Forbidden Region Virtual Fixtures for Surgical Tools Collision Avoidance

Cristina Iacono, Bruno Siciliano, Fanny Ficuciello
Department of Information Technology and Electrical Engineering
Università degli Studi di Napoli Federico II
Naples, Italy
cristina.iacono, bruno.siciliano, fanny.ficuciello@unina.it

***Abstract*—In robot-aided surgery, during the execution of typical bimanual procedures, surgical tools can collide and create serious damage to the robot or tissues. The da Vinci robot is one of the most widespread robotic system dedicated to minimally invasive surgery. Although the procedures performed by da Vinci-like surgical robots are teleoperated, potential collisions between surgical tools are a very sensitive issue declared by surgeons. Shared control techniques based on Virtual Fixtures (VF) can be an effective way to help the surgeon prevent tools collision. This paper presents a surgical tools collision avoidance method that uses Forbidden Region Virtual Fixtures. To ensure the correct definition of the VF, a marker-less tool tracking method and the Extended Kalman Filter (EKF) are used for tool pose estimation.**

***Index Terms*—surgical robotics, teleoperation, virtual fixtures.**

I. Introduction

During the execution of a surgical procedure, in Minimally Invasive Robotic Surgery (MIRS), two or more tools can come dangerously close to each other. Surgeons have a limited vision on the surgical site, which reduces dexterity and increases the cognitive workload. Moreover, collisions can cause tools or tissues damage. Haptic feedback could significantly affect the performances of novice surgeons, reducing training duration and improving the effectiveness of the procedures. Collisions between surgical tools in MIRS can be avoided with the application of shared control techniques, such as Virtual Fixtures. Forbidden Region Virtual Fixtures (FRVF) can be used to restrict the motion of the robot's tool through a repulsive force rendered to the surgeon. The da Vinci Research Kit (dVRK) is already used to test VF-based methods [1] [2]. Since dVRK robot joints are driven through cables that introduce elasticity, backlash and nonlinear friction [3], tools pose obtained through direct kinematics is affected by errors. Therefore, to ensure a correct application of the VF, a method for tool tracking is strictly needed. In our work, we propose a surgical tool collision-avoidance method, to improve safety in surgical procedures. The method is tested on the dVRK and includes marker-less surgical tool tracking using an Extended Kalman Filter (EKF) that couple vision and kinematics information to enhance the robustness of VF application.

II. MATERIALS AND METHODS

The dVRK robot is composed of two Patient Side Manipulators (PSMs) and an Endoscope Camera Manipulator (ECM) commanded by two Master Tool Manipulators (MTMs). The surgical scene can be seen by the surgeon thanks to an endoscope, including a stereo camera with 5 mm baseline. Each PSM has a reference base frame, $\mathcal{F}_b$, positioned at the PSM Remote Center of Motion (RCM). The direct kinematics of the dVRK allows computing the current pose of each gripper frame $\mathcal{F}_g$ respect to the corresponding base frame. The tools tip frames $\mathcal{F}_t$ of each PSM have their origins in the PSM tool tips. The method directly uses laparoscopic images to track the surgical instrument. A deep learning solution for instrument semantic binary segmentation is employed. The system adopts the U-Net modification proposed in [4], called TernausNet that is trained using the dataset provided for MICCAI 2017 Endoscopic Vision Sub-Challenge: Robotic Instrument Segmentation. The tool tip position on the image plane is computed from the binary mask, reducing the search area range re-projecting the tip kinematic position on the image plane. Then, the 3D position of the PSM2 tip, expressed in the camera frame $\mathcal{F}_c$, is reconstructed by using a triangulation method with direct linear transform.

For the estimation and tracking of the instrument pose, the Extended Kalman Filter (EKF) is used, combining visual information from the endoscope with the robot kinematics. The prediction step provides a preliminary estimation of the instrument pose and, then, the vision-based estimated pose is used in the filter correction step. The filter provides an estimate of the tool tip pose $\boldsymbol{\zeta} = [\boldsymbol{p}_t, \boldsymbol{q}_t]^T$, being $\boldsymbol{p}_t$ the true tool position, and $\boldsymbol{q}_t = [\eta_t, \boldsymbol{\epsilon}_t]^T$ its quaternion-based true orientation in the base frame $\mathcal{F}_b$.

The process dynamics for the state vector $\boldsymbol{\zeta}$ and the measurement model are given by:

$$\begin{cases} \dot{\boldsymbol{p}}_t = \boldsymbol{v}_g + \boldsymbol{S}\left(\boldsymbol{\omega}_g\right)\boldsymbol{r}_{gt} + \boldsymbol{n}_p \\ \dot{\boldsymbol{q}}_t = \dfrac{1}{2}\boldsymbol{\Omega}\left(\boldsymbol{\omega}_g\right)\boldsymbol{q}_t + \boldsymbol{n}_q \end{cases} \qquad (1)$$
$$\boldsymbol{y} = \boldsymbol{\zeta} + \boldsymbol{m}$$

where $[\boldsymbol{v}_g, \boldsymbol{\omega}_g]^T$ are the linear and angular velocity of the gripper frame, $\boldsymbol{S}(\cdot)$ is the skew-symmetric operator, $\boldsymbol{r}_{gt}$ is the position vector of the tool tip respect to the gripper, $\boldsymbol{n} = [\boldsymbol{n}_p, \boldsymbol{n}_q]^T \sim \mathcal{N}\left(0, \boldsymbol{N}\right)$ and $\boldsymbol{m} \sim \mathcal{N}\left(0, \boldsymbol{M}\right)$ are the process and measurement noise respectively and

$$\boldsymbol{\Omega}\left(\boldsymbol{\omega}\right) = \begin{bmatrix} 0 & -\boldsymbol{\omega}^T \\ \boldsymbol{\omega} & \boldsymbol{S}\left(\boldsymbol{\omega}\right) \end{bmatrix}. \qquad (2)$$

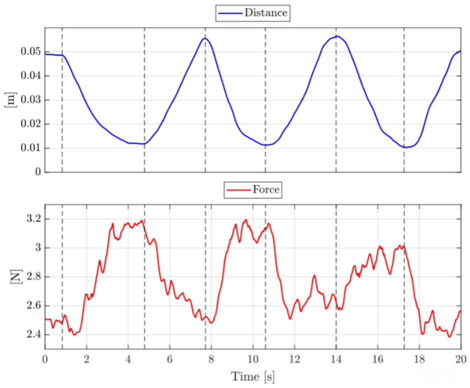

Fig. 1: First evaluation experiment. Duration: 20 seconds. Time histories of: (Blue) Distance between surgical tools; (Red) Related estimated force norm.

Then, the control and measurement matrices used in the EKF implementation are easily computed:

$$\boldsymbol{F} = \begin{bmatrix} \boldsymbol{S}(\boldsymbol{\omega}_g) & \boldsymbol{O}_3 \\ \boldsymbol{O}_3 & \boldsymbol{S}(\boldsymbol{\omega}_g) \end{bmatrix}; \qquad \boldsymbol{H} = \begin{bmatrix} \boldsymbol{I}_3 & \boldsymbol{O}_3 \\ \boldsymbol{O}_3 & \boldsymbol{I}_3 \end{bmatrix}. \quad (3)$$

The collision avoidance between the two tools is ensured by the application of a FRVF. To this purpose, the VF is defined as the swept surface along one of the tool axis. The VF has a cylindrical shape with a radius which is double the tool radius. The minimum distance between the PSM tool tip position $\boldsymbol{x}$ and the cylindrical FRVF of the other tool corresponds to the length of the line segment which joins perpendicularly the point to the axis minus the radius of the cylinder. A constraint enforcement method is defined, consisting in the application of a spring-damper like force $\boldsymbol{f}_{vf}(\tilde{\boldsymbol{x}}, \dot{\tilde{\boldsymbol{x}}}) = -\boldsymbol{K}_{vf}\tilde{\boldsymbol{x}} - \boldsymbol{D}_{vf}\dot{\tilde{\boldsymbol{x}}}$ where $\tilde{\boldsymbol{x}} = \boldsymbol{x}_d - \boldsymbol{x}$ is the displacement between the point $\boldsymbol{x}_d$, belonging to the constraint geometry having minimum distance from $\boldsymbol{x}$. The matrices $\boldsymbol{K}_{vf}$ and $\boldsymbol{D}_{vf}$ are properly designed diagonal and positive definite. The external force is not directly measurable, it is estimated by resorting to a non-linear dynamic observer [2]. Finally, the force imposed by the Virtual Fixture is mapped on the MTM, that is controlled through an impedance controller, to generate the force cues.

III. RESULTS

The collision avoidance strategy is evaluated in two different tasks. During the first evaluation test, the PSM1 tool is fixed and the PSM2 is moved by the user in teleoperation mode towards PSM1. Fig. 1 shows the distance between the two surgical tools, computed considering the proposed tracking method, and the related repulsive haptic force norm rendered to the user through the master side (MTM) during the task. The maximum reached force is 3.2 N. The second evaluation test consists in a human subject study to show significant differences in performance caused by the introduction of force feedback. The study involves 12 subjects divided into two groups, 6 experienced and 6 novice surgeons, based on self-evaluation about their experience in the use of daVinci Robotic system for minimally invasive surgical procedures. During each test, the subject keeps the PSM1 centered in the middle of a circle with a diameter of 20 mm. Meanwhile, the PSM2 has to follow the circular path for 270° from a definite starting point. In the first experiment, the subjects perform the test 5 times moving the surgical tool in free motion and 5 times with the proposed collision avoidance constraint applied. The minimum distance between the tools is considered as performance parameter and it is computed using the proposed tracking method. To demonstrate the statistical relevance of the results, a comparison is made between the mean values of minimum distance, through a statistical unpaired t-test, with a significance level $\alpha = 0.05$. As presented in Table I, the test shows statistically significant differences between the means for all subject in the novice group and an increase in the minimum distance values of $\sim 10\%$ in collision tests with respect to free-hand tests.

TABLE I: Maximum force and t-test results on minimum distance for novice and expert users. The result of the test is 1 if the test rejects the null hypothesis at the 5% significance level, and 0 otherwise.

Novice	test	p	F_M [N]	Expert	test	p	F_M [N]
1	1	0.0044	2.4416	1	0	0.1352	3.4527
2	1	0.0127	3.0749	2	0	0.0856	2.8175
3	1	0.0030	3.3411	3	0	0.8286	3.5239
4	1	0.0219	2.8188	4	0	0.8757	2.6180
5	1	0.0206	3.9998	5	0	0.1140	3.0035
6	1	0.0012	3.4170	6	0	1	2.8800

IV. CONCLUSIONS

This paper introduces a method based virtual fixtures that allows avoiding surgical tools collision in MIRS. A marker-less algorithm allows estimating the PSM pose, using kinematic and visual information. The PSM estimated pose is used to generate a FRVF, that aims to avoid collision between the two instruments through a repulsive force felt at the MTM during the surgical task execution. The proposed strategies are evaluated through multiple experiments on dVRK, showing good results in improving novice surgeon's performance. The goal for future works is to improve the accuracy of the tool pose estimation. For this purpose, more advanced methods for hand-eye calibration and 3D reconstruction will be considered. Moreover, the application of the method can be extended to the collision avoidance of both PSMs and the ECM, when automatic movement of the ECM is imposed.

REFERENCES

[1] R. Moccia, M. Selvaggio, L. Villani, B. Siciliano, and F. Ficuciello, "Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures," *Proc. IEEE International Conference on Intelligent Robots and Systems*, 2019.

[2] M. Selvaggio, G. A. Fontanelli, F. Ficuciello, L. Villani, and B. Siciliano, "Passive Virtual Fixtures adaptation in minimally invasive robotic surgery," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3129–3136, 2018.

[3] G. A. Fontanelli, F. Ficuciello, L. Villani, and B. Siciliano, "Modelling and identification of the da Vinci Research Kit robotic arms," *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1464–1469, 2017.

[4] A. A. Shvets, A. Rakhlin, A. A. Kalinin, and V. I. Iglovikov, "Automatic Instrument Segmentation in Robot-Assisted Surgery using Deep Learning," *Proc. 17th IEEE International Conference on Machine Learning and Applications*, pp. 624–628, 2018.