Orientability evaluation of concentric tube robots deployed in natural orifices

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Assessment of concentric tube robot orientability is considered in this work. A numerical method is proposed to estimate the robot capability to be oriented around a fixed point of interest, typically a surgical site in natural orifices.

1 Introduction

Concentric tube robot (CTR) is a promising class of continuum robot for medical interventions [1] which require to operate through natural orifices, such as trans-nasal skull base surgery [2], middle-ear surgery [3] and trans-urethral surgery [4]. During these applications, the access to the surgical site is difficult due to the narrowness of the natural orifices. In addition, capability to orient the surgical tool at the surgical site is of importance.

CTR consists in a telescopic assembly of pre-curved tubes. The elastic interaction between the tubes creates distributed forces and torques which deform the robot backbone. The rotation and translation of the tubes allow then to control the shape of the robot during its deployment through natural orifices, as well as its tip pose during the operation. The capability of CTR to orient their tip while maintaining the same tip position at the surgical site, that is referred as orientability in [5], is of interest and actually limited in the above-mentioned applications. Orientability is indeed not yet a criterion for CTR tube selection, and it is even today still difficult to assess. This work is dedicated to the development of a numerical evaluation of CTR orientability.

2 Orientability

Orientability analysis of continuum robot is a very recent topic, and only one evaluation method exists which is described in [7, 5]. In these works, the studied robots have more than 3 degree of freedom (DoF), which allows to control their tip position at the surgical site position, denoted here $\boldsymbol{p_E}$, and to vary their tip orientation. When transposed to CTR, the evaluation method consists in computing all the possible configurations of the robot for given ranges of rotation and translation of the tubes. The specified actuation ranges are randomly discretized, and the forward kinematic model (FKM) of the CTR has to be solved for each possible combination of actuation input. This provides a discrete set of robot configurations and robot tip poses. The different tip orientations of the robot at the surgical site can then be determined following two approaches. The workspace volume of the robot can be discretized in terms of Cartesian coordinates, forming a cluster of voxels with given dimensions which represents each possible surgical site [5], or a spherical voxel can be defined as centered on the surgical site [7]. The robot configurations which tip position lies in the targeted voxel are finally gathered, giving a set of tip orientations.

This discretization-based method allows to assess the orientability of the robot in all of its workspace. However, it does not seem adapted to the medical constraints when only a very small volume around $\boldsymbol{p_E}$ is admissible. In particular, it is difficult with the current method to compute the local orientability of the robot, since it uses a FKM which does not allow to target one specific tip position. Moreover, the CTR may experience large shape variations during tip orientation, which are difficult to capture with standard numerical methods due to the FKM non-linearity.

We propose then a new numerical method to evaluate the local orientability of CTR. It is based on an inverse kinematic model which allows to constrain the robot tip position at the surgical site. The different orientations are then computed by applying to this model the numerical framework described in [9], which is robust to non-linear behaviors.

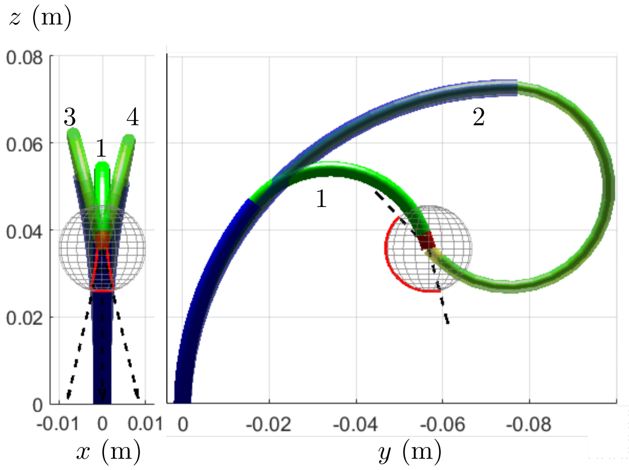

Figure 1: *Configurations of CTR sharing the same tip position, tip tangent in dotted line.*

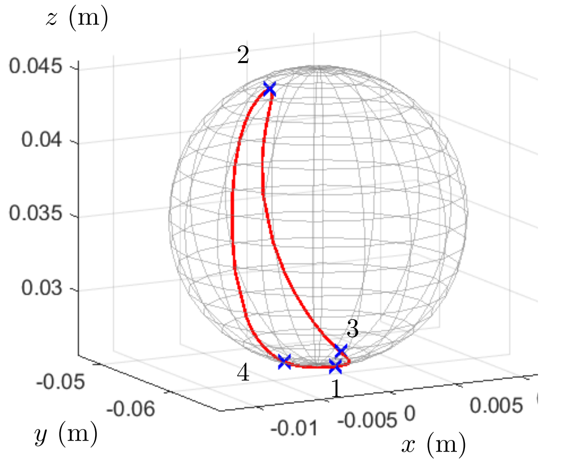

Figure 2: *Service sphere representing the evolution of the tip orientation. The 4 configurations of Fig 1 are marked with blue crosses.*

3 Method

We consider an inverse kinematic model (IKM) of a CTR composed of n tubes, which provides the robot configuration and the $2n$ actuation inputs as a function of the required robot tip position $\boldsymbol{p_E}$. We build such a model by considering first of all a FKM composed of the equations presented in [9], which computes the robot configuration in terms of torsion angle of the tubes according to the actuation inputs, and the equations in [6] which computes the robot tip position $\boldsymbol{p}$ and orientation $\boldsymbol{a}$ represented with Euler angles. Euler angles provide a minimal and intuitive representation of the tip orientation, without leading to any geometrical singularity in the case studies considered so far. Following the approach in [9] for the numerical analysis of CTR, the robot is then discretized along its backbone in a finite number of nodes, transforming the FKM into a set of non-linear equations:

$$\boldsymbol{G}(\boldsymbol{X}, \boldsymbol{u}) = \boldsymbol{0} \tag{1}$$

where $\boldsymbol{X} = \begin{bmatrix} \boldsymbol{Y^T} & \boldsymbol{p^T} & \boldsymbol{a^T} \end{bmatrix}$ is the state vector to compute, with $\boldsymbol{Y}$ a vector of states containing the torsion angles and the position and the orientation of the nodes, and $\boldsymbol{u} = \begin{bmatrix} u_1 & u_2 & \dots & u_{2n} \end{bmatrix}$ the actuation inputs set by the user.

Following the approach in [8], the IKM is finally built by considering that a subset of actuation inputs is used to set the tip pose at $\boldsymbol{p_E}$. This task requires three DoF, that we consider to be parametrized by three of the available actuation inputs, denoted generally u_1, u_2 and u_3. The IKM is then written:

$$\boldsymbol{G}(\boldsymbol{X}^\star, \boldsymbol{u}^\star) = \boldsymbol{0} \tag{2}$$

where $\boldsymbol{X}^\star = \begin{bmatrix} \boldsymbol{Y^T} & \boldsymbol{a^T} & u_1 & u_2 & u_3 \end{bmatrix}$ is the new state vector to determine, and $\boldsymbol{u}^\star = \begin{bmatrix} u_4 & \dots & u_{2n} & \boldsymbol{p_E^T} \end{bmatrix}$ is the vector of parameters set by the user.

The different possible orientations of the robot tip at $\boldsymbol{p_E}$ can be obtained by varying one by one the free actuation inputs and by solving the IKM for each resulting value. This last task is challenging since the CTR kinematics may exhibit non-linear behavior, difficult to predict. Therefore, we perform it with the numerical framework described in [9], which captures efficiently the intricate kinematics of CTR when one actuation input is varied.

4 Results for a two-tube CTR

The method developed above is used to evaluate the local orientability of a CTR composed of two tubes made in NiTi alloy, represented in Fig 1. The pre-curvature of the inner and outer tubes equals respectively 43.5 m^{-1} and 7.2 m^{-1}. Their outer and inner diameters are respectively $(0.65, 0.41)$ mm and $(1.07, 0.77)$ mm. The two tubes can be both rotated and translated, giving a 4-DoF continuum robot. The position of interest $\boldsymbol{p_E}$ is determined by solving the FKM with an initial set of actuation inputs and by picking the robot tip position. The initial configuration is labeled 1 on Fig 1. We choose then to use the translation of the two tubes and the rotation of the inner tube to constrain the tip position at $\boldsymbol{p_E}$. The rotation of the outer tube is varied in order to sweep the possible tip orientations. Our method finds successfully the different configurations of the robot which lead to the same tip position. The robot shapes obtained during the continuation process which provides the most different tip orientations are represented in two planes on Fig. 1.

The resulting orientations are also represented on a service sphere centered at $\boldsymbol{p_E}$ like in [5]. The robot tip tangent intersects with the sphere, creating a point on the sphere surface. The tip orientations obtained with successive variations of the outer tube rotation give then a succession of points, that can be represented as a curve on the sphere surface. The resulting service sphere is represented on Fig. 2. It provides information about the tip orientation ranges at $\boldsymbol{p_E}$, which equals 151.3 degrees around the $\boldsymbol{x}$-axis.

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