A Dual-Arm Robotic Neuroendoscope: Early Results

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INTRODUCTION

Robotic-assisted Minimally Invasive Surgery (MIS) is becoming a standard practice in many therapeutic procedures in hospitals around the world. Adopting robots in many MIS procedures has been proven to be effective in reducing the postoperative trauma, and the length of hospital stay amongst other benefits. However, due to the size of the available surgical robotic tools, application of robotic-assisted MIS has remained limited to adults and procedures with relatively large workspace. At Centre for Image-Guided Innovation and Therapeutic Intervention (CIGITI), along with several other research centers around the world, we have been working on developing miniaturized robotic tools to bring the benefits of robotic surgery to challenging procedures such as neurosurgery. It is expected that these tools will offer superior dexterity over the current manual endoscopic tools while traversing to the surgical site through small ports.

Performing brain intraventricular procedures including endoscopic third ventriculostomy (ETV) and tumor biopsy/excision using standard endoscopic tools is technically challenging or sometimes not possible. An ETV procedure is performed by introducing an endoscope into the brain through a small burr hole in the skull to create a small perforation in the floor of the third ventricle to discharge the cerebrospinal fluid (CSF) that has blocked the ventricle. This is usually followed by choroid plexus cauterization (CPC) to ensure a sufficient reduction in CSF production. In this paper, a bi-manual robotic neuroendoscopic tool is presented that can provide additional dexterity and stiffness over the standard endoscopic tools for performing procedures such as ETV and tumor biopsy or excision.

MATERIALS AND METHODS

The system is composed of a slave device, two haptic master devices and an embedded controller, which consists of Quanser QPID boards, and a PC running Simulink and Quanser QUARC. The slave device is a dual-arm concentric-tube robot equipped with miniaturized end-effectors (Fig. 1). Of all common miniaturized manipulator design concepts, concentric-tube robots (CTRs) [2] have proven to deliver an optimum blend of dexterity and stiffness with a relatively straight-forward fabrication process. The slave device is composed of a trocar, (with dimensions close to a standard trocar), two arms and the actuation unit. The trocar is 120 mm extended beyond the trocar holder and has a diameter of 9 mm. It has five channels including two 2.7-mm channels for the instrument arms, a 5.5-mm channel for the camera, and three 2-mm channels for suction, irrigation and overflow.

Each arm is composed of two NiTi superelastic tubes and an end-effector. The actuation unit houses eight Maxon DC motors for rotation and translation of the tubes, and two Firgelli linear actuators (Firgelli Technologies Inc., BC, Canada) for the end-effectors. The left arm is equipped with a pair of biopsy forceps taken from Olympus Inc., Japan, and the right arm is equipped with a pair of scissors from Hipp Endoskop Service, Germany. The linear motion of the tubes is realized using four lead screws with a pitch of 5 mm. The unit is equipped with 4 linear and 4 rotary potentiometers along with motor encoders, i.e. a total of 16 sensors.

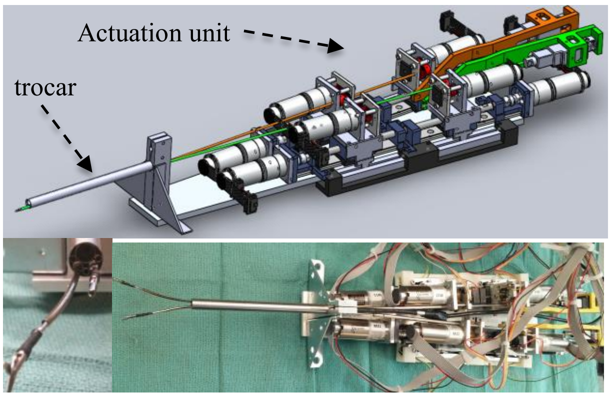

Fig. 1 The slave device is a dual-arm concentric-tube robot that is composed of the trocar, the arms and the actuation unit. The CAD model (top), the actual prototype (bottom right), the trocar (bottom left).

As indicated in Table I, each arm consists of a straight 0.94 mm by 1.37 mm inner tube and a precurved 1.95 mm by 2.41 mm outer tube rendering 4 degrees of freedom that is superior to what can be achieved by standard endoscopes. Theoretically, with this design, torsion in the system will be eliminated and the inverse kinematics can be solved analytically.

Table I. The tubes dimensions

	ID (mm)	OD (mm)	κ (1/mm)
Inner tube	0.94	1.37	0
Outer tube	1.95	2.41	0.012

The arms are operated by means of two Geomagic touch haptic controllers (Geomagic Inc., NC, USA), and a real-time video of the surgical site is captured by a camera endoscope. This visual feedback enables the operator to intuitively operate the robotic arms to manipulate tissue using the master controllers.

A snapshot of the workspace of the dual-arm system is shown in Fig. 2. (left) This workspace is significantly different from the workspace of the master devices we used. This dissimilarity could potentially make the teleoperation less intuitive. In order to address this issue, a reactive barrier force (aka virtual fixture) is implemented to confine the operator's hand position to a subset of the master workspace with a similar geometry to that of the slave. In order to avoid energy leaks and guarantee stability, the barrier force is modeled as a spring/damper system [1].

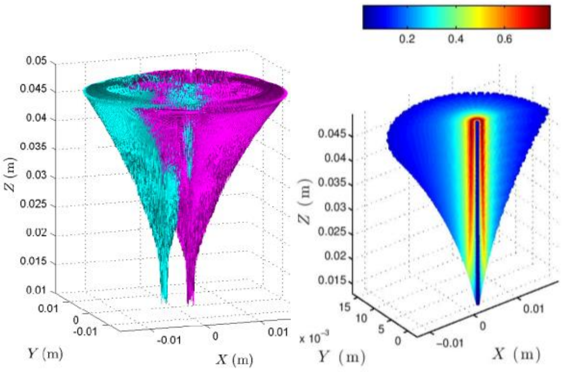

Fig. 2 The dual-arm workspace (left) Dexterity (right).

RESULTS

The system performance is quantitatively evaluated in terms of various measures such as system accuracy, dexterity, and stiffness. Table II outlines the accuracy and stiffness of the arms and Fig. 2 (right) shows the dexterity distribution of the arms over the workspace.

Table II. System Performance

	Accuracy (mean, 95th percentile)	Minimum stiffness
Right Arm	(0.7 mm, 1.3 mm)	6.73E-3 Nm^2
Left Arm	(1.2 mm, 2.2 mm)	6.73E-3 Nm^2

Finally, the system was evaluated qualitatively through two experiments. In the first experiment, a silicon phantom model created from the MR images of the brain of a patient diagnosed with hydrocephalus was used to evaluate the reachability of the slave arms. The brain phantom and the ventricle measured 120 mm x 140 mm and 30 mm x 40 mm respectively. The trocar was inserted through a burr hole into the phantom and the arms were deployed through the trocar. Under direct vision the arms were teleoperated to touch various locations inside the ventricle. As shown in Fig. 3, the experiment demonstrated that the intraventricular extremities were reachable by the arms.

In the second experiment, the system capability was qualitatively tested through a peg transfer task (Fig. 4). On the first attempt, we were able to transfer three pegs on the board within a minute. The speed could have been further improved provided that a stereo camera endoscope had been adopted to improve the depth perception. This result also signifies that this teleoperation system provides an acceptable hand/eye coordination as well as sufficient dexterity for many complex tasks.

Fig. 3 Intraventricular reachability evaluation in a silicon brain phantom.

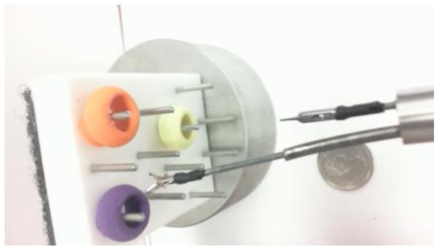

Fig. 4 A snapshot of the peg transfer demonstration[1].

DISCUSSION

In this paper, design and preliminary evaluation of a dual-arm teleoperated robotic neuroendoscope is reported. Through quantitative and qualitative analysis, it was demonstrated that the system is clinically advantageous by enabling miniaturized surgical tools to travel within a small workspace while maintaining a perfect balance of dexterity and stiffness for manipulation. While it is evident that the current system offers a significant advantage over standard neuroendoscopes, the preliminary evaluations suggest that the performance of the system could be drastically improved by incorporating additional degrees of freedom, i.e. more tubes, reducing the friction/backlash, and finally by accurate shape setting of the tubes.

REFERENCES

[1] Colgate J. E., Grafing PE, Stanley MC, Schenkel G. Implementation of stiff virtual walls in force-reflecting interfaces. InVirtual Reality Annual International Symposium, 1993., 1993 IEEE 1993 Sep 18 (pp. 202-208). IEEE.

[2] Webster III RJ, Romano JM, Cowan NJ. Mechanics of precurved-tube continuum robots. Robotics, IEEE Transactions on. 2009 Feb;25(1):67-78.

[1]Watch a demo video at: https://www.youtube.com/watch?v=kCwUAm8hnXE.