Suturing Needle Tracking for Grasping Optimization in Minimally Invasive Surgery

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INTRODUCTION

Minimally Invasive Robotic Surgery (MIRS) completely changes surgical procedures, improving surgeon's technical skills. Suturing represents a very difficult procedure, requiring the surgeon to continuously change the orientation of the needle in order to find the appropriate pose [1]. Difficult condition is also imposed by the robot itself. Particularly, joint limits and singularities are common issues, increasing surgeon's cognitive workload and causes degeneration in performances. Haptic shared control techniques are a powerful method to improve surgeon performances in suturing tasks. A crucial step for the application of such methods is the accurate detection and tracking of the needle. Vision-based techniques exploit colour-based segmentation using markers on the needle, generally not suitable for realistic applications. In [2], the 3D pose of the needle is computed using geometric information, but relying on multiple observations of the needle.

This paper proposes a vision-based tracking of suturing needle, exploiting basic tracking-by-detection techniques, defining the chosen grasping pose for immediate starting the suturing procedure. The method is tested using da Vinci Research Kit (dVRK) robot in a haptic shared control application, guiding the surgeon during reach-to-grasp the needle in suturing task, optimizing the cost of robot joint limits and task-oriented manipulability.

METHODS

Figure 1 shows the experimental setup, composed by the dVRK robot. $\mathcal{F}_r : (O_r - x_r y_r z_r)$ represents the inertial reference frame. Zhang stereo camera calibration is performed to estimate the transformation between the two endoscopic cameras and to define the camera reference frame $\mathcal{F}_c : (O_c - x_c y_c z_c)$. While, $\mathcal{F}_n : (O_n - x_n y_n z_n)$ is the needle center frame. $\mathcal{F}_t : (O_t - x_t y_t z_t)$ is the frame attached to the needle tip and $\mathcal{F}_g : (O_g - x_g y_g z_g)$ represents a frame attached to the robot end-effector corresponding with a generic desired grasping pose. The tracking algorithm allows defining the transformation ${}^cT_n$, mapping $\mathcal{F}_n$ in $\mathcal{F}_c$.

The system takes stereo endoscopic images, as input and the use of robot kinematics allows restricting the

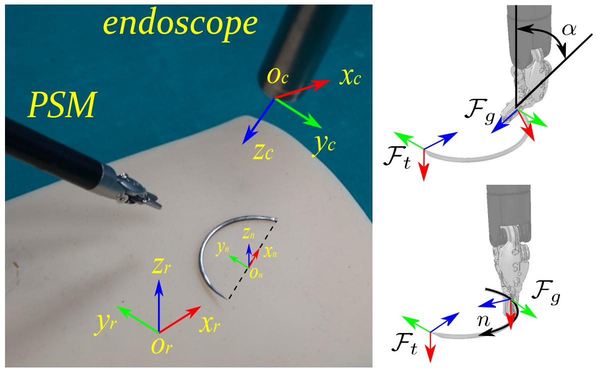

Fig. 1: Experimental setup with reference frames and grasp parametrization of the needle.

image to a region of interest in which the needle is present, thus speeding up computations, and increasing robustness with respect to visual occlusions. A pre-process step is performed, exploiting edges and colour. Then, the widespread *GrabCut* segmentation method is used, defining a binary mask of the needle. This allows computing the minimum rectangle area containing the needle and its ellipse-shaped projection, using least-square fitting method. This leads to the definition of the central point of the needle O_n as the center of the fitted ellipse. Finally, the needle pose is estimated, given the 3D coordinates of five specific points on the needle and their correspondent image projection coordinates on the minimum rectangle, solving the Perspective-n-Points problem with direct linear transform and RANSAC methods. Figure 2 shows the entire system pipeline.

Once the reference frame is defined, a parametrization of the needle grasping $z = [n, \alpha]$ is adopted, identifying the curvilinear abscissa n and the angle α around tangent, as shown in Fig. 1. The system computes the linear and angular velocities of the Patient Side Manipulator (PSM) in $\mathcal{F}_r$ and the joint coordinate vector q, combining the differential forward kinematics of the PSM. These parameters are used to optimize the grasping pose, defining a cost function according with the joint limits. With s as parameter of the trajectory of the needle tip in $\mathcal{F}_t$, the function is expressed as:

$$\mathcal{H}(z) = \int_0^{s^*} h(\hat{q}_g(s, z))ds. \tag{1}$$

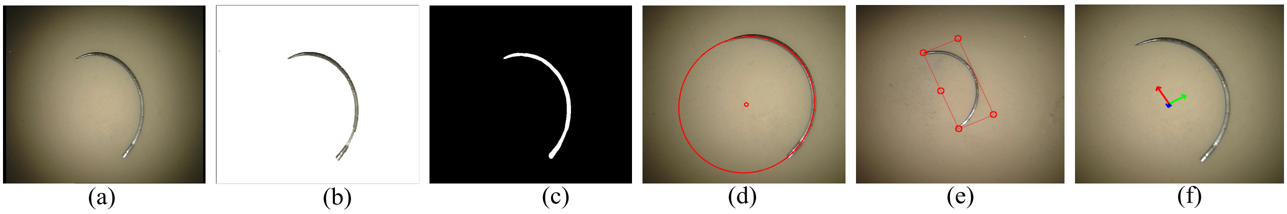

Fig. 2: System pipeline: (a) Original frame; (b) Segmented Image ; (c) Binary mask; (d) Ellipse fitting; (e) Minimum fitting rectangle ; (f) Reference frame generation.

The optimal grasping pose is obtained finding the parameter vector z that minimizes the cost function $\mathcal{H}(z)$, solving through the gradient descent iterative method. The Cartisian pose for the PSM is calculated from the optimal grasping parameter z^* given the needle kinematics and its global pose.
Finally, the corresponding desired Master Tool Manipulator (MTM) pose is determined from the optimal desired pose of the PSM, and a haptic cue is displayed on the MTM through impedance control, guiding the user toward optimal grasping configuration.

RESULTS

The system is validated by executing multiple suturing tasks using the dVRK robot. To evaluate the accuracy of the tracking method, the 3D coordinates of the first corner of a chessboard, positioned on the origin of $\mathcal{F}_n$ from the vision-algorithm, is calculated. A mean absolute error of 1.4 mm is obtained between the corner and origin coordinates.
During the experiments the dVRK is set in teleoperation mode, with the PSM commanded by one MTM, with impedance control implemented thanks to the dVRK dynamic model identified in [3]. The obtained grasping pose is used to generate force cues and inform the user during the reach-to-grasp phase. The operator feels haptic cues, shown in Fig. 4, during the experiment shown in Fig. 3 The force cues decrease by the closeness to the optimal grasping pose. Correspondingly, post-grasp movements during the suturing task execution are free from joint limits and singularities.

CONCLUSION

This paper proposes a vision-based tracking of suturing needle. The method finds application in haptic shared control technique using dVRK, minimizing the possibility of encountering joint limits and singularities during the suturing task. The optimal grasp pose is used to compute force cues which guide the user's hand via a MTM. The mean absolute error suggests the feasibility of the tracking method, while the effectiveness of the shared control for needle grasping is illustrated using experiments performed on dVRK.
The goal of future works is to consider kinematic information from the robot and fusing it with visual information using Kalman or Particle filter as in [4], exploiting the proposed vision-based tracking. Moreover, quantifying performance improvements via a proper human subject test is another future extension of this work.

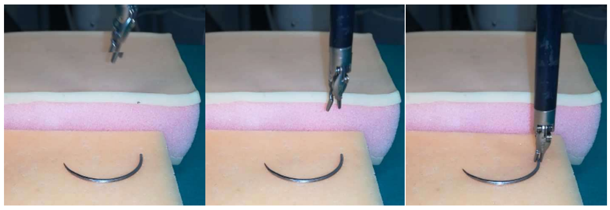

Fig. 3: Grasping a needle using PSM: (a) Initial pose; (b) Approaching; (c) Grasping.

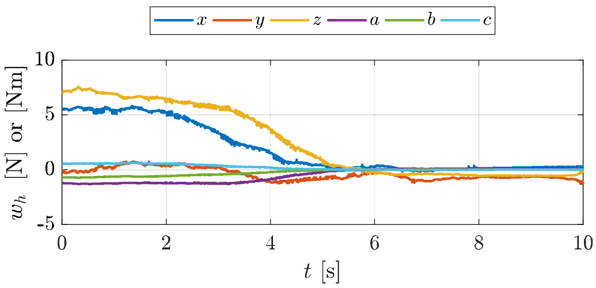

Fig. 4: Haptic guidance force felt by the user during experiment.

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