A framework for sensorless identification of needle-tissue interaction forces in robot-assisted biopsies

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***Abstract*— During teleoperated robot-assisted biopsies, force and visual feedback are fundamental to guarantee accuracy and safety in executing the task. To allow seamless introduction of the robot in the clinical flow, it is desirable to measure interaction forces without relying on dedicated, additional sensors. On the other hand, typical imaging systems do not offer a real-time 3D view of the remote site at the operator-side. In this document, we extend a previous work with two contributions: i) a *sensorless* needle-tissue interaction model identification algorithm; ii) a modular framework, interfaced with a virtual environment, offering a complete visualization of the procedure at the operator-side. The identification algorithm is validated on an isinglass-based phantom, while the framework is tested through the CoppeliaSim (former V-REP) software.**

I. INTRODUCTION

In teleoperated needle insertion procedures for robot-assisted biopsies, compensating the lack of direct feedback from the operating room to the clinician typically requires rendering visual and force information by using enhanced imaging systems and haptic interfaces. The acquisition of visual data at the patient-side is achieved through the surgical instrumentation available in the operating room (e.g., computed tomography (CT) or magnetic resonance imaging (MRI) systems), that could be used to reconstruct reliable 3D models of the anatomical target. On the other hand, due to the geometrical constraints imposed by the narrow gantry of imaging devices, the material's EM compatibility, the need to achieve seamless integration of the robot in the clinical workflow, adding dedicating sensors to measure interaction forces, is not desirable: therefore, *sensorless* approaches should be preferred. In [1], we addressed the identification problem of the needle-tissue interaction model. The identification process was accomplished by commanding the robot manipulator with different control paradigms and kinematic motion constraints, based on the different operative phases of the task, thus increasing the flexibility of the system. In this document, we formalize this adaptable behaviour by presenting a modular framework for *sensorless* robot-assisted needle insertion tasks. The designed framework allows to model the main physical components of the surgical workspace plan desired behaviours and accomplish multiple control objectives, replicating movements and interactions within the simulation environment CoppeliaSim (see Fig. 1). The modularity property also allows to generalize the framework and define arbitrary tasks to be accomplished simultaneously, possibly in a shared autonomy fashion, e.g., combine teleoperation control with autonomous motion compensation to accomodate patient movements during the surgery. The sensorless needle-tissue interaction identification process, along with the architecture of the proposed framework, are described in the following.

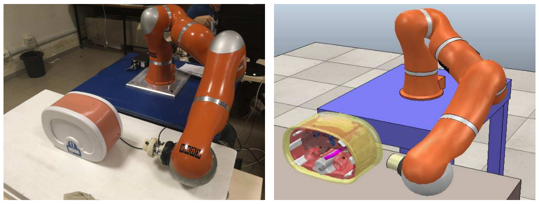

Fig. 1. Robot-assisted needle insertion scenario reconstructed in the simulated environment CoppeliaSim, with a realistic 3D model of abdomen phantom built from CT-scans.

II. INTERACTION MODEL IDENTIFICATION

The adopted needle-tissue interaction identification method is described in [1] and is based on results of [2]. Given a surgical rigid unbeveled-tip needle, mounted at the end-effector (EE) of a robot manipulator, we model the force between the needle and target tissues through the Kelvin-Voigt (KV) model:

$$f_z = -K(t)z(t) - D(t)v_z(t) \tag{1}$$

being $z(t)$ and $v_z(t)$, respectively, the position and velocity of the needle tip along the z-axis, and $K(t)$ and $D(t)$, respectively, the unknown elastic and damping coefficients of the tissue in contact with the needle. A Recursive Least-Square (RLS) algorithm, with Covariance Resetting (CR) condition, is used to reconstruct an estimation $\hat{\boldsymbol{\theta}} = (\hat{K}, \hat{D})^T$ of the dynamic parameters by evaluating, at each time instant k, the error $e_{z,k} = f_{z,k} - \hat{f}_{z,k}$ between measured and predicted force, the latter built from (1) with the current estimates of K and D parameters. Differently from [1], we compute a direct measurement of the interaction force $\boldsymbol{f} = (f_x, f_y, f_z)^T$ by exploiting the knowledge of the robot dynamic model and computing the residual vector [3]:

$$\boldsymbol{r}(t) = \boldsymbol{K}\left[\boldsymbol{p}(t) - \int_0^t (\boldsymbol{\tau} + \boldsymbol{\alpha}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{r})\, ds - \boldsymbol{p}(0)\right] \tag{2}$$

where $\boldsymbol{p}(t)$ is the generalized momentum, $\boldsymbol{\tau}$ are the joint torques and $\boldsymbol{\alpha}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is a function of the robot dynamic model parameters. From (2), we have $\boldsymbol{f} = \boldsymbol{J}^{T^{\#}}\boldsymbol{r}$, being $\boldsymbol{J}^{T^{\#}}\boldsymbol{r}$ the pseudo-inverse of the transpose of the robot Jacobian matrix $\boldsymbol{J}$. The CR condition is adopted to restore the covariance matrix of the estimation and to handle discontinuous variations of the parameters, due to the passage of the needle through different tissues.

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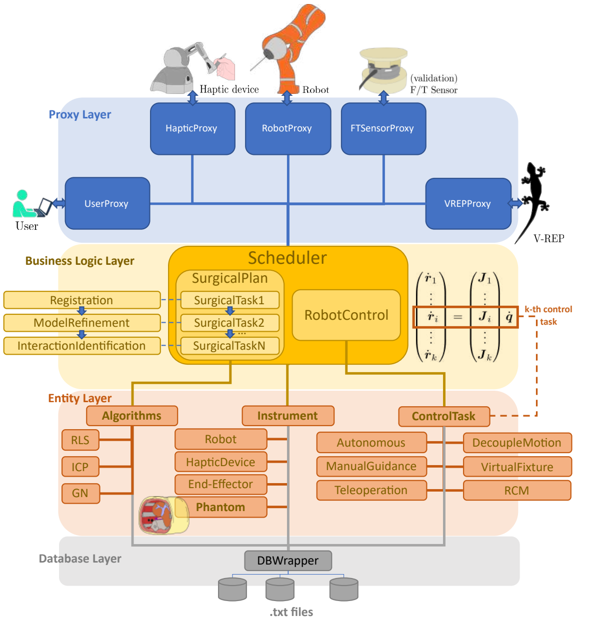

Fig. 2. Software architecture of the framework for robot-assisted needle insertion procedures. On the top of the figure, the external involved components are highlighted: a Geomagic Touch haptic interface; a KUKA LWR manipulator arm; a force sensor used for validation purposes only; the CoppeliaSim virtual environment.

III. THE DIGITAL TWIN FRAMEWORK FOR NEEDLE INSERTION SUPPORTED BY ROBOTS

The software architecture, depicted in Fig. 2, is inspired to the multi-layer *Entity-Control-Boundary* software engineering pattern [4] , where the top Boundary layer contains the *proxy* objects to communicate with all the external systems involved in the setup. The middle *Control* – or *Business Logic* (BL) – layer represents the core of the framework and defines the *Surgical Plan* of the operation in terms of subsequent surgical tasks (e.g., robot and target registration, robot model refinement, interaction identification), along with a *Robot Control* object that implements a number of user-requested robot control tasks. Both BL plan and control functionalities rely on a set of shared instances of components from the Entity layer, collecting the involved instruments, the employed algorithms and the requested control tasks. To improve the flexibility of the system and extend the framework also to different surgical procedures, considered control tasks cover different control modalities and kinematic constraints on the robot motion. In particular, considered control modalities are: i) *manual guidance*, for a rough positioning of the robot through external force inputs commanded by the user pushing/pulling the manipulator structure; ii) *teleoperation*, for fine regulation, possibly accounting motion scaling; iii) *autonomous*, to automatically perform predefined trajectories. Analogously, the kinematic constraints considered in the framework are: i) *decoupled motion*, to separately command linear and angular velocities and achieve a more intuitive motion; ii) *virtual fixture*, to constrain the robot to move along the needle shaft direction and prevent undesired dangerous lateral motions against tissues; iii) *Remote Center of Motion* (*RCM*), to restrict the needle to a single entry point in the patient's body, allowing only translation along the axis or rotation about the point [5]. The selected control modality and kinematic constraint are simultaneously accomplished through a task-priority formulation.

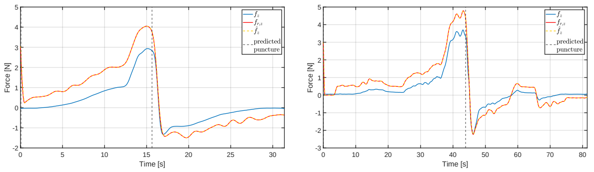

Fig. 3. Results of the senorless force reconstruction and layer transition detection, on autonomous (left) and teleoperated (right) trajectory. Ground Truth sensor measurement, sensorless measurement and reconstruction from identified parameters are highlighted in blue, red and yellow, respectively. Dashed black line shows the detection of the layer transition, corresponding to the tissue rupture event.

IV. RESULTS

Our experimental setup is built with the components highlighted in Fig. 2 and interfaced with the CoppeliaSim virtual environment, as also highlighted in Fig. 1. Validation has been accomplished on a simple isinglass phantom built with two different layers separated by a disposable glove to emulate both elasticity and viscosity of a target tissue. Results, shown in Fig. 3, reveal the quality of the sensorless force reconstruction with respect to a ground-truth sensor measurement, and prove the effectiveness of the tissue transition detection on the considered target.

V. CONCLUSIONS AND FUTURE WORKS

We presented a modular framework for surgical procedure, within which we have developed methods for needle-tip interaction forces identification. The framework is based on an open-source simulator and allows easy extension to different surgical tasks and control modalities. We are working at enriching the framework with additional functionalities, like automatic motion compensation, soft tissue simulation and registration of images acquired in real-time to the 3D model reconstruced from pre-operative data.

REFERENCES

[1] N. Cacciotti, A. Cifonelli, C. Gaz, V. Paduano, A. V. Russo, and M. Vendittelli, "Enhancing force feedback in teleoperated needle insertion through on-line identification of the needle-tissue interaction parameters," in *2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)*, Aug 2018, pp. 79–85.

[2] L. Barbè, B. Bayle, M. de Mathelin, and A. Gangi, "In vivo model estimation and haptic characterization of needle insertions," *The International Journal of Robotics Research*, vol. 26, no. 11-12, pp. 1283–1301, 2007. [Online]. Available: https://doi.org/10.1177/0278364907082666

[3] A. De Luca and R. Mattone, "Actuator failure detection and isolation using generalized momenta," in *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*, vol. 1, 2003, pp. 634–639 vol.1.

[4] J. Ivar, C. Magnus, J. Patrik, and O. Gunnar, "Object-oriented software engineering, a use case driven approach," *MA.: Addisson-Wesley*, 1992.

[5] N. Aghakhani, M. Geravand, N. Shahriari, M. Vendittelli, and G. Oriolo, "Task control with remote center of motion constraint for minimally invasive robotic surgery," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2013, pp. 5807–5812.