Towards more versatile concentric tube robots using stiffness modulation

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Concentric tube robots (CTR) are particularly suited for assistance in minimally invasive interventions. However their use is hampered by possible unsafe behaviour due to elastic instabilites, reducing their achievable workspace. We propose here to deal with stability issues through active stiffness modulation of the tubes, which may also allow to improve interactions with environment during surgical tasks. Initial design specifications are introduced with a novel numerical tool for CTR stability analysis, based on continuation methods and bifurcation analysis.

1 Introduction

Concentric tube robots (CTR) are a class of robots which has been extensively used in medical applications such as brain surgery [3], vitreoretinal surgery [4], and nasal cavity exploration [5]. They consist in telescopic assemblies of thin pre-curved tubes, rotated and translated at their base, whose tip can reach operation sites even in narrow spaces.

Their use is however limited by the elastic interactions at the origin of CTR kinematics. During its deployment, a CTR can store elastic energy due to tube internal torsions. Multiple states of equilibrium can as a consequence exist, with sudden motions between these states [1]. This so-called snapping effect generates hazardous movements and seems unacceptable in MIS context.

An interesting approach to solve this issue has been proposed in [7] and consists in creating tube anisotropy by internal modifications. We propose here to go beyond this passive approach and to investigate the use of active anisotropy modulation for the tubes, which can be considered using smart materials as described in [6]. The goal is to be able to reduce stiffness only when necessary, allowing to deal with the robot stability while maintaining sufficient interaction force generation on tissues when needed.

In this work we investigate the influence of active anisotropy on CTR behaviour, in order to elaborate a strategy for stiffness modulation in a future CTR proof of concept. A numerical evaluation tool is implemented and described in the next section. A realistic scenario of CTR deployment is then considered to assess the number of tubes to actively control and the required range of stiffness modulation.

2 Numerical kinematic analysis

The analysis of a CTR behaviour is a difficult task. The existing approaches are analytical or semi-analytical, and for most of them limited to robots with constant tube stiffness and/or without considering environment interactions [12] because of kinematic model complexity. The only general-enough work focuses on local stability evaluation [11], and gives no other information about the robot behaviour according to anisotropy. In particular the existence of multiple states of equilibrium cannot be monitored. We propose here to overcome these limitations thanks to a numerical and generic approach based on dynamic relaxation, continuation methods and bifurcation analysis.

The dynamic relaxation, a classical form-finding method for structures with elastic interactions [8], consists first in discretizing the CTR in a finite number of points and in expressing the boundary value problem describing its kinematic model [2] with finite differences. The robot is then constrained in an initial arbitrary shape and relaxed until it reaches an equilibrium, transforming the original static problem into a resolution of ODE system. This system is obtained without any

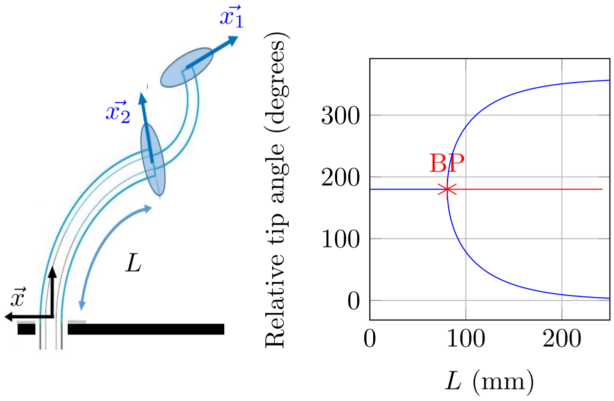

Figure 1: *Bifurcation diagram according to L. Stable branches in blue and unstable branches in red.*

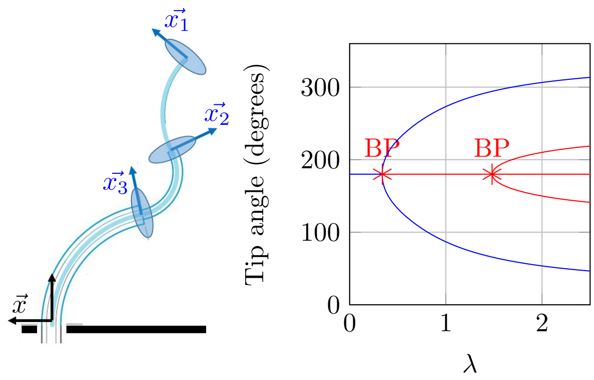

Figure 2: *Bifurcation diagram according to λ. Stable branches in blue and unstable branches in red.*

Tube 1	Tube 2	Tube 3	λ_c
×			N.R.
	×		0.185
		×	N.R.
×	×		0.350
	×	×	0.163
×		×	0.167
×	×	×	0.346

Table 1: *Critical stiffness ratios obtained with ×-labelled anisotropic tubes.*

assumption on the CTR kinematic model. Its formulation can then directly be implemented in a continuation and bifurcation software such as MatCont [13].

Continuation methods allow for computing the evolution of a initial steady state according to one parameter of the ODE system, forming so-called branches of equilibria [10]. Bifurcations can be detected along these branches, indicating changes of stability regime and variations of the number of equilibria [9].

The use of continuation and bifurcation analysis for assessment of CTR behaviour is new to our knowledge. The numerical approach has thus been validated by generating reference results for a two-tube CTR in free space. Variation of interaction length L of two tubes in opposition [12] is represented on Figure 1. The tubes are indexed from the innermost to the outermost. The $\vec{x_i}$ vectors are normal to the robot backbone and are rotated between them of 180 degrees in each point. Starting from an initial low value of L the corresponding equilibrium is continued until the branch reaches a branch point bifurcation (BP), indicating that the branch becomes unstable and that two distinct stable equilibria are possible beyond this point. Relative errors between numerical results and reference values issued from the analytical criteria of [12] are negligible if proper discretization is performed. Here, a 0.02% error is obtained with 100 samples along the robot length, which is acceptable.

3 Influence of anisotropy

Analysis of stiffness modulation is performed by using a realistic scenario issued from nasal cavity exploration. The corresponding CTR is described in [5]. The tubes are mounted in opposition for follow-the-leader deployment, during which the shape of the robot corresponds to the trajectory of its tip. The tubes have the same flexural to torsional stiffness ratio, called λ, which quantifies the anisotropy. Figure 2 shows the branches of equilibria according to λ as obtained using our continuation technique. Two BP are detected, one being on the unstable portion leading to one new unstable branch of equilibria, non existing physically. There is consequently a critical stiffness ratio λ_c, defined by the first bifurcation point, beyond which the kinematic model has multiple solutions. By analogy with the notion of critical interaction length, snapping effect during tube rotation can thus be prevented by choosing $\lambda < \lambda_c$.

Thanks to our numerical tool, it is easy to determine the critical value λ_c for different situations in terms of anisotropy. Results are reported in Table 1, where 'N.R.' indicates that only unstable behaviour was obtained. The analysis shows that modification of the middle tube only, or of any couple of tubes, guarantees stability under tube rotations if their stiffness ratio is reduced enough. Thresholds are identified, which helps to formulate the design objectives for active stiffness modulation. We can see in addition that selection of tubes to modify is of importance. Choosing tube 1 and tube 2 provides the highest critical ratio, thus relaxing design constraints.

4 Conclusion

In this work we have proposed to use active anisotropy modulation to improve CTR stability and interaction with environment. First specifications, such as the modulation amplitude and the number of tubes to be actuated, have been generated on a realistic deployment scenario with a novel numerical tool based on continuation methods and bifurcation analysis. Other specifications such as the localisation of the modulation on the tubes and the control strategy will now be investigated.

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References

[1] Webster, R. J. and Romano, J. M. and Cowan, N. J. (2009). Mechanics of Precurved-Tube Continuum Robots *IEEE Transactions on Robotics*, 67–78.

[2] Lock, J. and Laing, G. and Mahvash, M. and Dupont, P. E. (2010). Quasistatic modeling of concentric tube robots with external loads *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2325–2332.

[3] Burgner, J. and Swaney, P. J. and Lathrop, R. A. and Weaver, K. D. and Webster, R. J. (2013). Debulking From Within: A Robotic Steerable Cannula for Intracerebral Hemorrhage Evacuation *IEEE Transactions on Biomedical Engineering*, 2567–2575.

[4] Lin, F. Y. and Bergeles, C. and Yang, G. Z. (2015). Biometry-based concentric tubes robot for vitreoretinal surgery *37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 5280–5284.

[5] Girerd, C. and Rabenorosoa, K. and Renaud, P. (2016). Synthesis of a New Concentric Tube Robot for Olfactory Cells Exploration *Computer/Robot Assisted Surgery (CRAS).*

[6] Chikhaoui, M. T. and Rabenorosoa, K. and Andreff, N. (2014). Kinematic Modeling of an EAP Actuated Continuum Robot for Active Microendoscopy *Advances in Robot Kinematics*, 457–465.

[7] Lee, D. Y. and Kim, J. and Kim, J. S. and Baek, C. and Noh, G. and Kim, D. N. and Kim, K. and Kang, S. and Cho, K. J. (2015). Anisotropic Patterning to Reduce Instability of Concentric-Tube Robots *IEEE Transactions on Robotics*, 6:1311–1323.

[8] Olsson, Jens (2012). Form finding and size optimization - Implementation of beam elements and size optimization in real time form finding using dynamic relaxation *Chalmers University of Technology.*

[9] Kuznetsov, Yuri A. (2004). Elements of Applied Bifurcation Theory *Springer New York*, 112.

[10] Doedel, E. and Keller, H. B. and Kernevez, J. P. (1991). Numerical analysis and control of bifurcation problems (i): bifurcation in finite dimensions *International Journal of Bifurcation and Chaos*, 03:493–520.

[11] Ha, J. and Park, F. C. and Dupont, P. E. (2016). Elastic Stability of Concentric Tube Robots Subject to External Loads *IEEE Transactions on Biomedical Engineering*, 06:1116–1128.

[12] Gilbert, H. B. and Hendrick, R. J. and III, R. J. Webster (2016). Elastic Stability of Concentric Tube Robots: A Stability Measure and Design Test *IEEE Transactions on Robotics*, 01:20–35.

[13] Dhooge, A. and Govaerts, W. and Kuznetsov, Yu.A. and Mestrom, W. and Riet, A.M. and Sautois, B. (2006). MATCONT and CL_MATCONT: Continuation roolboxes in MATLAB *Universiteit Gent, Utrecht University.*