Enhancing Dexterity with a 7-DoF Laparoscopic Suturing Tool

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INTRODUCTION

Minimally invasive robotic surgery (MIRS) exhibits numerous benefits for patients compared to open surgery. MIRS procedures are possible thanks to dexterous instruments allowing to perform precise manipulation. In a previous work, we have developed a 7-degree-of-freedom (DoF) instrument for the da Vinci Research Kit (dVRK) that allows in-hand needle reorientation through rolling motion [1]. To alleviate the surgeon cognitive workload of simultaneously controlling all the instrument DoFs, shared-control techniques might be employed. This is motivated by the fact that steering a manipulator by simultaneously controlling its position and orientation is a rather complicated and cognitively demanding task. Joint limits and singularities of currently adopted instruments limit the surgeons' dexterity leading to several hand-off movements and reconfigurations.

In this work we propose: (i) the development of a shared-control technique for simultaneous teleoperation and joint limits avoidance; (ii) the assessment of the benefits introduced by the additional DoF on a single stitch trajectory through a dexterity analysis.

METHODS

We consider the modified laparocopic instruments presented in [1], that can be modelled as a 7-DoF manipulator whose end-effector is the needle tip Σ_t (see Fig. 1). Assuming that the manipulator is velocity controlled, it can be described by the equation $\dot{\boldsymbol{q}}_s = \boldsymbol{v}$, where $\boldsymbol{q}_s \in \mathbb{R}^7$ denote the vector of the manipulator generalized coordinates and $\boldsymbol{v}$ is the control input. Employing the standard inverse Jacobian map the joint control input $\boldsymbol{v} \in \mathbb{R}^7$ can be written as [2]

$$\boldsymbol{v} = \underbrace{\boldsymbol{J}_s^{\dagger}\boldsymbol{u}_s}_{\text{primary task}} + \underbrace{(\boldsymbol{I} - \boldsymbol{J}_s^{\dagger}\boldsymbol{J}_s)\dot{\boldsymbol{q}}_{s,0}}_{\text{secondary task}}, \quad (1)$$

where $\boldsymbol{J}_s \in \mathbb{R}^{6\times 7}$ is the manipulator task Jacobian, $\boldsymbol{J}_s^{\dagger}$ denotes its Moore-Penrose pseudoinverse. The control input includes a Cartesian space velocity vector $\boldsymbol{u}_s \in \mathbb{R}^6$ representing the primary task, and an additional velocity $\dot{\boldsymbol{q}}_{s,0} \in \mathbb{R}^7$, projected into the null space of the primary task.

The shared control strategy adopted in this work consists in a human operator action that steers the manipulator along its 6-D Cartesian space and an autonomous regulation of the manipulator redundancy for joint limits avoidance.

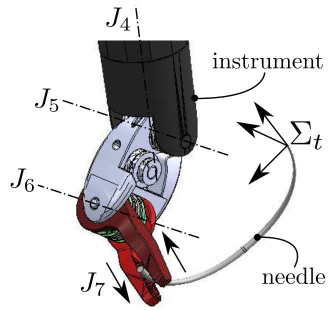

Fig. 1: Representation of the modified dVRK instrument proposed in [1]. $J_4, \ldots, J_7$ represent the joints 4 to 7 axes of the instrument.

This is realized by putting $\boldsymbol{u}_s = \boldsymbol{u}_m \in \mathbb{R}^6$, where $\boldsymbol{u}_m$ is the Cartesian velocity of the master input device, while $\dot{\boldsymbol{q}}_{s,0}$ is the autonomous control action that maximizes the distance from joint limits.

To compute $\dot{\boldsymbol{q}}_{s,0}$ we consider the scalar cost function $h(\boldsymbol{q}_s) : \mathbb{R}^7 \to \mathbb{R}$ [3]

$$h(\boldsymbol{q}_s) = \sum_{i=1}^{n} \frac{1}{4} \frac{(q_{si,max} - q_{si,min})^2}{(q_{si,max} - q_{si})(q_{si} - q_{si,min})}, \quad (2)$$

that is a differentiable function of the generalized coordinates vector $\boldsymbol{q}_s$ which tends to infinity as the i-th joint variable q_{si} approach one of the corresponding joint limits $(q_{si,min}, q_{si,max})$. The gradient $\nabla h(\boldsymbol{q}_s)$ is used to compute the autonomous control contribution for joint limits avoidance according to

$$\dot{\boldsymbol{q}}_{s,0} = -\nabla h(\boldsymbol{q}_s). \quad (3)$$

This term is used to implement the secondary task in (1). It is worth to note that the case $\dot{\boldsymbol{q}}_{s,0} = \boldsymbol{0}$ corresponds to the least-norm joint velocity solution.

A suitable dexterity measure must be adopted to quantify the enhanced motion capability of the 7-DoF tool compared to the standard dVRK tool (6-DoF). This measure can be inferred directly from the robot Jacobian matrix. The influence of the joint limits on the robot dexterity can be taken into account by weighting the entries of the Jacobian matrix according to a joint limits performance criterion [4]. More in detail, a penalization matrix $L(\boldsymbol{q}_s) \in \mathbb{R}^{6\times 7}$

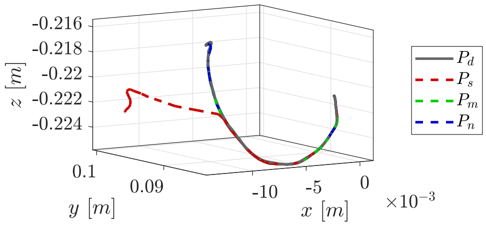

Fig. 2: Desired needle tip path (P_d) versus standard tool (P_s), modified tool least-norm (P_m) and null-space (P_n) paths.

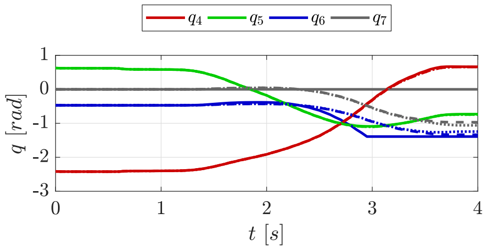

Fig. 3: Time history of joint angles during the proposed experiment. Solid lines represent the 6-DoF case, dashed and dotted lines represent the 7-DoF case least-norm and null-space solutions, respectively.

is introduced to compute the elements of the augmented Jacobian $\tilde{J}(\boldsymbol{q}) \in \mathbb{R}^{6\times 7}$ as

$$\tilde{J}_{i,j}(\boldsymbol{q}_s) = L_{i,j}(\boldsymbol{q}_s) J_{i,j}(\boldsymbol{q}_s), \quad i = 1, \dots 6, \quad j = 1, \dots 7, \tag{4}$$

where $J_{i,j}(\boldsymbol{q}_s)$ is the (i, j) element of the robot Jacobian and $L_{i,j}(\boldsymbol{q}_s)$ is defined as

$$L_{i,j}(\boldsymbol{q}_s) = \frac{1}{\sqrt{1 + |\nabla h_j(\boldsymbol{q}_s)|}}. \tag{5}$$

At this point, taking inspiration from [5], a weighted dexterity measure d can be computed from the augmented Jacobian as

$$d = \frac{\sqrt{rn}}{\sqrt{\mathrm{tr}\left[\left(\tilde{J}\tilde{J}^{\mathrm{T}}\right)^{-1}\right]}}, \tag{6}$$

where $\mathrm{tr}(\cdot)$ denote the trace operator, r and n denote the task and the joint space dimensions, respectively. This index provides similar information of the standard manipulability index [6], but allows comparing manipulators with the same task space dimension independently from the joint space dimension. Moreover, it takes into account the distance from both joint limits and singularities.

EXPERIMENTS AND RESULTS

We performed simulated experiment using the V-REP simulator. The simulated setup recreates the real dVRK slave side. We used a pre-recorded single stitch trajectory and compute $\boldsymbol{u}_m(t)$ from this. The task is executed using both the 6-DoF and 7-DoF tools. In the latter case both the least-norm (i.e., $\dot{\boldsymbol{q}}_{s,0} = 0$) and the null-space solutions are considered. Results of the proposed experiments are given in Figs. 2, 3 and 4. As it can be noticed in the 6-DoF case the trajectory is not successfully completed due to the occurrence of joint limit on the sixth joint (Figs. 2 and 3). This is quantitatively explained by the dexterity measure which approaches zero accordingly (Fig. 4).

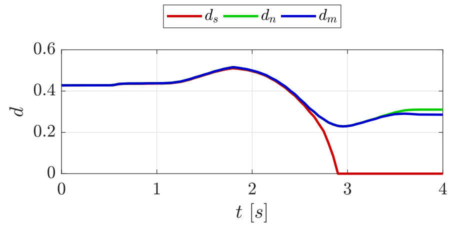

Fig. 4: Dexterity measure along the executed trajectory. d_s represents 6-DoF case, d_m and d_n the 7-DoF least-norm and null-space solutions, respectively.

In the 7-DoF case both the least-norm and the null-space solutions are efficient in terms of joint limits avoidance (Figs. 2 and 3). However, the null space solution demonstrates slightly improved dexterity towards the end of the experiment (Fig. 4) .

We note that, although simulated results are encouraging, the 7-DoF case requires accurate and robust sensing technologies for needle-grasper relative pose estimation in the real scenario.

CONCLUSION

We have presented a shared-control approach for simultaneous teleoperation and joint limits avoidance for a 7-DoF laparoscopic instrument. The results have demonstrated improved dexterity with respect to the 6-DoF case along a single stitch suturing trajectory. Future works will focus on shared control with multi-objective optimization and experiments with the real prototype.

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