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Admittance Control for Robot Assisted Retinal Vein Micro-Cannulation under Human-Robot Collaborative Mode

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Abstract

Retinal vein occlusion is one of the most common retinovascular diseases. Retinal vein cannulation is a potentially effective treatment method for this condition that currently lies, however, at the limits of human capabilities. In this work, the aim is to use robotic systems and advanced instrumentation to alleviate these challenges, and assist the procedure via a human-robot collaborative mode based on our earlier work on the Steady-Hand Eye Robot and force-sensing instruments. An admittance control method is employed to stabilize the cannula relative to the vein and maintain it inside the lumen during the injection process. A pre-stress strategy is used to prevent the tip of microneedle from getting out of vein in prolonged infusions, and the performance is verified through simulations.

Keywords

retinal vein cannulation; admittance control; human-robot collaboration; performance constraint

I. Introduction

Retinal vein occlusion (RVO) is the second leading retinal vascular disease affecting about 16.4 million adults worldwide and is a common cause of blindness [1]. Retinal vein cannulation (RVC) is a currently experimental treatment for RVO aiming to dissolve the clot causing the occlusion by injecting tissue plasminogen activator (t-PA) into the affected vein directly [2].

To perform RVC, the surgeon needs to insert micro-instruments through the sclera to approach the affected region on the retina and perform fine manipulations on the very delicate retinal vasculature. The manipulation has to be done in an extremely confined space with limited visual feedback through the surgical microscope, especially in terms of depth perception. In addition, the diameter of branch retinal veins is typically less than 100 μ m, which requires precisely manipulating an even smaller cannula tip although the average

amplitude of physiological hand tremor of vitreoretinal surgeons was found to exceed 100 μm [12]. Furthermore, the tactile sensory threshold of humans is well above the very fine interaction forces between the cannula and the retina during RVC. Once the cannula tip pierces through the vein wall, it needs to be kept within the lumen while delivering t-PA until the occlusion is resolved, which can take several minutes. In the presence of unpredictable movements of the eyeball, holding the cannula fixed relative to the vasculature freehand throughout the infusion is almost impossible. Robotic systems and sensitized instruments can effectively enhance and extend the surgeon's capabilities during this microsurgical task. In the domain of retinal microsurgery, many robotic platforms and advanced instruments have been developed proposing different operational modes: hand-held robotic instruments such as the Micron [3], tele-operated robotic system such as Preceyes Surgical System [4] and untethered microrobots such as the OctoMag [5]. These robotic systems focus on enhancing the precision and sensitivity of the operation, improving the consistency in the quality of surgeries, lessening the intra-operative risks and effort of the surgeon, and thereby enabling treatment of more patients and new surgical methods. In RVC operation, not all the tasks are well suited to be done by the robotic system: for some complex tasks the human has higher operating efficiency than the robot does [6]. We have developed the Steady-Hand Eye Robot [7, 8] with hands-on operating function, where the surgeon and the robot hold and guide the surgical instrument together. The robot moves the surgical instrument with a speed that is proportional to the forces applied by the surgeon on the surgical instrument's handpiece. While approaching the target vein, this mode of operation provides a smooth tremor-free manipulation of the cannula with an intuitive control for the surgeon. However, once the cannula is inside the vein, previous experiments have shown that it is not sufficient to hold the cannula fixed for a prolonged infusion. In addition, there exists no feedback mechanism to maintain the cannula inside the vein in case of a potential movement of the eyeball.

In this paper, we present an approach to achieve and maintain cannulation by following a human-robot collaborative mode. In the following sections, firstly, we will present the planning of tasks to achieve RVC. Second, admittance control method will be applied to solve the hands-on problem in cooperative process, and performance constraints are introduced to prevent the surgeon from moving the robot to its extreme postures. Third, a pre-stress strategy will be introduced for keeping the cannula tip inside the vein during infusion, and an admittance controller will be designed to make the cannula follow the movement of retinal vein while the eyeball moves randomly. Finally, simulations will evaluate the system operation. The paper concludes with a discussion of results and future directions.

II. Human-robot collaborative mode

A. System Components

Our robotic system for RVC includes a microscope, the Steady-Hand Eye Robot [7, 8] and a force-sensing microneedle instrument as the cannula [9, 10] (Fig. 1). The robot has 5 actuated degrees-of-freedom (DOF). There is a 6-DOF force sensor integrated on the tool mount of the robot so that the robot senses the user's forcing and therefore intended

movement of the surgical tool. By holding the tool handle and forcing it in 6-DOF, the user can move the robot and hence the attached cannula to the desired position and orientation based on admittance control.

As the end effector of the robot, we attached a force-sensing micro-needle to the tool mount. This tool was developed in our earlier work [9, 10] and has a pre-bent tip (45°) with a diameter of $70\text{ }\mu\text{m}$ to approach the small branch retinal veins at an optimal angle for easier and safer insertion. Three fiber Bragg gratings (FBG) are integrated on the tool shaft (Fig. 2). In this way, the force-sensitive segment of the tool is remained inside the eye close to the surgical site to accurately capture the interaction forces between the needle tip and the retinal vein, which lead to a fine enough resolution of 0.25 mN .

B. Planning of Human-Robot Collaborative Mode

There are two consecutive challenges in RVC: (1) achieving cannulation by puncturing the retinal vein, (2) maintaining cannulation by holding the cannula inside the vein lumen while delivering the drug. Until the venous puncture, our robot assisted system performs at a cooperative mode (Fig. 3). The stiff robotic arm damps out the tremulous input from the operator's hand as the user guides the cannula onto the occluded vein and orients the cannula at the desired approach angle before puncture based on the visual feedback from the microscope. After touching the vein surface, the force-sensing micro-needle quantifies tool-tissue interaction forces and can detect the instant of venous puncture based on these measurements [9]. During this manipulation, the operator may move the robot toward the boundaries of its workspace, which is an issue that will be addressed in Section III.A.

After the venous puncture, during the drug delivery period, our system works in an autonomous mode consisting of two steps. First, the robot moves the needle gradually into the vein to apply a desired stress on it. Second, the robot makes the micro-needle follow the movement of vein according to variation of this pre-stress to avoid being out of vein. Pre-stress, defined as maximum tool-tissue safe contact force, is applied at the needle tip before injecting drug. This strategy is proposed to ensure that the physical contact is stable and the needle tip reliably remains inside the vein even when the eye moves unpredictably (i.e. it is necessary to ensure the effective physical contact tool tip-to-tissue). This strategy will be presented in section III B.

III. Cartesian admittance robot controller

In the cooperative process surgeon holds the tool together with manipulator to guide them to the right position and posture, there is interactive force between surgeon's hand and the end of manipulator. Moreover, in the autonomous process robot keeps the tip of needle in the vein, interactive force between tip of needle and tissue of vein occurs. Cartesian admittance control is just the method to map these interactive forces to the task space velocities. However, addressing the problems of providing feedback to the surgeon about the manipulator's performance and reliably keeping the tip of microneedle in the vein are also challenges.

A. Performance Constraint in Admittance Control for Hands-on Cooperative Task

Safe and efficient interaction requires that robot operates within its capabilities. We proposed a method that applies a performance constraint to the frame of admittance controller (Fig. 4), this virtual constraint according to the distance from the extreme position applies feedback force to operator's hand [11].

The performance index $\delta(q) \in \mathbb{R}$ should be above the lowest performance index δ_{ep} , it depends on the configuration $q \in \mathbb{R}^5$ of this 5 DOF manipulator. The virtual force $F_p \in \mathbb{R}^6$ is proposed as the virtual constraint to prevent the manipulator from a low performance configuration. The value of F_p is determined from the difference between current performance index $\delta(q)$ and the safety performance threshold δ_{pt} as

$$F_p = \gamma(\delta)A(q) \quad (1)$$

where $A(q) \propto \nabla \delta(q) \in \mathbb{R}^6$ is the performance measure related with the principal axes of the Cartesian frame attached to the end of manipulator. The $\gamma(\delta)$ is activated when the performance is lower than the safety performance threshold and increases asymptotically as it is getting close to the desired threshold:

$$\gamma(\delta) = \begin{cases} \lambda \left(\frac{1}{\delta(q) - \delta_{ep}} - \frac{1}{\delta_{pt} - \delta_{ep}} \right), & \delta(q) \leq \delta_{pt} \\ 0, & \delta(q) > \delta_{pt} \end{cases} \quad (2)$$

where the positive gain $\lambda \in \mathbb{R}$ affects the magnitude of $\gamma(\delta)$, that is the surgeon realizes the manipulator soft or hard.

The virtual force F_p is added to the dynamics of manipulator:

$$M_{cd}\dot{V}_{cref} + C_{cd}V_{cref} = F_h + F_p \quad (3)$$

where $V_{cref} \in \mathbb{R}^6$ is the desired velocity of the manipulator in Cartesian space, F_h is a vector represents the force that surgeon hands on the tool fixed on the end of manipulator. The coefficients M_{cd} and $C_{cd} \in \mathbb{R}^{6 \times 6}$ are decided to the inertia and damping such as the manipulator end-effector adapts to the interactive force applied by surgeon's hand.

B. Admittance Controller Following the Pre-stress for Keeping the Microneedle inside the Vein

To keep the needle tip inside the vein, the desired force F_{pre} is applied by the needle to the vein with the same direction as the motion of puncture along the axis of vein. The task of keeping the microneedle tip inside the vein is transformed to maintaining this interactive force. Admittance controller can compensate the variation of interactive force by adjusting

the microneedle velocity. Reciprocating movement of eyeball occurs in a small range unpredictably, so the admittance controller should response quickly as well as be stable.

The FBG-based force sensor integrated in the tool shaft can sense the interactive force, which feeds back to the robotic system, so the robot can keep the microneedle inside the vein automatically.

The pre-stress F_{pre} manipulator with force sensing instrument (Fig. 5):

$$M_{ad}\dot{V}_{aref} + C_{ad}V_{aref} = F_{av} \quad (4)$$

where $V_{aref} \in \mathbb{R}^6$ is the desired velocity of the microneedle in Cartesian space, F_{av} is a vector represents the variety of interactive force. The coefficients M_{ad} and $C_{ad} \in \mathbb{R}^{6 \times 6}$ according to the desired inertia and damping of the microneedle. The variety of interactive force:

$$F_{av} = F_t - F_{pre} \quad (5)$$

where F_t is a vector representing the output force of the microneedle.

IV. Simulation and results

We created a 5-DOF robot arm with the same configuration as the Steady-Hand Eye Robot and with the corresponding D-H parameters in simulation. In the following simulations, the controllers designed in section III are evaluated and the results are discussed.

A. Admittance Controller with Performance Constraint for Hands-on Task

To simulate the hands-on task in the cooperative process, a hand force of $F_h = [0, 1, 0]$ N is applied to the end of manipulator. Results in Fig. 6a show that the position of the manipulator end-effector varies uniformly and smoothly along the Y-axis at the beginning. During this time, the virtual force is zero since the manipulator is in a “good performance” status, meaning that it can follow the movement of the hand stably (Fig. 6b). As manipulator is driven in the same direction continuously, it is led toward a configuration with “low performance.” At time t_a in Fig. 6b, the constraint index becomes lower than the safe performance threshold δ_{pb} , which triggers the performance constraint to quickly apply a virtual force on the operator’s hand as a feedback to prevent from leading the manipulator to lower performance continuously. In order to further evaluate this controller, the hand continues to move along Y-axis with constant force 1N instead of changing the path. Simulation results show that the performance constraint can effectively increase the virtual force faster and faster as the performance index getting lower along Y-axis. Finally, the value of virtual force increases to 1N, which is enough to offset the external force (from hand) before manipulator, crosses the lowest performance.

The proposed admittance controller with performance constraint is not only able to achieve stable hands-on following movement of manipulator, but also can prevent the robot from becoming low performance effectively by feeding.

B. Pre-stress Strategy in Admittance Controller for Keeping the Microneedle inside the Vein

According to the characteristics of eyeball movement in RVC operation, in the simulation, reciprocating movement of vein is made along the Y-axis in the region $[-2, 2]$ mm, the initial position is at the origin (Fig. 7a). We assume the tissue of vein is characterized only by elasticity that varies linearly. For the simulation, the pre-stress is set at 1.5 mN. In a real scenario, the pre-stress will be experimentally determined as maximum safe tool-tissue interaction force. We accomplished the simulation with and without the pre-stress strategy to compare the results.

Blue area (Fig. 7) is the effective contact range between microneedle and vein. When the contact force along the vein is in blue area, the microneedle tip must be inside the vein. In contrast, white area is the ineffective contact range: if interactive force gets into the ineffective contact range, it is unable to keep the microneedle tip inside the vein. The brown line is the interactive force without admittance controller and the red line is the result with admittance controller during the retinal vein movement process. Results show that this admittance controller can effectively make the microneedle follow the reciprocating movement in range of $[-2, 2]$ mm. In addition, this controller gets into stable state fast enough to avoid sudden change of movement at the maximum position, which could affect the controller stability. However, without the pre-stress, sometimes the variable interactive force could get into the ineffective contact range before the controller becomes stable. In this case, the controller is unable to ensure that the microneedle tip is inside the vein. Nevertheless, the results (Fig. 7b.) show that pre-stress strategy can effectively prevent the interactive force from getting into the ineffective contact range. Consequently, the proposed admittance controller is successful in making the needle following the reciprocating movement of vein in a small range, and the pre-stress strategy further prevent the needle tip from being out of the vein.

V. Conclusion

In this work, we reported on an admittance controller with performance constraints for human-robot collaboration to achieve and maintain cannulation for a longer period. In our system, the surgeon and the robot together hold and guide the cannula to perform RVC. The implemented controller provided stable manipulation of the cannula towards the vein, and prevented the robot from reaching its extreme configurations with low performance by feeding back virtual force to the surgeon's hand during the cooperative process. A pre-stress has been added to the admittance controller to make sure that the microneedle tip stays inside the vein even when the eyeball moves unpredictably. Our future work will focus on implementing the methods presented above to the actual physical setup and validating the operation through experiments using moving phantoms.

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Figure 1.
Robot-assisted vein cannulation: *in-vivo* experimental setup.

Figure 2.

The force-sensing microneedle during RVC. The bent tip enables a gradual approach into the vein and easier venous puncture with less tissue recoil. The attached fiber Bragg grating strain sensors measure tool-tissue interaction forces and detect the instant of venous puncture. The goal is to maintain this configuration (needle tip inside the vein) throughout the drug delivery.

Figure 3.
Process of human-robot collaboration for robot assisted RVC.

Figure 4. Block diagram of admittance controller with performance constraint for hands-on cooperative task

Figure 5.
Block diagram of admittance controller following the desired force to keep the microneedle in the vein.

Figure 6. Simulation results for the implemented performance constraint in admittance control: (a) Cartesian position. (b) Constraining force along X, Y and Z axes while driving the manipulator towards an extreme position/orientation, which triggers the performance constraint to generate assistive external force to resist and slow down reaching the extremum.

Figure 7. Simulation results of pre-stress strategy in admittance controller for tracking a reciprocating movement in small range: (a) Admittance controller without pre-stress strategy. (b) Admittance controller with pre-stress strategy.