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Improving Surgical Robotics Training with Haptic Virtual Fixtures: An Experimental Study

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Abstract—**The lack of high-level assistive control strategies in the field of teleoperated surgical robots has been linked to intra-operative injuries and increased fatigue experienced by practitioners. Virtual Fixtures analogous to the one proposed in this study may be beneficial for the patient's safety and the outcome of the operation; this work aims at evaluating their effectiveness in the context of surgical training. Tracking the position and orientation of a teleoperated surgical instrument with respect to a reference trajectory - planned in the pre-operative phase - allows one to compute and apply feedback forces to the manipulators held by the practitioner, which will provide haptic guidance towards an improved surgical performance. This high-level control strategy is here tested on a suturing task emulated in a virtual environment, where a group of participants was evaluated on the distance and angle error committed during the execution with and without assistance. The assistive modality proposed here is able to reduce the average error committed in the execution of the virtual suturing task: virtual fixtures and other similar assistance mechanisms may be most beneficial in the surgical training scenario, improving the learning curve and achieving better performances.**

Index Terms—**Robotic Surgery, Haptic Assitance, Virtual Fixtures**

I. INTRODUCTION

Robot-Assisted Minimally Invasive Surgery (RAMIS) has revolutionized the healthcare industry in the last 20 years by providing safer, more effective and beneficial solutions to patients undergoing delicate and complex surgical procedures. Improved dexterity, higher accuracy, tremor filtration and magnified viewing are among the most notable benefits of teleoperated surgical robots, a category which encloses all systems where the surgeon's hand movement is directly translated to the motion of the robot-controlled surgical instrument.

Most of these systems, however, do not provide haptic feedback to the performing practitioner: the lack of tactile forces, friction and texture sensitivity have been linked to surgical errors and intraoperative injuries [1]. In this context, Virtual Fixtures (VFs) may grant an additional level of safety to the patient, as well as decreasing the cognitive load of the practitioner [2].

Virtual Fixtures are formally defined as high level collaborative control strategies where the motors in the hand-held "master" device are energized so that the operator holding the manipulator will feel a mechanical force prompting him/her to avoid obstacles or to follow a prescribed trajectory. Magnitude and direction of this force are determined from the "slave" device position and orientation in relation to the elements in the surgical space registered pre-operatively, in a feedback fashion. The combination of the motion commands from the surgeon and the VF forces applied to the master device will result in the minimization of the error committed in the slave robot space.

II. STATE OF THE ART

Although commercially available surgical systems are not featuring VFs yet, a number of research projects have been published on the topic, most of which are collected and reviewed in [3]. Trajectory Guidance virtual fixtures have been studied in [4], where the implemented VF was assisting users in following planar predefined paths; the applicability of this assistance strategy was not evaluated in a surgical context. A guidance assistive paradigm was also formulated in [5] with an extension to 2D surfaces: this dynamic adaptive algorithm aims at emulating the haptic feedback of an open-heart procedure on the manipulator of a robotic system. This implementation is, although, only focused on re-creating the tactile forces experienced by the surgeon in cutting procedures, and it is not an "assistive" system *per se*. Kapoor and Taylor [2] studied the assisted performance of users in a knot-positioning task on a real (non-simulated) phantom: their assessment, however, is not directly linked to the execution of a knotting task in a real surgical scenario, which features a number of additional difficulties, like the proper gripping of the needle, the interaction with the sutured tissue and the limited workspace in view of the endoscope camera.

To overcome these limitations, this study proposes to evaluate the assisted performance in a realistic virtual environment, where the teleoperation commands originating from the "master" manipulators are sent to the 3D model of a "slave" robot in a virtual scene, which features a virtual recurve surgical needle and a virtual sutured tissue.

III. MATERIALS AND METHODS

A. Implementation of the Virtual Fixture

This study implements a *Trajectory Guidance Virtual Fixture* which re-directs the surgical tool towards a predefined trajectory, by applying adaptive forces and torques to the master manipulator. Considering a generic three-dimensional trajectory planned in the pre-operative stage, the feedback forces will be calculated according to the relative position and orientation of the trajectory itself and the tooltip reference frame. Both the forces and torques are computed in real time

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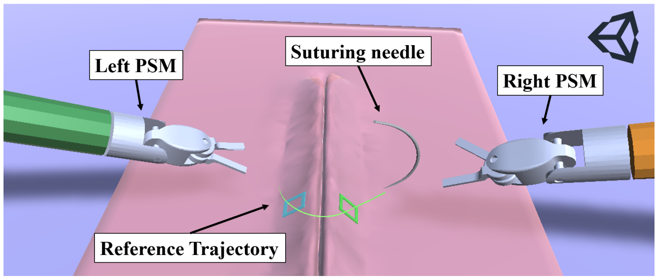

Fig. 1. Virtual surgical suturing task in the Unity virtual environment. Two virtual PSMs, one for each hand, are used in the surgical scene. The operator must pass through the entry and exit points (green and cyan squares, respectively) and stay as close as possible to the reference trajectory (lime-colored line)

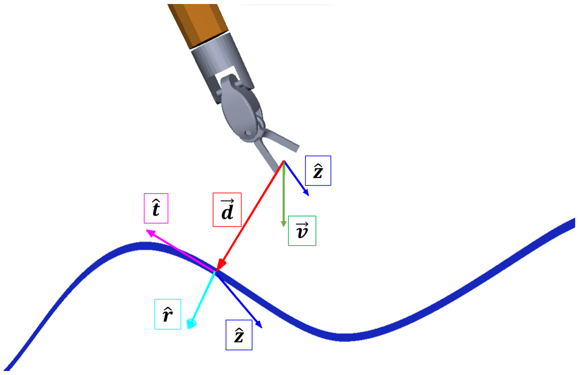

Fig. 2. The surgical tool and a reference trajectory (blue). All vectors involved in the calculation of the virtual fixture are also displayed

as the sum of an elastic and a viscous contribution: while the elastic component accounts for the positional or angular error to the closest point of the reference trajectory - and the tangent computed in such point, accordingly - the viscous components are proportional to the temporal rate of change of the errors themselves.

A viscoelastic model allows to achieve a guiding error-compensating assistance that is less prone to overshooting behaviors and to oscillations. Moreover, with the force and torque being calculated as

$$\boldsymbol{F} = k_F \cdot \boldsymbol{F}_{elastic} + \eta_F \cdot \boldsymbol{F}_{viscous} \tag{1}$$

$$\boldsymbol{T} = k_T \cdot \boldsymbol{T}_{elastic} + \eta_T \cdot \boldsymbol{T}_{viscous} \tag{2}$$

one tunes the elastic gains k_F and k_T and the viscous damping coefficients η_F and η_T in order to achieve a comfortable balance between the components and a stable behavior of the feedback force, which may vary from operator to operator, as well as from task to task.

Fig. 2 illustrates the vectors involved in the computation of the virtual fixture; specifically, contributions in Eq.1 expanded as:

$$\boldsymbol{F}_{elastic} = \boldsymbol{d} \tag{3}$$

$$\boldsymbol{F}_{viscous} = \begin{cases} \boldsymbol{d}, & \textit{if } \boldsymbol{v} \cdot \boldsymbol{d} < 0 \\ rotate(\boldsymbol{v}, \theta, \boldsymbol{r}), & \textit{otherwise} \end{cases} \tag{4}$$

Here, $\boldsymbol{d}$ is the distance vector going from the surgical instrument to the closest point in the trajectory, $\boldsymbol{v}$ is the velocity of the surgical instrument, while θ and $\boldsymbol{r}$ are the angle and axis of rotation which will align the velocity vector $\boldsymbol{v}$ with $\boldsymbol{d}$, respectively:

$$\theta = (1 + \boldsymbol{v} \cdot \boldsymbol{d}) \cdot \frac{\pi}{2} \tag{5}$$

$$\boldsymbol{r} = \boldsymbol{v} \times \boldsymbol{d} \tag{6}$$

This implementation is adapted from a previous in-house work [6]. Similarly, contributions to the torque (Eq.2) are expanded as:

$$\boldsymbol{T}_{elastic} = acos(\boldsymbol{z} \cdot \boldsymbol{t}) \cdot \boldsymbol{z} \times \boldsymbol{t} \tag{7}$$

$$\boldsymbol{T}_{viscous} = \frac{d}{dt}\left[acos(\boldsymbol{z} \cdot \boldsymbol{t})\right] \cdot \boldsymbol{z} \times \boldsymbol{t} \tag{8}$$

The role of the torque is to align the z-axis of the surgical tool's reference frame with the tangent of the trajectory $\boldsymbol{t}$ at its closest point. In Eq.7 and Eq.8, the angle and axis of rotation which will achieve this alignment are $acos(\boldsymbol{z} \cdot \boldsymbol{t})$ and $\boldsymbol{z} \times \boldsymbol{t}$, respectively.

B. *Experimental Protocol*

The efficacy of this assistance strategy has been assessed with an experimental study involving 8 volunteers teleoperating a *da Vinci* surgical robot, integrated in a virtual environment equipped with the Unity physics engine and managed by a ROS framework. The participants (5 males and 3 females, age 23 to 26 years old, all right-handed, all with little to no experience in surgical robotics) were required to perform a bi-manual suturing task (Fig.1) for 8 repetitions without assistance, followed by another 8 repetitions assisted by the virtual fixture. A balanced visco-elastic behavior was achieved setting the parameters in Eq.1 and Eq.2 as $k_F = 1.5$, $k_T = 5 \cdot 10^{-4}$, $\eta_F = 10$, and $\eta_T = 15$. A constraint on a maximum deployable force was set at $3N$ and a maximum torque at $0.1Nm$: these values were set in order to not stress the operator's wrist over acceptable loads.

Suturing is chosen as the surgical task for this assessment phase since its correct execution requires to position the thread properly, and in addition to guide the needle (1/2 circle, CT1) at an optimal angle with respect to the approached tissue. Moreover, the region and pose of gripping will require very different wrist movements for guiding the needle, only few of which are considered optimal in a real surgical scenario.
The experimental protocol is organized as follows:

- Each user is given 2 minutes to familiarize with the teleoperation in the virtual environment: they are allowed to move the manipulators, grasp and release the needle, and pass the needle from the right to the left gripper. They are also allowed to perform the first practice suturing without their performance being recorded.

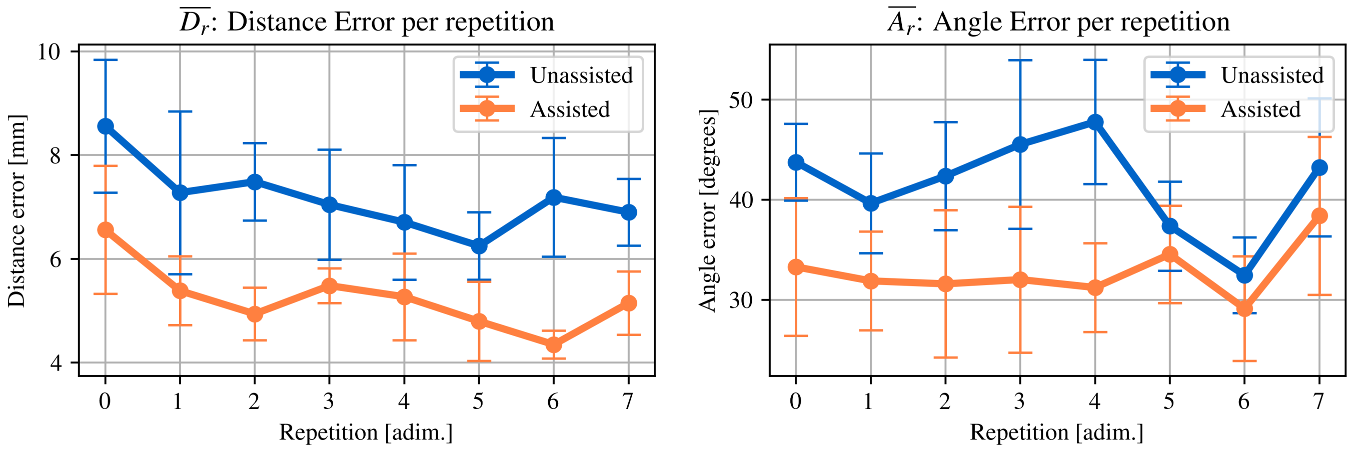

Fig. 3. Trend of the performance metrics as a function of the repetition number. The average errors among the 8 volunteers is displayed as the thick line, accompanied by the standard deviation at each repetition displayed as error bars. The plot on the left refers to the distance error, while the plot on the right to the angular error.

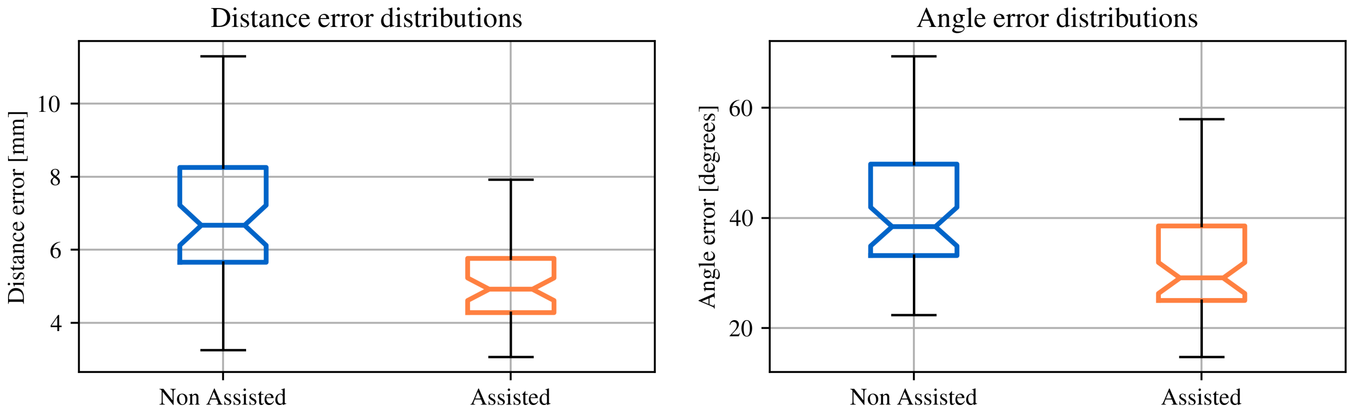

Fig. 4. Boxplots of the average distance and angular errors over all repetitions for the assisted and unassisted suturing task

- Each user then performs 8 repetitions of the suturing task without assistance, while their performance is being logged by the system.
- Each user finally performs 8 repetitions of the suturing task assisted by the virtual fixture, while their performance is again being logged by the system.

For the performance analysis, each suture is considered to begin when the tip of the curved needle passes through the entry point, while the end of the suture is marked when the needle feather traverses the exit point (green and cyan squares in Fig.1). During this period, the system acquires and logs, at a frequency of 30Hz, the following performance metrics:

- $D_{u,r}$: Average distance error from the needle tip to the closest point on the reference trajectory, from the user u at repetition r
- $A_{u,r}$: Average angular error between the z-axis of the needle reference frame and the trajectory tangent vector, considered at the closest point, from the user u at repetition r

Since the assistive force and torque calculated are independent of each other, these two performance metrics are evaluated separately.

IV. RESULTS

Fig. 3 shows the trend of the performance metrics as a function of the repetition number, where the average performance per repetition is calculated averaging across all users

$$\overline{D_r} = \frac{1}{U}\sum_{u=1}^{U} D_{u,r} \tag{9}$$

$$\overline{A_r} = \frac{1}{U}\sum_{u=1}^{U} A_{u,r} \tag{10}$$

with $U = 8$ being the number of volunteers. The standard deviation of the performance metrics is also displayed as error bars. While both the assisted and unassisted performances show a decreasing trend for the distance error, when the VF was applied the surgical instrument was consistently closer to the reference trajectory. As this last observation holds true for the angular error as well, a decreasing trend is not evident.

Boxplots of the distributions of average performances on the overall 8 repetitions, as in Fig.4, clearly display a reduction of both the distance and angular errors when the subjects are assisted. This graphical interpretation analyses the user performance as a whole, averaged on the $R = 8$ repetitions:

$$\overline{D_u} = \frac{1}{R}\sum_{r=1}^{R} D_{u,r} \tag{11}$$

$$\overline{A_u} = \frac{1}{R}\sum_{r=1}^{R} A_{u,r} \tag{12}$$

A statistical Mann-Whitney U-Test (significance designated at p-value < 0.005) assessed that the distance error in the non-assisted task (7.12 ± 2.22 mm) was significantly higher with respect to the assisted case (5.33 ± 1.66 mm), with a p-value of $8.61 \cdot 10^{-7}$. Similarly, the angular error when no haptic assistance was provided ($41.32 \pm 12.50°$) was significantly higher (p-value $2.72 \cdot 10^{-4}$) with respect to the assisted case ($33.12 \pm 12.72°$).

V. DISCUSSION

While the results of this study are not conclusive, they provide an interesting preliminary insight into the feasibility of virtual fixtures for surgical teleoperation. Results showed that the employment of these assistance strategies allowed for improved performance. When questioned about the intrusivity of the virtual fixture in the teleoperation, some participants expressed a preference for a force of higher intensity, while others wished for the force to be less intrusive: it is possible that allowing the operator to fine-tune the level of assistance according to its needs may further improve the training process and the overall performance.

Finally, these high level control strategies may be most beneficial in the surgical training scenario: employing virtual fixtures in this context could positively impact the training process and the steepness of the associated learning curve. The retention and transferability of surgical skills will potentially be enhanced aswell. Conversely, the clinical relevance of this subject is still unclear: when, where and if to employ VFs for *in-vivo* surgical procedures are question that remain unanswered without large scale clinical investigations.

VI. CONCLUSIONS

Virtual Fixtures employed as assistive strategies in the manipulation of surgical robots represent a promising approach for improving surgical outcomes and reducing intra-operative errors or injuries. This preliminary study positively showed how employing a trajectory guidance virtual fixture in a simulated surgical scenario has reduced the error committed by the operator in following a pre-planned reference trajectory.

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