Extending the Reach and Stability of Manually Steerable Neuroendoscopes Through Robotics

Pierre E. Dupont[1], Szymon Chawarski[2], Evan J. Butler[2], Robert Hammond-Oakley[2], Andrew H. Gosline[1], Patrick Codd[1], Tomer Anor[1], Joseph R. Madsen[1] and Jesse Lock[2]

[1]*Children's Hospital Boston, Harvard Medical School, Boston, MA USA,*

[2]*Sterling Point Research, Winchester, MA USA*
pierre.dupont@childrens.harvard.edu

INTRODUCTION

Neurosurgical disease encompasses a wide range of devastating pathologies, ranging from brain tumors, epilepsy, hydrocephalus and vascular malformations to brain trauma. Over 2 million neurosurgical procedures are performed annually in the United States alone, including roughly 380,000 operations requiring intracranial access [1]. During open brain surgery, adequate visualization and tool maneuverability often require significant bone removal and harmful traction on otherwise uninvolved brain to accomplish the surgical task.

Surgeries abutting the fluid-filled spaces of the brain have provided the opportunity to reduce invasiveness through the use of endoscopy. Examples include straight rigid endoscopes inserted transphenoidally for procedures at the skull base, e.g., removal of lesions in or near the pituitary gland, and manually steerable flexible endoscopes employed through small cranial burr holes into the ventricular spaces to treat tumors, cysts, hydrocephalus and epileptogenic lesions. Despite this progress, there are many procedures in the fluid-filled regions that still require open surgery owing to limitations in the ability to navigate the endoscope to the surgical site and to provide precise tool control.

To address these limitations, this paper presents a robotic drive system for controlling the degrees of freedom of a manually steerable endoscope. By eliminating the need for the surgeon (or surgeons) to continuously maintain the manual forces and positions on the endoscope needed to achieve the desired configuration, the precision and stability of the endoscope's motion is enhanced. Furthermore, the workspace of the endoscope's tip is extended by also providing robotic control of concentric pre-curved elastic tool-delivery tubes extending through the endoscope's working channel [2]. This enables tools to reach deeper into the ventricles than existing instrumentation allows (Fig. 1).

MATERIALS AND METHODS

A robotic drive system was constructed to control the degrees of freedom of a manual neuroendoscope as well as those of a port-deployed tool (Fig. 2). In manual use, one hand controls endoscope position and orientation at the entry point into the brain while the other hand controls tip curvature and tool deployment. Not shown, a second surgeon may also assist in endoscope positioning and in tool deployment. Since the entry location into the brain is fixed, the endoscope possesses five actively controlled degrees of freedom. These correspond to two rotational axes for pivoting about the entry point, roll angle, insertion length and tip curvature.

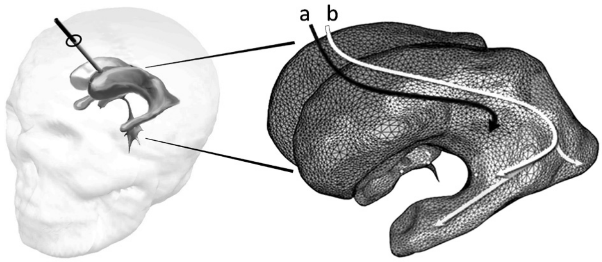

Fig. 1 – Intraventricular access through cranial burr hole. (a) Workspace of manual endoscope. (b) Desired workspace.

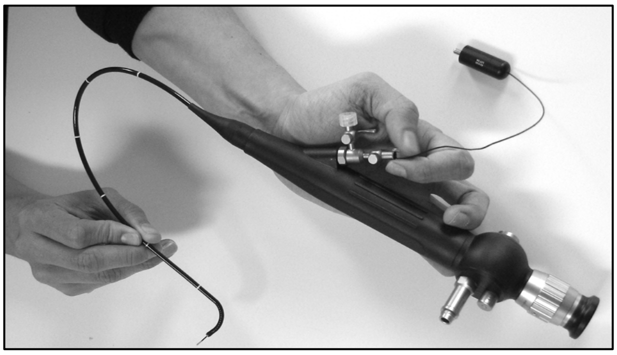

Fig. 2. Steerable manual neuroendoscope (Karl Storz). Inserted through cranial burr hole, scope tip possesses 5 degrees of freedom. Right hand controls 3 orientation axes at insertion point plus insertion length. Left hand controls tip curvature plus additional tool degrees of freedom as shown.

The robotic drive system is comprised of two major components. The first is designed to support and control the five endoscope degrees of freedom. The second component controls the concentric tube robot used for tool positioning. For the specific clinical application of choroid plexus cauterization to treat hydrocephalus, a concentric tube robot consisting of two telescoping fixed curvature segments was designed to enable navigation throughout the temporal horns of the lateral ventricles as shown by the longest white arrows of Fig. 1, which constitute the farthest reach from the frontal burr hole [3]. These sections, depicted extended in Fig. 3, conform to the curvature of the endoscope when retracted inside it. The proximal fixed-curvature section possesses two degrees of freedom corresponding to extension from the endoscope tip and rotation about its axis. The distal section is comprised of a monopolar cautery tool whose relaxed shape is straight and so possesses a single degree of freedom corresponding to extension from the proximal section.

The drive system is shown in Fig. 4 with actuated degrees of freedom labeled. The endoscope body is secured to the center of a frame that can rotate and translate along its central axis. The endoscope neck passes through a two-axis actuated gimbal cannula just proximal to the skull insertion point. The variable curvature of the endoscope is controlled via actuated rotation of the lever mounted on the endoscope body. The tool drive subsystem has three actuated degrees of freedom and has been designed to allow convenient substitution of alternate tools, such as biopsy forceps or a laser. The robot is controlled using a dual joystick master with additional input buttons. The 1 kHz controller is a Simulink model downloaded to a PC104 CPU board running the XPC Target real-time operating system (Mathworks, Inc.)

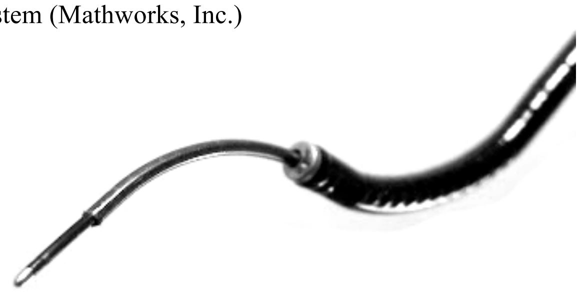

Fig. 3. Two-section concentric tube robot deployed through endoscope working channel. Distal section is monopolar cautery tool.

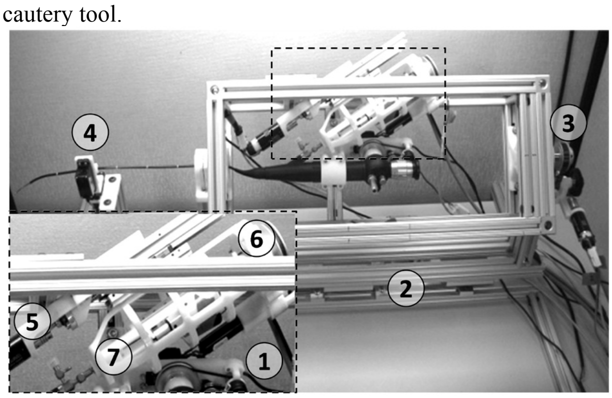

Fig. 4. Robotic drive system. (1) scope tip curvature, (2) scope insertion, (3) scope rotation, (4) two-axis actuated gimbal, (5) proximal concentric tube extension, (6) proximal concentric tube rotation, (7) distal cautery tool extension.

RESULTS

As a preliminary evaluation of the robot, the reachable workspace of the cautery tool in the temporal horns of the lateral ventricles (Fig. 1) was compared with and without the addition of the curved concentric tube of Fig. 3. This experiment was performed in a ventricle phantom produced using stereolithography from MRI images of a hydrocephalic brain. The phantom included cutouts to allow direct visualization of the endoscope and extended tools. Using a left frontal approach, the endoscope was introduced into the phantom, crossing the septum pellucidum to the contralateral lateral ventricle, and navigated inferiorly toward the temporal horn. Under joystick control, the cautery tool was positioned on a grid of points covering the inner surface of the ventricle. The sets of surface points that could be reached with and without the curved concentric tube are depicted in Fig. 5. As shown, the curved concentric tube is needed to reach the roof of the inferior horn. Note that the dashed boundary shown in Fig. 5(a) lies on the surface of the ventricle.

To provide a quantitative comparison of workspaces, the sets of reachable points were transferred to the CAD model used to produce the phantom. Using the curved concentric tube, the robot was able to reach the entire 1300 mm^2 surface area of the inferior horn and only 65% (853 mm^2) of the total area without it.

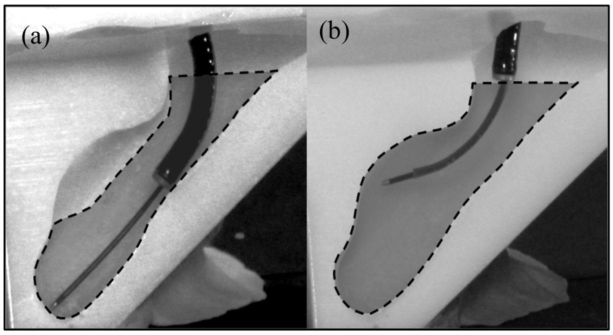

Figure 5. Neuroendoscope workspace with and without concentric tube extension. Shaded region can be reached by cautery tool tip. (a) Cautery tool only. (b) With curved concentric tube.

DISCUSSION

To address the current limitations of neuroendoscopes, we have proposed combining robotic control of a manual neuroendoscope with concentric tube robot technology. By adapting existing endoscope technology rather than creating an entirely new device, it is anticipated that barriers to clinical acceptance and regulatory approval will be reduced. Furthermore, robotic control of a manual endoscope will likely provide safer and smoother control of its existing degrees of freedom while also providing the means to integrate the control of the concentric tube degrees of freedom. Future experiments will focus on validating our approach and on refining the user interface.

Acknowledgement: This work was supported by the National Institutes of Health under grant R43EB014063.

REFERENCES

[1] "National Neurosurgical Procedural Statistics," American Association of Neurological Surgeons, vol. Survey, 2006.

[2] Dupont P, Lock J, Itkowitz B, Butler E. Design and Control of Concentric Tube Robots. IEEE Trans Robotics 2010;26(2):209-225.

[3] Warf B. Endoscopic third ventriculostomy and choroid plexus cauterization for pediatric hydrocephalus. Clinical Neurosurgery 2007;54:78-82.