dVRK-based teleoperation of a CTR robot with stereovision feedback for neurosurgery

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INTRODUCTION

Flexible robotic tools can be used to perform procedures inside the brain with a minimally invasive approach by providing enhanced dexterity with their tentacle-like bodies. However, intuitive and efficient manipulation of the robotic tools remains challenging because currently the surgeon manipulates the robotic tools with feedback of monocular vision from a standard clinical neuro-endoscope suffering from lack of depth perception. In this paper, we propose a robotic system with a flexible end-effector and stereovision feedback for neurosurgery by integrating our previously-developed Concentric Tube Robot (CTR) [1], the da Vinci Robot Research Kit (dVRK) [2] and a customized dual endoscope camera subsystem. The CTR manipulator was teleoperated with the dVRK master tool manipulator (MTM). A virtual motion boundary was applied for the MTM by haptic feedback based on the CTR's workspace to guide the operator to control the CTR within its motion range. The manipulation performance of the proposed system was experimentally evaluated and the results showed that under the stereovision feedback the manipulation accuracy of the CTR was 2.8 mm and the image transmission latency was 1.5 seconds. This preliminary study suggests that our proposed system has the potential of improving surgeons' manipulation performance in robot-assisted minimally invasive neurosurgery.

MATERIALS AND METHODS

A. Robotic system

The proposed robotic system mainly consists of three components, as shown in Fig. 1, including the MTM, the CTR manipulator, and a customized dual camera endoscope. The MTM is a haptic console with 7 degrees-of-freedom (DoFs) and was used to operate the CTR manipulator remotely. A vision system with two monitors was mounted above the MTM and was utilized to provide stereo visual perception for the operator. The CTR manipulator was developed with three concentric deployed NiTi tubes and has six DoFs at its tip. The workspace of the CTR is obtained as the shape of an inverted bell with bottom diameter of 32 mm and height of 35 mm. The absolute error of the CTR's tip positioning is 2.8 mm with a standard deviation 1.5 mm [1]. Two USB mini-camera probes (MODOSON, China) with 3.9 mm diameter and resolution of 720p were selected as the endoscopes. The two camera probes were aligned manually to provide the images with proper orientations for stereo vision reconstruction, which were then fixed side-by-side by a 3D-printed trocar, and deployed parallelly with the CTR's tube holder.

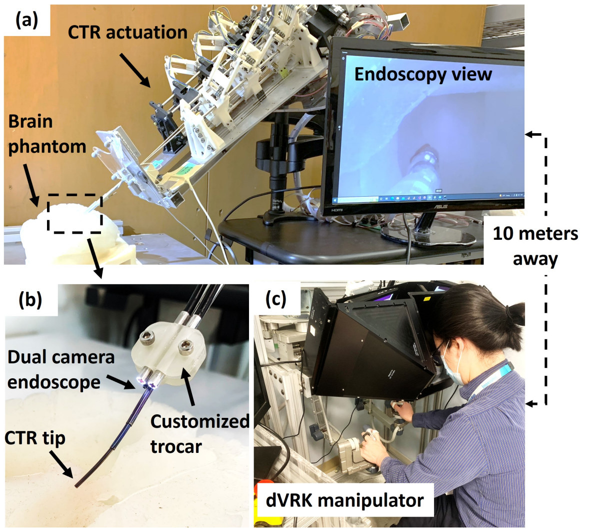

Fig. 1 Overview of the robotic system. (a) CTR, (b) dual endoscopy cameras, (c) master manipulator of the dVRK.

B. Control architecture

The control architecture of the robotic system is shown in Fig. 2. The operator sits beside the MTM and teleoperates the CTR, while obtaining the stereo vision feedback from the customized dual-camera endoscope at the CTR side. The control command, i.e., the MTM's gripper real-time position, is converted from ROS messages to UDP messages and then sent to the CTR system via the local area network (LAN). The received data is fed

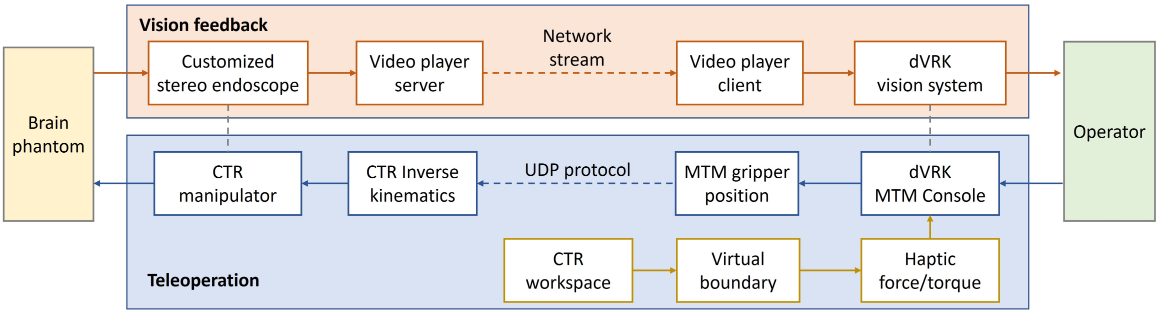

Fig. 2 Control architecture of the robotic system. The operator controls the CTR manipulator via the dVRK MTM and gets the stereo vision feedback from the customized dual endoscope cameras at the CTR side.

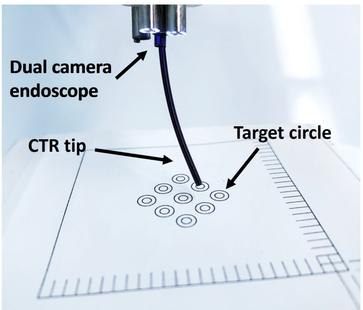

Fig. 3 Experimental setup. A group of concentric circles is printed on a sheet of paper and is used to evaluate the CTR's teleoperation accuracy.

into the CTR's inverse kinematic model to generate the CTR's desired position. The real-time images from the two USB camera probes are fetched with a video player sever (VLC media player, VideoLAN) and then streamed through the LAN to a video player client. The received images are projected on the two screens of the dVRK vision system. The vision system has a calibrated stereo observer which fuses the two images into the stereo vision for the surgeon. We set virtual boundaries for the MTM based on the CTR's reachable workspace using haptic feedback. The operator is guided to control the CTR within its motion range all the time. This feature intuitively avoids invalid command positions sent to the CTR and thus can improve the operation efficiency.

C. Experiments

A set of experiments were carried out to evaluate the teleoperation accuracy of the CTR manipulator. Nine groups of two concentric circles with diameters of 2 mm and 4 mm were printed on a sheet of paper. The paper was stuck to a stage and placed under the CTR, as shown in Fig. 3. The circles cover the entire workspace of the CTR. In the experiment, a human operator was expected to maneuver the MTM with the stereo feedback to control the CTR's tip to touch all circle centers in sequence. The hit locations of the CTR's tip were recorded and used to calculate the accuracy with the below rules: the accuracy is 1 mm if the CTR's tip was located inside of the inner circle and 2 mm if the CTR's tip was located inside of the outer circle but out of the inner circle. One engineer who was familiar with both CTR and MTM was recruited to perform the experiment. The experiment was repeated 5 times.

TABLE I Evaluation Result

	Mean value	Standard deviation
Teleoperation accuracy	2.8 mm	0.3 mm
Stereovision latency	1.5 second	0.2 second
Completion time	9 minutes	1.2 minutes

RESULTS

The experimental results are shown in Table I. The accuracy of the CTR's tip localization under teleoperation was 2.8 mm with a standard deviation of 0.3 mm. The image stream latency is also evaluated with a timer and the result showed the delay was 1.5 seconds. The average completion time for the experiments was 9 minutes.

DISCUSSION

This preliminary study indicates that our proposed robotic system has the potential to be used in brain surgery, although the performance could be further improved. The video delay could be a significant source affecting the robot manipulation accuracy and could be caused by using the USB format and non-direct LAN setup. We tested the video live stream with a direct camera connection to the dVRK and found the delay was diminished to 0.3-0.4 seconds. Such a fast video relay subsequently resulted in a shorter task completion time. We set the robotic system 10 meters away from the dVRK MTM to show the feasibility of remote operation but the distance can be changed as required. Future study will investigate the minimization of the customized trocar and video latency. Simulated procedures on a brain phantom will also be explored.

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