Concentric Tube Robots: Task Oriented Optimization of Tube Parameters and Motion Planning

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Concentric tube robots are continuum robots that comprise of nested super-elastic tubes. The elastic interactions between the tubes allow a concentric tube robot to attain snake like motion, making the robot feasible for medical applications. These types of robots can potentially be used for complex tasks like suturing in hard to reach small spaces because of the flexibility, small size, and dexterity these robots exhibit. However, the shapes that a concentric tube robot can adopt are highly dependent on the initial tube geometries and joint values, leading to a large volume swept for a task for non-optimized geometries and control. This can lead to collisions with other tools used simultaneously during operations or fragile anatomical structures. Therefore, it is pivotal to optimize the individual tube's parameters and their deployment sequence to ensure that the robot occupies a minimum space, while still performing the specified tasks. Utilizing OpenMDAO, an open source optimization software, the joint values and tube parameters for three tubed robot were optimized to occupy minimum space possible while following a pre-defined path with the tip. Three different objective functions were implemented and compared.

I. Nomenclature

l_1 = link 1
l_2 = link 2
l_3 = link 3
l_4 = link 4
l_c = total length of link 2 and link 3
κ = curvature of link 2
kb_1 = stiffness of link 1
kb_2 = stiffness of link 2
kb_3 = stiffness of link 3
ψ = Rotation of link 2
P = Set of backbone points
q = Path points
n = Number of path points
b_i = Backbone point at the i^{th} level

II. Introduction

Concentric Tube Robots (CTR) are needle sized continuum robots that possess the ability to generate complex snake like motion. The small size of CTR which is comparable to that of the catheters qualifies the robots for minimally invasive procedures[1]. Furthermore, the lumen of the tubes can be utilized to house additional tubes and wires for controlling tip mounted tools or as a transportation channel. $Fig.1$ shows a four tubed CTR configuration[2].

These robots are constructed from a set of concentric pre-curved tubes made from super elastic materials. The rotation and translation of individual tubes result in elastic interactions between the tubes allowing the robot to attain a large set of curves. The work-space of the desired surgical procedure governs the allowable shapes which depend on the tube parameters like the curvature, stiffness, and length of the individual tubes used in the robot configurations. Thus, it

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is of pivotal importance to select right set of tube parameters for the design of a robot that can perform a desired task at the specified work[3].

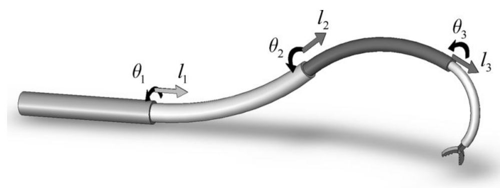

Fig. 1 [2] Concentric-tube robot comprising four telescoping sections that can be rotated and translated with respect to each other.

III. Background

The use of minimally invasive surgery has increased substantially over the past decade[4]. Extensive research on robot assisted surgery has further added to the applicability of minimally assisted procedures[5][6]. However, single port minimally invasive surgery still remains as a challenge because of the small work-space associated with the single port surgery. We propose a dual arm concentric tube robot which can potentially operate in a single-port due to the CTR's high degree of freedom, flexibility, and small scale.

We selected the suturing task be our objective because suturing is often regarded as a challenging endeavor during minimally invasive single port surgeries[7]. As a result, there is a need to design and optimize the tube parameters and the joint values for a concentric tube robot to follow the entire trajectory and accomplish the task in the limited work-space. Moreover, suturing tasks in complex and difficult to reach areas require the tool used to occupy minimum possible space. Therefore, the entire work space and volume swept by the concentric tube robot plays a crucial role in minimally invasive robotics surgery specifically single port surgeries.

IV. Kinematics Model

The distal end motion in CTR is the result of translation and rotation in the proximal end of the robot. The motion mimics that of a snake as a result of the elastic interactions between the overlapping concentric tubes. The interaction between two overlapping curved tubes can sometimes result in the instability because of the sudden release of accumulated energy during the rotation of the tubes. This phenomenon of sudden release of energy is called snapping[8].

Instability in CTR can be avoided by selecting right set of tubes. Moreover, the right set of tubes would also make it easy to map the target point for the distal end of the robot to the tube parameters for the body of the robot.

A. Tube Selection

Tubes can be pre selected with desired curvatures to avoid instability in the robot during its application. We selected straight-curved-straight tube configuration for our study as shown in $Fig.2$. The outermost and the innermost tubes are straight whereas the second tube has two distinct regions, a straight proximal section and a pre-curved distal section. This configuration makes sure that the curved part of the second tube only interacts with the straight sections of the other tubes thereby avoiding any instability in the robot configuration.

Moreover, the availability of closed loop kinematics model that maps the tip position of this robot configuration to the tube parameters of entire robot body makes this selection of tubes ideal for optimizing the tube parameters and the link lengths of the robot for a defined set of tip positions for any objective function.

B. Kinematics

The assembly of straight-curved-straight tubes results in four distinct links as shown in $Fig.3$ It is clear from $Fig3$ that there is an introduction of section marked as 3 because of the interaction between the outer straight tube and the curved part of the second tube. This curved link in the outer tube is treated as an individual link during modeling. The curvature of the link 3 is the result of the overlap between the curvatures of the individual tubes as given by equation (1).

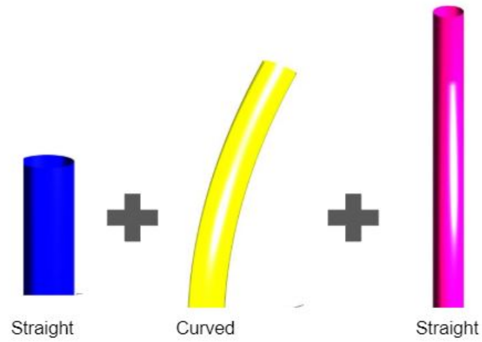

Fig. 2 Individual tubes selected for optimization study on the suturing task.

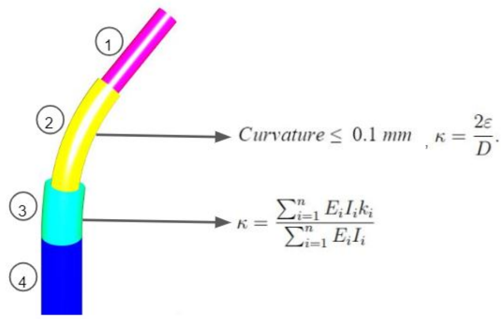

Fig. 3 Assembly of straight-curved-straight tubes with four distinct links.

$$\kappa_3 = \frac{\sum_{i=1}^{N} E_i I_i k_i}{\sum_{i=1}^{N} E_i I_I} \tag{1}$$

Similarly, the curvature of the second tube is constrained by the upper limit for which the plastic deformation of the second tube does not occur. Nitinol, a common super-elastic material used for tubes has plastic deformation for the strain of about 8% to 11%. The upper limit by which the curvature of the second tube, a tube parameter, is constrained by is given by equation (2). D_2 is the outer diameter of the second tube[9].

The designed robot's tip has a pre-defined path to follow as obtained from the trajectory for suturing task. The selection of straight-curved-straight tubes allows the desired tip position to be mapped backed to the tube parameters of the robot body because of the existence of appropriate kinematic model. The backbone coordinates are obtained using the homogeneous transformation matrix with respect to the base of the tube assembly.

$$\kappa_{2max} = \frac{2\epsilon}{D_2} \tag{2}$$

V. Optimization

A. Optimization problem

1. Objective function 1 : Time dependent

$$\begin{gathered} min f_1(x,y,z) = \sum_{i=1}^{b}\sum_{j=1}^{n}\left\|\mathbf{P}_{j+1}^{i} - \mathbf{P}_{j}^{i}\right\|^2 \\ subject\ to\ q = fk(\mathrm{l}_1, l_2, l_3, l_4, \kappa,\ kb_1, kb_2, kb_3, \psi) \\ \mathrm{l}_c\text{-}l_2 \geq 0 \\ \mathrm{kb}_3\text{-}kb_2 \geq 0 \\ \mathrm{kb}_2\text{-}kb_1 \geq 0 \end{gathered} \tag{3}$$

2. Objective function 2 : Time independent for entire set

$$\begin{gathered} min f_2(x,y,z) = \sum_{i=1}^{b}\sum_{j=1}^{n}\sum_{r=1}^{n}\left\|\mathbf{P}_{j}^{i} - \mathbf{P}_{r}^{i}\right\|^2 \\ subject\ to\ q = fk(\mathrm{l}_1, l_2, l_3, l_4, \kappa,\ kb_1, kb_2, kb_3, \psi) \\ \mathrm{l}_c\text{-}l_2 \geq 0 \\ \mathrm{kb}_3\text{-}kb_2 \geq 0 \\ \mathrm{kb}_2\text{-}kb_1 \geq 0 \end{gathered} \tag{4}$$

3. Objective function 3 : Time independent for single configuration

$$\begin{gathered} min f_3(x,y,z) = \sum_{i=1}^{n}\left\|\mathbf{P}_{j}\right\|^2 \\ subject\ to\ q = fk(\mathrm{l}_1, l_2, l_3, l_4, \kappa,\ kb_1, kb_2, kb_3, \psi) \\ \mathrm{l}_c\text{-}l_2 \geq 0 \\ \mathrm{kb}_3\text{-}kb_2 \geq 0 \\ \mathrm{kb}_2\text{-}kb_1 \geq 0 \end{gathered} \tag{5}$$

f_1 is the sum of all distances between two adjacent points in the backbone of the robot configurations. Therefore, the robot configuration at any time frame would be dependent on the configuration of the robot at the adjacent time frame. f_2 is the sum of all the distances of corresponding points at each backbone level in the robot configurations for the entire defined path. Similarly, f_3 is the sum of distances of all the points in the backbone of a particular robot configuration to the base of the robot.

The volume swept by the robot while following the pre-defined path for suturing could not be analytically represented in a closed form. Therefore, the objective functions were an attempt at minimizing the space occupied by the robot. In f_1, any robot configuration is optimized to be as close as possible to the adjacent configuration. In f_2, the deviation of the entire body with respect to the general configuration of the robot is minimized independent of any particular configuration. f_3 makes sure that the robot configuration at any time frame is as simple as possible while reaching the target point irrespective of configurations at other time frames.

fk is the forward kinematics function that is determined by design variables,backbone points P = $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$,for each desired tip position in the path q. The total number of points in the pre-defined path is given as n. $b_{1,6}$ defines the set of backbone points along the body of the robot at six different levels. The backbone points are obtained using the homogeneous transformation matrices for the tip of each link and the middle points of link 1,2, and 3 as shown the fig.4.

B. SLSQP algorithm

We used Sequential Least Squares Programming as our optimizer to solve our optimization problem. SLSQP is a powerful optimization algorithm that uses iterative method for constrained optimization. In addition, SLSQP algorithm

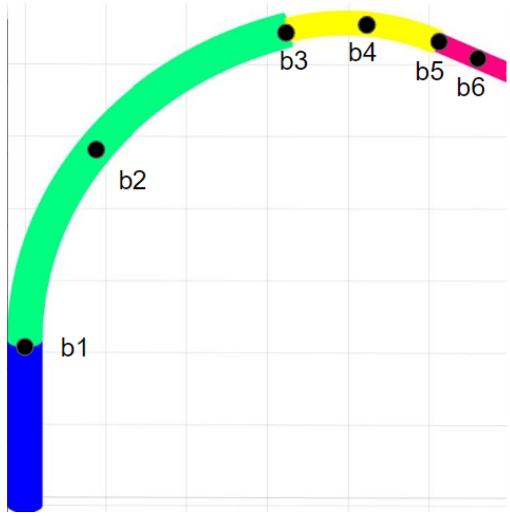

Fig. 4 A robot configuration with predefined backbone points

is capable of solving complex non-linear problem by treating it as a sequence of small quadratic problems[10]. This algorithm also allows us to solve our non-linear constrained optimization at less computational expense.

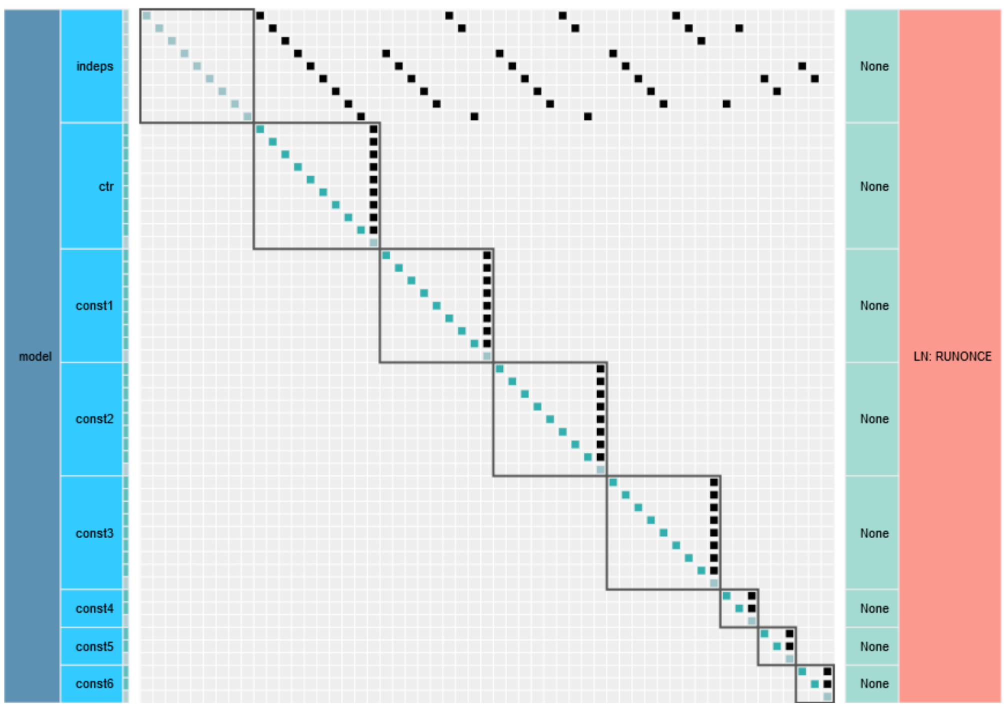

Fig. 5 Design structure matrix of the model

VI. Results and Discussion

We were able to successfully implement our model in OpenMDAO[11][12] and were able to optimize our pre-selected robotic configuration for reaching defined path points while satisfying our objective function f_1 or f_2 or f_3. We were able to optimize for the length of four links for each individual path point along with the curvature of the second tube, and stiffness of individual tubes. Therefore, the total number of design variables was the sum of fourth fold of the number of path points, individual tube stiffness for three tubes, the curvature of the second tube, and the angle of rotation for the second tube. Thus, the large number of design variables makes our problem a large scale optimization problem. Visual representation of the design structure matrix of our model is shown in Fig.5.

It can be seen from the Fig.6 and Fig.9 that results from the objective function: f_3 generate tubes that have extremely small links 3 and 4. CTR configurations with extremely small links are impractical to use for real life applications. Fig.7 and Fig.10 show the results using the objective function f_1. Similarly, Fig.8 and Fig.11 show the results using the objective function f_2. It can be seen that the results generated using objective functions f_2 and f_3 are better because combination of link lengths look better for these objective functions. However, results obtained from objective function f_3 seem to be the most feasible. Also, results from f_3 show the least deviation in the robot body shapes while following the pre-defined suturing path points.

For all three methods, we were able to successfully implement vectorization algorithm which is a faster computational alternative to the use of for and while loops for iterations. f_2 takes the most time to compute because the objective function requires the computation of distance from a backbone point of any configuration to the backbone points of all the other robotic configurations in the work-space iterated for each and every possible configuration.

Therefore, we were able to optimize all the joint value corresponding to every path point in the suturing trajectory. Also, the stiffness of three tubes and the curvature of second tube was also optimized. The design variables were constrained to reach the path points while maintaining feasible physical form and elasticity for the tubes while reaching for pre-defined target points.The tube material for our study was selected to be nitinol, an alloy of nickel and titanium. The applied constraints were deemed as sufficient from the obtained results.

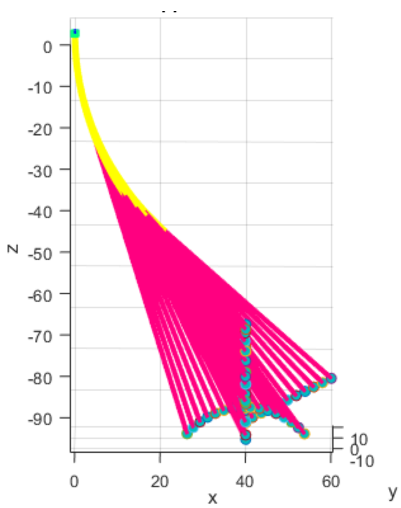

Fig. 6 Objective function: f3

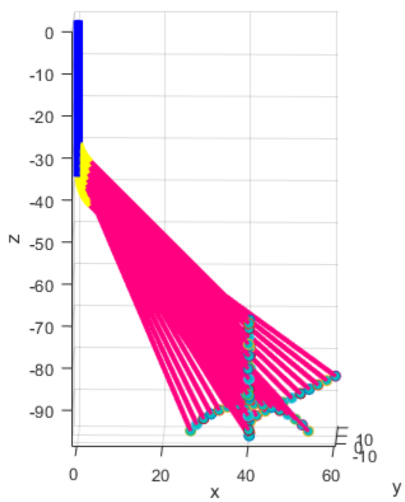

Fig. 7 Objective function: f2

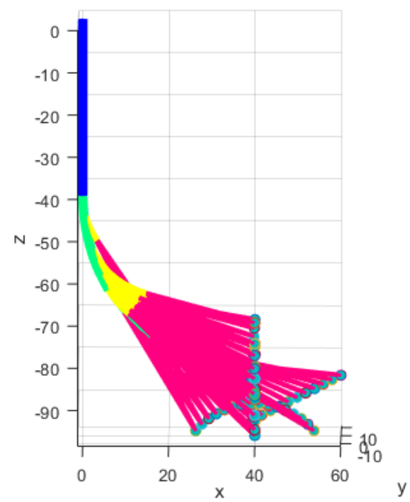

Fig. 8 Objective function: f1

VII. Conclusion

From our results, it can be proven that the optimization problem for task specific concentric tube robots can be solved efficiently using OpenMDAO. The simplified model we implemented was that of a straight-curved-straight tube configuration that allowed us to avoid the problem of instability which is often encountered in other configurations. The current research work in CTR has not yet resulted in successful simultaneous optimization of all tube parameters and joint values. Further research work and expertise with OpenMDAO is required to optimize for more complex models with complex configurations. Furthermore, It is also possible to successfully implement the optimization method for efficient real time control and motion planning for the concentric tube robots. Overall, exciting research endeavors can stem out from the application of OpenMDAO for optimization of concentric tube robots and other continuum robots for specified tasks.

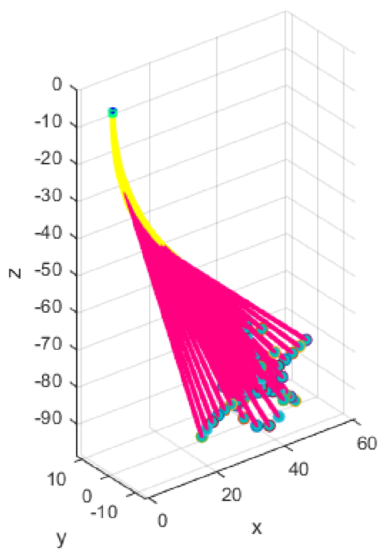

Fig. 9 Objective function: f3

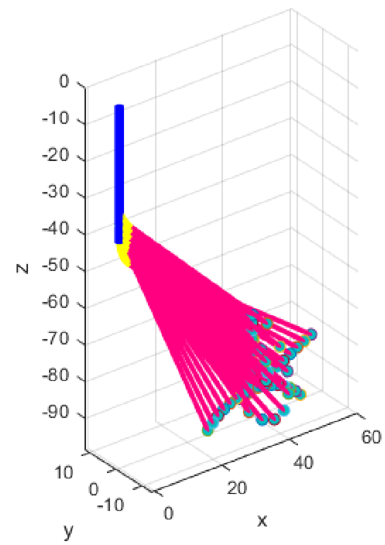

Fig. 10 Objective function: f2

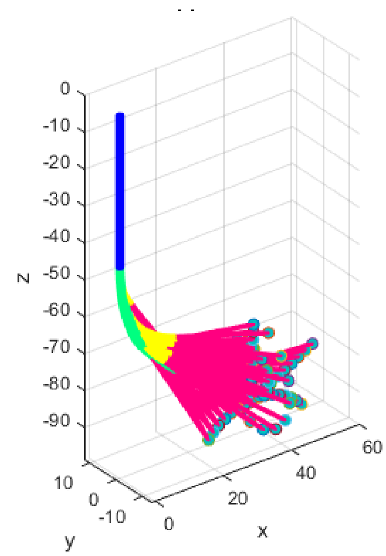

Fig. 11 Objective function : f1

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