Institute of Biomaterials & Biomedical Engineering
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Groove cutting topology selection to eliminate the snapping problem in concentric tube manipulators

M.A.Sc Thesis Proposal

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CIGITI Centre for Image Guided Innovation & Therapeutic Intervention

SickKids

Abstract:

Background: Recently, there has been intensive research in the use of concentric tube robots for minimally invasive surgery. A concentric tube manipulator consists of one or more pre-curved tubes inserted within another tube that is fixed. Relative rotational and translational motion between the tubes will result in movement of the distal tip of the manipulator. One major issue associated with concentric tube manipulators is the occurrence of the undesirable snapping phenomenon. **Aim and Methodology:** This proposed research aims to evaluate methods of eliminating the snapping problem by laser cutting topologies, (i.e. grooves/slots) in order to reduce the ratio between bending stiffness and torsional stiffness of the tube. The effect of these groove topologies will be first simulated using FEM software. The different topologies will be evaluated based on the decrease in stiffness ratio as well as increase in maximum local stress. The best performing topologies will be manufactured and tested to see if snapping is eliminated and if the strength of the new tube holds up. **Expected Results:** We expect to see that while most of the chosen topologies improve stiffness ratio, there are 2 to 3 topologies that perform better than others. **Significance:** This research could potentially make the choice of concentric tube cutting topologies easier in the future, so that the snapping problem is avoided.

Keywords: *concentric tube, laser cutting, snapping, surgical robot, topology, groove, stiffness ratio*

Introduction:

In recent years, there has been extensive innovative research on the uses of concentric-tube telescopic robots in minimally invasive surgery. A concentric-tube system is a set of two or more metal tubes in which one tube is inserted into the next tube. In a set of two tubes, at least one of the tubes is pre-curved at the distal end. The translational and rotational degrees of freedom of the pre-curved tube are individually actuated at the tube's proximal end. If a system consists of more than one pre-curved tube, then each pre-curved tube would typically be actuated to separately rotate and translate in their length-wise direction with respect to one another [1]. As each tube moves with respect to another, their differing curvatures and orientations would cause the tubes to conform to one orientation for the portion of their lengths that are overlapping. Thus, by actuating the rotation and translation of each tube at the proximal end, we can steer a very small distal end of the innermost tube (on the scale of a few millimetres in diameter) in a confined space. The ability to not only precisely steer the end effector but also the shape of the entire length of the concentric tubes makes this method especially suitable for minimally invasive surgery [1]–[4].

One mechanical limitation that exists with the use of pre-curved concentric tube robots is the occurrence of the "snapping problem" [5], [6]. As pre-curved tubes move with respect to one another, they build up stored elastic energy due to both bending and torsion. The stable orientation and shape of the concentric tubes is where the stored energy is at a minimum. However, there can at times be more than one minima [5]–[7]. When this occurs, the shape can suddenly change, exhibiting an undesired snapping motion.

Background and Literature Research:

Review of the snapping problem:

When a set of two tubes are chosen such that there are more than one local minima in the energy landscape, snapping can occur, and this is known as bifurcation. This is highly unwanted for surgical applications because having such instabilities make it extremely difficult for an operator to work with. The critical point at which bifurcation occurs has been analyzed by DuPont et al. [8], and it can be avoided if the inequality (1) is satisfied.

$$L\sqrt{\kappa_1\kappa_2\frac{\frac{E_2I_2}{G_2J_2}+\frac{E_2I_2}{E_1I_1}\frac{E_1I_1}{G_1J_1}}{1+\frac{E_2I_2}{E_1I_1}}} < \frac{\pi}{2} \qquad (1)$$

Here, the parameter L represents the length of overlap between tubes 1 and 2. K1 and K2 are expressions of the curvatures of each of the tubes. E and G are the elastic and shear moduli respectively, and I and J are the area moment and polar moment of inertia respectively. (1) Shows that one approach to avoiding bifurcation is by minimising the extent of curvature of one or both of the tubes. However, one drawback to this is that a tube with less pre-curvature would result in a smaller workspace. This would limit the range of the range of motion of the robot and detriments the capabilities of a concentric tube system [6].

Previous Efforts:

An alternative approach would be trying to minimize the ratio EJ/GJ, which represents the quotient of bending stiffness over torsion stiffness. It has been shown in the past that it is possible to reduce this ratio by cutting groove topologies (patterns) on the tube in order to decrease area moment of inertia, and thus reducing the stiffness ratio [6], [7].

This method has been shown to be viable by Azimian et al. [ref] and Kim et al. [ref]. In the aforementioned research, both experimental results and FEM simulations show that the EI/GJ ratio is reduced by cutting groove topologies similar to that shown in figures (1) and (2). Research by Azimian et al. [7] and Kim et al. [6] has also shown through experiments that cutting grooves/slots on the tubes was capable of eliminating the snapping problem that existed without the grooves.

The majority of research on the mechanical properties of concentric tube systems has been performed with a super elastic nickel-titanium alloy named nitinol as the tube material [7], [9]–[12] . Nitinol is a super-elastic alloy that can be re-shaped easily by heating a specimen to above its transition temperature, and has high yield strains compared to most other metals such as steel and aluminum.

While previous research has identified that groove cutting is a viable method to avoid the snapping problem, effects of factors such as reduced yield strength has not been extensively explored. Furthermore, no attempt has been made in experimentally testing a sufficiently wide variety of groove topologies in order to identify which patterns are superior when the above two factors are considered. These factors are relevant because if one of the concentric tubes becomes plastic during an operation, its movement will be extremely difficult to predict and control [6]–[9].

Project Aims, Research Questions, Hypotheses and Methodology:

Aim 1: Use FEM simulation to characterize and rate a series 20 well-differed groove topologies based on their effect on the reduction of 1. bending to torsion stiffness ratio, and 2. bending strength.

Research Question: How will the choice of groove topologies aimed at reducing the bending to torsion stiffness ratio affect limiting factors such as decreased bending strength?

Hypothesis: Through simulation, it will be shown that while certain groove topologies have greater effect in reducing stiffness ratio, they may also prove to be more detrimental to the strength of the tube. This will lead to an identification of 5 to 10 groove topologies that have relatively better performance (when all aforementioned factors are considered).

Methods:

20 different cut topologies will be chosen and created using 3D modeling software. These cut patterns should all be designed to remove more material in the lateral direction than in the longitudinal direction. This is so that the decrease in the area moment of inertia in the Y-X plane is more than the polar moment of inertia decrease in the Y direction (refer to figure 3). These

models will then be put in to ANSYS FEM software and simulated separately under torsional load and bending load. The displacements under torsional and bending stress will be used to obtain torsional stiffness GJ using equation (1) and bending stiffness EI using equation (2) respectively.

$$\theta = L\ T / (J\ G) \tag{1}$$

$$\delta_{max} = \frac{Pl^3}{3EI} \tag{2}$$

Here, L represents the overall length of the tube, P represents the downward force creating the bending load, and T represents applied torque. Both loading conditions will consist of a single torsion or bending load at the distal end of the tube. The stiffness values from these results will be compared to the results of a simulation performed with an unmodified tube of the same thickness, diameter, and length.

As part of the simulation, the element under highest stress will be examined, and the stress will be compared to the maximum stress exhibited on a tube without cut patterns. The hypothesis implies that the maximum stress in cut tubes will be higher. 5 to 10 different groove topologies based on their ability to decrease the stiffness ratio while also minimising the increase in maximum stress.

Aim 2: Use test equipment to test the selected grooved tubes in order to verify simulation results of decrease stiffness ratio, while also testing to see if the grooved tubes exhibit yielding.

Research Question: Do the results of experimental testing of groove topologies comply with theoretical implications derived from FEM simulation? Specifically, is the snapping problem eliminated as predicted, and do the tubes yield during movement?

Hypothesis: The grooved tubes will not exhibit snapping under test conditions that are identical to conditions and parameters prescribed in the FEM simulation. However, some tubes will show signs of local yielding, which will help us point to two or three optimal tube cut patterns that do not yield.

Methods: After choosing 5 to 10 groove topologies, these topologies are then cut out from identical tubes using a laser tube cutting machine. This type of pattern cutting has been shown to be accurate enough to suit the needs of this experiment. Laser cutting has been used in manufacturing nitinol tube structures in the past [6], [7], [12]. These tubes will then be tested in a torsion testing setup built for this specific purpose, this will tell us the torsional stiffness. The bending stiffness will then be tested using an Instrom tensile testing system. The bending to torsional stiffness ratios of each tube will then be compared to that of the unmodified tube with the same length, diameter and wall thickness.

Next, the tubes will be set into an aluminum mold that defines the pre-curvature of the tube, and then heated to above nitinol's transformation temperature. This pre-curvature will be selected so that an unmodified tube will exhibit snapping when reaching the extents of its workspace. The unmodified tube will undergo this process as well. Each tube will then be placed within a larger tube of the same curvature in an experimental setup. The larger tube will be fixed while the smaller tube is actuated and turned. The unmodified tube will be tested first to confirm that snapping does occur at some point in its workspace. The cut tubes will then be tested to see if snapping occurs in them. This process will be done using video tracking, with a camera placed so that it sits in front of the testing setup, facing the distal end of the concentric tubes. To determine if plastic yielding is occurs, a cycle of movement will be repeated for 20 times to see if the path of the distal end remains consistent every time. This is because once nitinol reaches its yield stress, it loses elasticity and does not return to its original shape when load is taken away.

Expected Results:

We expect to see through FEM simulation that the majority of the 20 selected tube topologies will have a lower bending to torsional stiffness ratio EI/GJ than the unmodified tube. The relatively large variety of topologies chosen will give us a better idea of which kind of patterns and pattern parameters will yield better results. We also expect to see that the bending and torsional stiffness ratio is shown to be lower in cut tubes through experimental testing. We expect to eliminate the snapping problem in the two-tube experimental setup, while also seeing that some of the tubes show yielding.

Timeline:

The general proposed timeline for this research is presented in form of a Gantt chart (see Appendix Table 1). The start date is considered to be September 2016, and the end date is targeted to be September 2016.

Dissemination Plan:

The results of this research could potentially yield one peer-reviewed publication.

1. Groove cutting topology selection to eliminate the snapping problem in concentric tube manipulators.

This can be potentially published in the journals:

1. IEEE Transactions in Robotics

2. Mechanism and Machine Theory

Conclusions and Significance:

This study will point out which topologies of groove cutting perform better in concentric tube robots through both simulation and experiments. This makes future choices of tubes and tube cutting topologies much easier and provides rationale. This study provides multiple solutions to eliminating the snapping problem whenever it poses a problem to designing for a specific surgical operation.

Appendix A: References

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Appendix B: Figures and Tables

Figure 1: 3-D model of modified tube topology used by Azimian et al. [7]

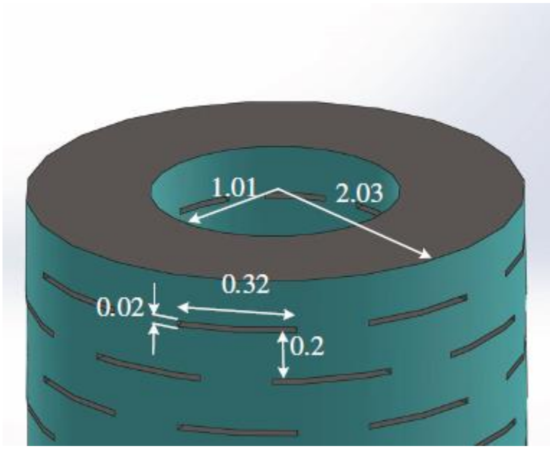


Figure 2: Modified tube topology used by Kim et al. [6]

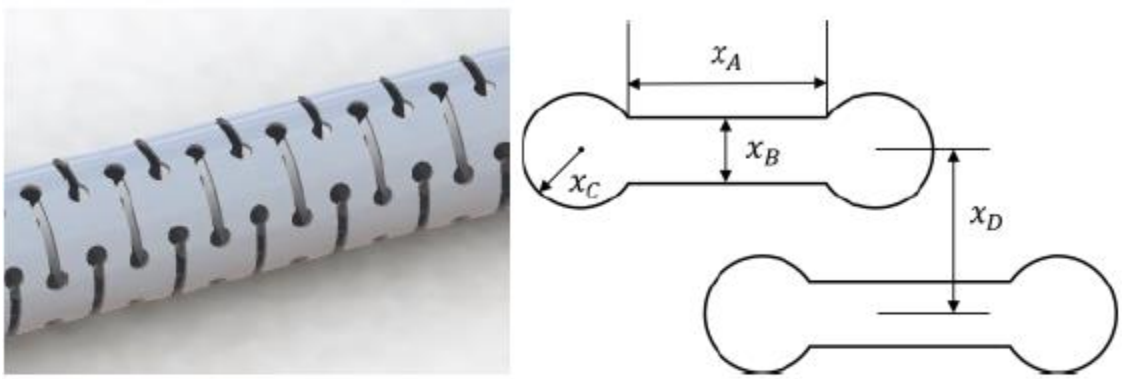
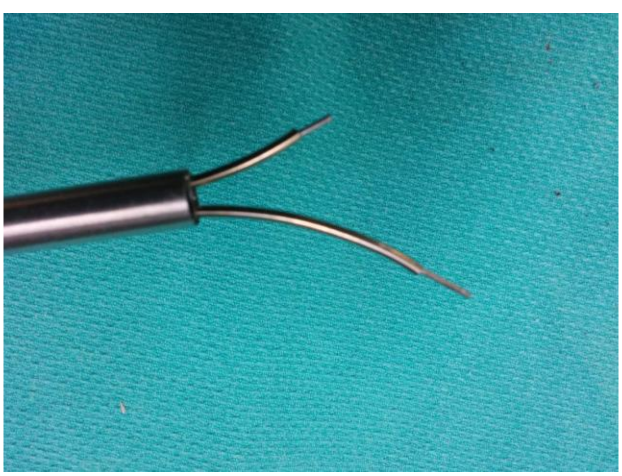


Figure 3: (left) view of tube in the XY plane, (right) view of tube in the Y axis cross section



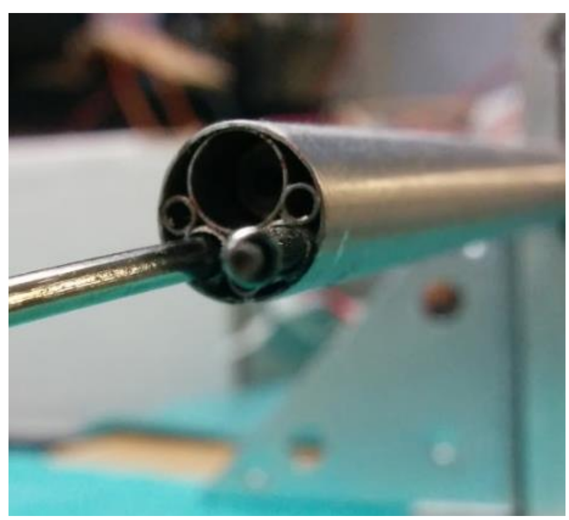


Table 1: Gantt Chart Timeline of Research Activities over 24 months

Activity	Time (Months)											
	2	4	6	8	10	12	14	16	18	20	22	24
Literature review												
Thesis proposal formulation												
Preparation for first Committee meeting												
Building of tension testing setup												
Procurement and testing laser cutting machine												
Creating 3-D models of 20 groove patterns												
Running FEM Simulations of 20 tubes												
Analysis of FEM simulation results and comparison												
Cutting selected groove patterns												
Torsion and bending testing of tubes												
Testing of tube to see if snapping exists												
Analysis of results from experiments												
Writing: Publications												
Writing: Thesis												
Thesis Defense												