine the desired instrument tips position related to the robot reference frame as well as the torque control approach implemented in the robot are presented in Section 4. The last section presents the conclusions and perspectives of the presented work.

II. ROBOT-ASSISTANT PLATFORM

The proposed robot-assistant platform during a surgical training session is presented in Fig. 1. A potential surgeon executes training tasks with a pelvic trainer, whereas a 7-DoF collaborative robot, i.e. Franka Emika, holds and orientates the camera according to the instrument movements. During the task execution, the surgeon receives a visual feedback from the surgical camera, allowing him to keep visible his task execution.

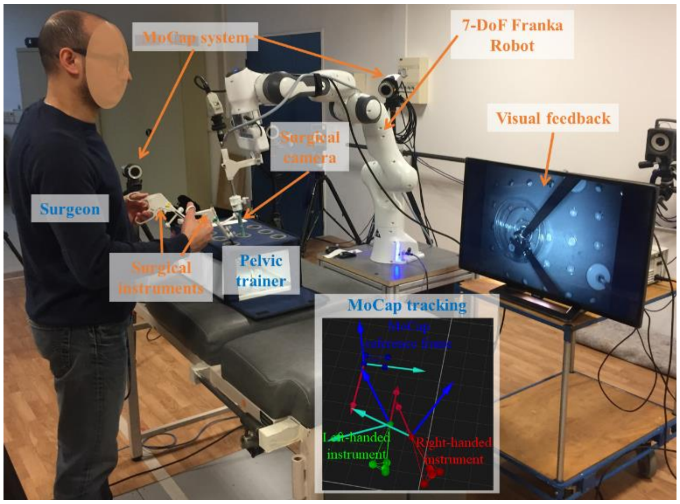

Fig. 1. Robot-assistant platform for camera holder assistant during MIS

The MoCap system, i.e. Qualisys, is composed of 8 high resolution IR cameras allowing to identify the position of 4 markers fixed on each surgical instrument. The identification of these markers allowed to reconstruct the overall position and orientation of each instrument as a rigid-body, with respect to the Qualisys reference frame fixed to the base of the robot. Knowing the relative distances between the markers and the tip of each instrument, it is possible to online track the position coordinates of each instrument tip. A screenshot of the instrument bodies tracking is shown at the bottom of Fig. 1, where the relative reference frame for each instrument has been placed at its tip.

III. COLLABORATIVE SETUP PROCEDURE

The setup procedure of the platform is achieved through a physical human-robot interaction. Two main features must be configured before starting the surgical procedure: the recognition of the incision point by the robot, and its available null-space range motion.

A. *RCM constraint definition*

Before starting the surgical procedure, a gravity compensation law is activated in the robot controller, allowing a member of the medical staff to manually move the robot so that the camera tip coincides with the trocar placed to insert the camera into the patient's body. A reference frame $\{C\}$ is then defined, fixed with respect to the camera, and with its origin coincident with the RCM generated by the trocar, as shown in Fig. 2.

B. *Null-space range motion definition*

A second setup step performs the restriction of the available null-space motion range [11]. Due to its anthropomorphic kinematics, the extra degree of redundancy of the robot is represented by its elbow motion ψ (Fig. 2), called swivel angle. Considering the implementation of a compliance control approach, as detailed in the following section, the robot's elbow can be manually moved around an axis defined between the robot's wrist and shoulder. This available null-space movement is very useful to deal with undesired contacts with the robot's body or to deliberately modify the robot's configuration without affecting the task execution. Nevertheless, it is useful to constraint the elbow motion into an available motion range. For instance, this restriction can be employed to avoid undesired collisions with the rest of the medical equipment. Thus, during the setup procedure, the user is able to freely move the elbow until the desired limits ψ_{min} and ψ_{max}, by allowing the robot controller to save these limits and define a null-space compliance strategy by increasing the stiffness in the vicinity of these limits. Frontal view of the proposed strategy is depicted in Fig. 2.

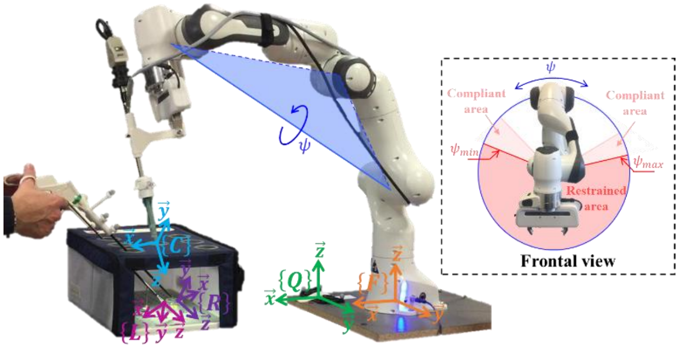

Fig. 2. Reference frames defined in the platform and definition of the null-space available range

IV. CONTROL APPROACH

Communication between the Qualisys system and the Franka robot has been established through ROS framework, using the User Datagram Protocol (UDP) for data exchange. To ensure a safe torque-control performance, the Franka controller runs at 1Khz, whereas the Qualisys laptop runs at 0.1Khz.

In the following, the mapping between the MoCap and Franka coordinates is described. Then, the compliance control approach implemented to guarantee smooth movements is depicted.

A. *Coordinates definition*

Figure 2 shows the reference frames defined for each element of the platform, where $\{F\}$ is the fixed reference frame attached to the base of the robot. The reference frame of the MoCap system, denoted by $\{Q\}$, has been fixed to the base of the robot. The reference frames $\{R\}$ and $\{L\}$ are attached to the right-handed and left-handed instruments, respectively, with the origin located at each instrument tip. In order to simultaneously focus the camera towards the two instruments tips, a virtual focus target point $P_T^Q = \frac{P_R^Q + P_L^Q}{2}$ has been calculated as the middle coordinate point between the two tips, with respect to $\{Q\}$. Then, the target point can be mapped to the robot reference frame $\{F\}$ through the transformation matrix of $\{Q\}$ with respect to $\{F\}$, i.e. T_Q^F,

$$P_T^F = T_Q^F P_T^Q \tag{1}$$

The desired camera orientation is achieved by orienting the z-axis of $\{C\}$ towards the target point P_T^F. Defining the target unit vector $\hat{V}_T^F = \frac{P_T^F - P_C^F}{\|P_T^F - P_C^F\|}$, the error between the current and the actual camera orientation can be represented as an angle error θ_e measured around an axis e_{axis}^F, based on the axis-angle representation. Thus, the orientation error $e_o^F \in \Re^3$ can be written as follows,

$$e_o^F = \theta_e \cdot e_{0_{axis}}^F = \cos^{-1}\left(\hat{V}_T^F \cdot \hat{z}_C^F\right) \cdot \left(\hat{V}_T^F \times \hat{z}_C^F\right) \tag{2}$$

where $\hat{z}_C^F$ is the unit vector of the z-axis in $\{C\}$, with respect to $\{F\}$.Finally, the position error $e_p^F \in \Re^3$ can be defined as the difference between the origin position of $\{C\}$ with respect to $\{F\}$, P_C^F, and the RCM position P_{RCM}^F generated by the trocar,

$$e_p^F = P_C^F - P_{RCM}^F \tag{3}$$

B. Robot control

The proposed camera holder robot is a 7-DoF ($n = 7$) collaborative robot conceived to share a common workspace with human. Since the robot has torque-controlled features, a compliant control strategy [10] can be implemented. As explained before, the compliance feature allows to smooth robot movements, avoiding sudden gestures, as well as to reduce the intensity of the interaction forces at the insertion position of the camera into the patient's body, i.e. trocar position. Thus, it is possible to define the torque control input T_i as follows:

$$\begin{aligned} T_i = J^T\left[K_{p_x} e_X - K_{d_x} \dot{X}_c\right] - \aleph(q_c)\left[K_{p_\psi} e_\psi - K_{d_\psi} \dot{q}_c\right] \\ + \widehat{H}(q_c, \dot{q}_c) \end{aligned} \tag{4}$$

The cartesian error $e_X \in \Re^6$ is composed of the orientation and position errors defined in (2) and (3), i.e. $e_X = \begin{bmatrix} e_p^F & e_o^F \end{bmatrix}^T$. The current cartesian velocity is represented by $\dot{X}_c \in \Re^6$. The torque input compensates the Coriolis and gravity effects through $\widehat{H}(q_c, \dot{q}_c) \in \Re^n$, calculated according to the current joint position and velocity vectors $q_c, \dot{q}_c \in \Re^n$. The degree of compliance is regulated along each cartesian axis by the choice of the stiffness and damping values of the diagonal matrices $K_{p_x}$and K_{d_x}, respectively.

Moreover, the null-space compliance strategy is regulated through the diagonal matrices K_{p_ψ} and K_{d_ψ}, the null-space projector $\aleph(q_c)$ and the error $e_\psi \in \Re^n$, defined as follows:

$$e_\psi = \begin{cases} q(\psi_{min}) - q_c, & \psi \leq \psi_{min} \\ q(\psi_{max}) - q_c, & \psi \geq \psi_{max} \\ 0, & \psi_{min} < \psi < \psi_{max} \end{cases} \tag{5}$$

V. CONCLUSION

In this paper, an innovative collaborative robotic camera holding assistant for MIS was presented. The proposed system uses collaborative setup procedures, through physical contact, to show the robot where the incision has been made and to define an available range for the elbow's motion. The camera-holding robot autonomously focus the camera towards the instruments, with the aid of a MoCap system online tracking their movements. The presented innovative solution is validated through experimental tests performed under pelvic trainer during simple exercises of pick and place.

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