Towards clinical application of continuum active micro-endoscope robot based on EAP actuation

Mohamed Taha Chikhaoui, Kanty Rabenorosoa and Nicolas Andreff
AS2M Department, FEMTO-ST Institute, Besançon, France.
mohamed.chikhaoui@femto-st.fr, kanty.rabenorosoa@femto-st.fr, and nicolas.andreff@femto-st.fr

Keywords: continuum robots – surgical robotics – electro-active polymers – workspace analysis.

Introduction

Continuum robots have shown astounding abilities in the medical field as numerous robotized devices have emerged. For instance, colonoscopes, arthroscopes, catheters, endoscopes, and other medical tools have been developed [1]. Their ability to navigate through complex anatomy and narrow spaces represent the attractive features of continuum robots. We foresee to improve their usefulness for Minimally Invasive Surgery (MIS) and Natural Orifice Transluminal Endoscopic Surgery (NOTES). These robots may be downscaled depending on the target application, e.g., from endoscopy to neurosurgery. Shorter hospital stay, less pain and scarring, and quicker recovery might then be provided to the patient. Recently, active cannulas have been used for endonasal skull base surgery for pituitary gland cancer [2] as depicted in Figure 1a, transurethral laser prostate surgery [3], laser surgery [4], beating heart surgery [5], and neurosurgery [6]. Thus, we are interested in developing a micro-endoscope whether for diagnosis or laser surgery.

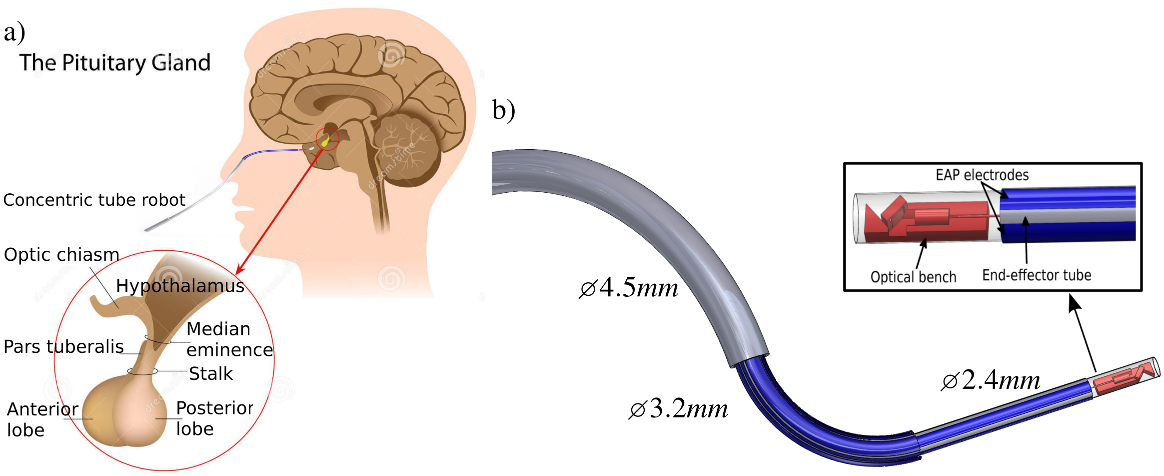

Figure 1: Concept of an EAP actuated concentric tube robot with: a) whole body reaching inserted in the nasal cavity to reach the pituitary gland detailed in the inset. b) CAD design of the robot. The inset shows the end-effector holding a laser tool.

Contribution

Our main idea is to add one or several degrees of freedom (DoF) to concentric tube robots by controlling the curvature of each tube. Doing so, we aim to compensate for the reduced mobility and dexterity of the usual concentric tube robots. Providing the extra DoF is possible through integrating embedded actuation using Electro-Active Polymers (EAP) [7]. In fact, coating thin EAP electrodes (about $10\mu m$) around the tube has demonstrated significant results [8]. One promising EAP material is the Polypyrrole (PPy). Adding to its biocompatibility, lightweight, and small size, this smart material requires very low activation voltages (less than one Volt) without any additional heating, in contrast with Shape Memory Alloys and piezoelectric materials. A curvature responding linearly to the applied voltage is the principal feature of PPy actuators [7] such as $\kappa = C_{PPy}V$, where κ is the curvature, V is the applied voltage and C_{PPy} is the PPy constant depending on tube and electrode geometry and material, and other empirical constants. Figure 1b shows the concept of an active cannula end-effector with embedded actuation.

Modeling and results

Modeling continuum robots is slightly more challenging than that of standard robots as there are no rigid links to determine the position and orientation of the tip. Instead, beam theory and constant curvature assumption are employed [9]. The robot final shape is divided into several sections, depending on the number and the shape of the overlapping tubes. For instance, the kinematic structure presented in this paper consists of 3 totally curved telescoping tubes (Figure 1b). With it, one can obtain 3 sections that can be automatically controlled to follow the trajectory defined by the surgeon through an appropriately ergonomic interface. The control-oriented modeling is based on a three-space decomposition: (i) the actuator space contains the actuation components, (ii) the configuration space holds the arc parameters of each section j, and (iii) the task space comprises the pose of the robot.

The kinematic improvement we propose relies principally on the comparison of specific Jacobian matrices J_{spec_j} of the j links depending on the actuator component derivatives. For the concentric tube robot, as only two components are available, J_{spec_j} is a 3 by 2 matrix. It leads to a non-holonomic behavior. This prompts a number of velocity directions to become unfeasible in a given state. Thanks to the proposed PPy actuation, the actuator space is broadened with a variable curvature yielding a square matrix 3 by 3 in equation 1. Matrix components and full computation are detailed in [10].

$$\begin{bmatrix} \dot{\kappa}_j \\ \dot{\phi}_j \\ \dot{\ell}_j \end{bmatrix} = \underbrace{\begin{bmatrix} J_{1,1} & J_{1,2} & 0 \\ J_{2,1} & J_{2,2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{J_{spec_j}} \begin{bmatrix} \dot{\kappa}_{in,j} \\ \dot{\theta}_{in,j} \\ \dot{\rho}_j \end{bmatrix} \tag{1}$$

This square matrix restores a holonomic behavior: all the velocity directions are accessible again. Therefore, for diagnosis purpose, the imaging tool (camera or OCT probe) can be swept linearly while bypassing an obstacle (robot is in bent position). In the same way, in a surgical goal, the practitioner may realize either linear or curved movements with a laser or a scalpel. Besides, using three tubes with embedded actuation induces redundancy. This is highly recommended in surgical robotics. Indeed, several actuation scenarios are available to the surgeon in order to achieve a task safely.

Moreover, embedded actuation enhances the workspace with two major contributions. On the one hand, Figure 2a displays that the covered area increases towards either straight or extremely curved configurations. This is obtained with merely in-plane middle tube curvature change, which is consistent with the ranges achieved in [7]. Different possibilities are thus available such as (i) reaching further parts of the anatomy, (ii) better apprehending a specific organ, and (iii) bypassing obstacles. For instance, skull base surgery suffers a limited dexterity of current instrumentation. Figure 1a shows the possibility to

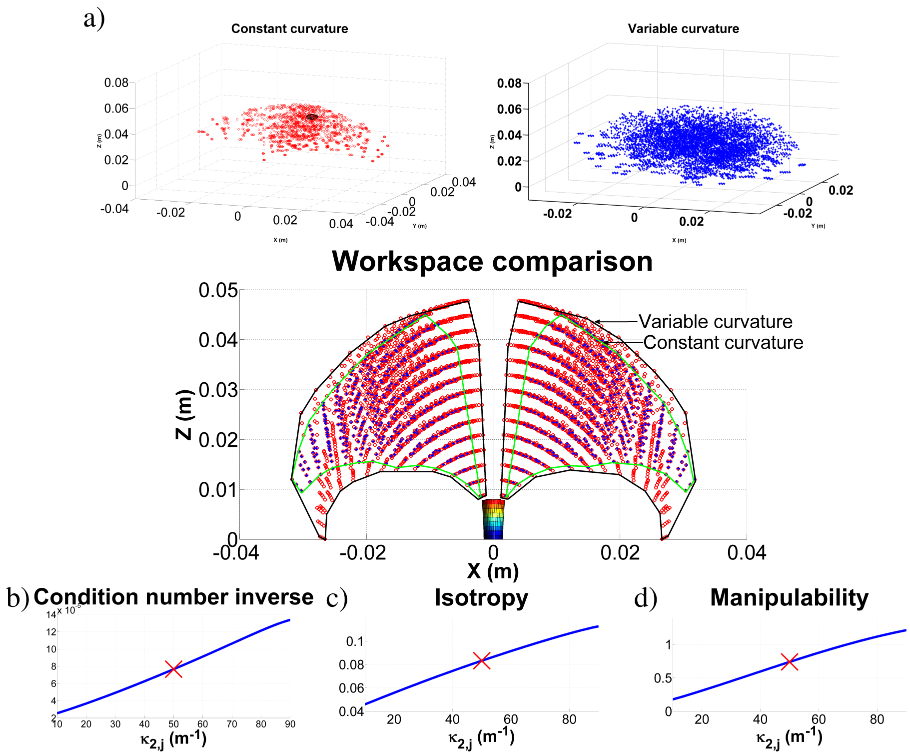

Figure 2: Workspace qualitative and quantitative analysis with a curvature sampling of $20m^{-1}$: a) the two upper insets show a 3D representation of the workspaces, the central figure displays a cross-section in the $x-z$ plane, b) Condition number inverse, c) Isotropy, and d) Manipulability versus second tube curvature.

reach a potential pituitary adenoma. For a malignant tumor, the cancer can spread to nearby tissue and structures. Such a device is then able to avoid the lobes (Figure 1a) or apprehend them in different poses.

On the other hand, the three most significant performance indices are slightly improved with embedded actuation. This means that the workspace is reached in a better manner when the middle tube bends beyond $54m^{-1}$ (the curvature used in [11]). Higher curvatures imply that the Jacobian kinematic matrix is better conditioned and isotropy increases, as depicted in Figures 2b,c. Hence velocities get more homogeneous in all directions. This provides the practitioner with a supplementary ease to control the concentric tube robot with embedded actuation when several orientations are required. Figure 2d shows the increasing system manipulability, which shifts the system further from singular positions. Thus, losing one or several velocity directions is prevented and a safe level of control of the surgical tool is ensured. In the pituitary gland area, the safety provided is critical as the optic nerves are close structures.

Conclusions

This paper highlights the benefits of adding a variable curvatures to concentric tube robots by the means of EAP. This embedded actuation should provide holonomy to the system and enhance its safety. Moreover, our theoretical analysis demonstrates that our proposal improves the kinematics of the system and enlarges the workspace both qualitatively and quantitatively. Hence it provides the practitioner better controllability and dexterity. A prototype is currently under construction to validate these theoretical results. Future work will concentrate on the technology in order to provide each tube with bending capacities in two directions.

Acknowledgement

This work has been supported by the LabEx ACTION project (contract ANR-11-LABX-0001-01) and by μRALP, the EC FP7 ICT Collaborative Project no. 288663.

References

[1] R. J. Webster III and B. A. Jones, "Design and kinematic modeling of constant curvature continuum robots: A review," *The International Journal of Robotics Research*, vol. 29, no. 13, pp. 1661–1683, 2010.

[2] J. Burgner, P. Swaney, D. Rucker, H. Gilbert, S. Nill, P. Russell, K. Weaver, and R. J. Webster III, "A bimanual teleoperated system for endonasal skull base surgery," in *Intelligent Robots and Systems, IEEE/RSJ International Conference on*, pp. 2517–2523, Sept 2011.

[3] R. J. Hendrick, S. D. Herrell, and R. J. Webster III, "A multi-arm hand-held robotic system for transurethral laser prostate surgery," in *IEEE International Conference on Robotics and Automation*, 2014.

[4] D. C. Rucker, J. M. Croom, and R. J. Webster III, "Aiming a surgical laser with an active cannula," *Journal of Medical Devices*, vol. 3, no. 2, p. 027506, 2009.

[5] P. Dupont, A. Gosline, N. Vasilyev, J. Lock, E. Butler, C. Folk, A. Cohen, R. Chen, G. Schmitz, H. Ren, *et al.*, "Concentric tube robots for minimally invasive surgery," in *Hamlyn Symposium on Medical Robotics*, vol. 7, p. 8, 2012.

[6] E. J. Butler, R. Hammond-Oakley, S. Chawarski, A. H. Gosline, P. Codd, T. Anor, J. R. Madsen, P. E. Dupont, and J. Lock, "Robotic neuro-endoscope with concentric tube augmentation," in *Intelligent Robots and Systems, IEEE/RSJ International Conference on*, pp. 2941–2946, IEEE, 2012.

[7] T. Shoa, J. Madden, N. Fekri, N. Munce, and V. X. Yang, "Conducting polymer based active catheter for minimally invasive interventions inside arteries," in *Engineering in Medicine and Biology Society. 30th Annual International Conference of the IEEE*, pp. 2063–2066, Aug 2008.

[8] T. Shoa, N. R. Munce, V. Yang, and J. D. Madden, "Conducting polymer actuator driven catheter: overview and applications," 2009.

[9] R. J. Webster III, A. M. Okamura, and N. J. Cowan, "Toward active cannulas: Miniature snake-like surgical robots," in *Intelligent Robots and Systems, IEEE/RSJ International Conference on*, pp. 2857–2863, Oct 2006.

[10] M. T. Chikhaoui, K. Rabenorosoa, and N. Andreff, "Kinematic modeling of an eap actuated continuum robot for active micro-endoscopy," in *Advances in Robot Kinematics* (J. Lenarčič and O. Khatib, eds.), pp. 457–465, Springer International Publishing, 2014.

[11] R. J. Webster III, J. P. Swensen, J. M. Romano, and N. J. Cowan, "Closed-form differential kinematics for concentric-tube continuum robots with application to visual servoing," in *Experimental Robotics* (O. Khatib, V. Kumar, and G. Pappas, eds.), vol. 54 of *Springer Tracts in Advanced Robotics*, pp. 485–494, Springer Berlin Heidelberg, 2009.