CIS Seminar Presentation Report

Project Name: IRIS02 Integrated Intraocular Robotic Snake
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1. Background: IRIS 2.0 is the second generation of tendon-driven millimeter scale eye surgery snake manipulator developed in LCSR lab. It has two features make it different from other tendon-driven manipulator. First, it's size is very small, with a 3mm length and a 1 mm diameter; Second, it is made up from twelve identical circular components, and there're no joints or other means of connection. The current actuation unit of IRIS 2.0 consists of four motors, each one is connected to a screw lead and linear guide. The linear guide is pulled when one of the motor rotates, thus pull the tendons and bend the snake. Each pair of motor control bending in one direction, thus IRIS could be bent in two directions forming a hemishpere workspace.

The purpose of this project is to interface IRIS control units with Phantom Omni, in which case snake could be bend to the same position as user inputs to Omni. In order to achieve this, we need two mappings, one is the mapping from Phantom Omni joints' rotation angles to IRIS snake bending angles, the other mapping is from IRIS bending angles to motor rotation angles. The former one is rather easy to handle because it could be defined as a gain coefficient, but the second one is much more difficult to get as the relationship between IRIS bending angles and motor rotation angles is not linear. This problem needs to be solved and I am motivated to read the first paper: "A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimally Invasive Surgery."

***First Paper*:** This paper proposed the prototype of IRIS mechanical design, the idea is to build a backbone-free snake by stacking up a couple of identical cylindrical components. Apart from mechanical deign, the authors also formulated the kinematics feature of the snake; modeled how it deflects under external force and the stiffness of snake with respect to tendon pretension.

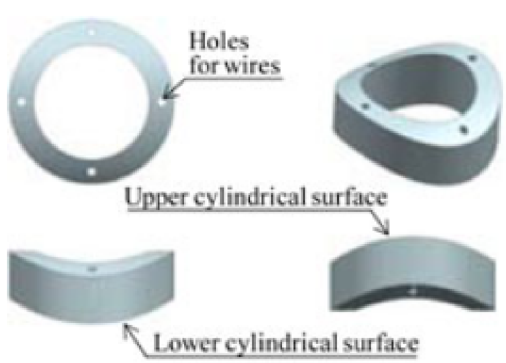


Fig. 1 Cylindrical component design

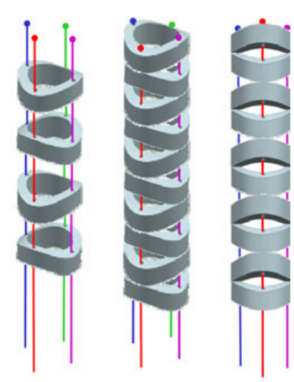


Fig. 2 Components stacked up using tendon

For kinematics model, authors started from simple one DOF case, in which they related change in tendon length to snake bending angle, then the model was extended into two DOFs case, and formula are presented as:

$$\Delta l_{pl}(\theta_p, \theta_t) = 2nr\left(\cos\alpha - \cos(\alpha - \frac{\theta_p}{2n}) + 1 - \cos\frac{\theta_t}{2n}\right)$$
$$\Delta l_{pr}(\theta_p, \theta_t) = 2nr\left(\cos\alpha - \cos(\alpha + \frac{\theta_p}{2n}) + 1 - \cos\frac{\theta_t}{2n}\right)$$

Eq. 1 Tendon displacement for pan motion

In which $\boldsymbol{\alpha}$ is the angle of curved upper and lower surfaces of a cylindrical component, and $\boldsymbol{\theta p}$ and $\boldsymbol{\theta t}$ are two bending angles (pan and tilt) of the snake. These two equations are for pan motion only, and equations for tilt motion are very same, except need to switch $\boldsymbol{\theta p}$ and $\boldsymbol{\theta t}$.

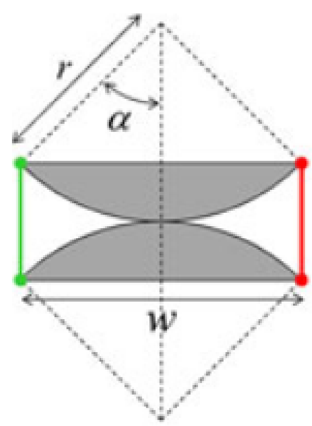


Fig.3 Definition of α

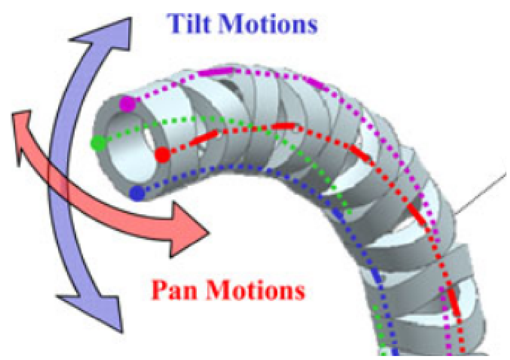


Fig.4 Pan and tilt angles of snake motion

To investigate the stiffness feature of snake manipulator under different pretension conditions, authors used both commercial simulation software and theoretical model. In the theoretical model, the problem was converted to find best stiffness coefficient by minimizing a energy conservation equation. They also did experiments to validate the stiffness model. Simulation parameters, results of both approaches and experimental results are shown as,

TABLE II
SPECIFICATIONS OF THE 2-DOF MANIPULATOR

Specification	Value
Number of Joints n	3
Half of Contact angle α	0.579 rad
Radius of Contact surface r	14.8 mm
Link Length l	29 mm
Pretension (N)	20.0, 33.1, 46.5, 59.9 N

TABLE III
STIFFNESS COMPARISON

Tension (N)	20.0	33.1	46.5	59.9
Simulated Stiffness (N/mm)	0.161	0.266	0.374	0.481
Calculated Stiffness (N/mm)	0.162	0.268	0.376	0.484

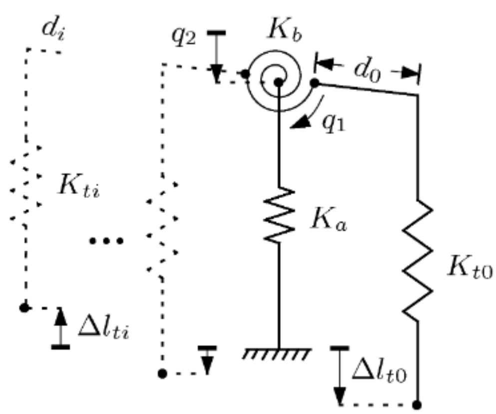
TABLE IV
STIFFNESS BY EXPERIMENTS

Tension (N)	20.0	33.1	46.5	59.9
Stiffness (N/mm)	0.242	0.334	0.437	0.529

Other topics in this paper will not be addressed with detail, and in general this paper provides a useful kinematics model which we can use in the project, also shed some light in the pretention setting we need in the experiment.

***Second Paper*:** Authors of this paper used solid mechanics method to model the mechanical property of tendon driven continuous manipulators. The subject manipulator they chose is steerable catheter, which has a similar design to IRIS snake. They developed both forward and inverse kinematics which map change in tendon length to beam bending and vice versa.

The model they use consists of a spiral spring, which analogs the bending of snake, and several linear springs, which stands for tendon and snake's axial deformation. It firstly computes the tendon tension, and then convert it into tendon length displacement.



$$\begin{aligned}\mathbf{y} &= [\Delta l_{t0}, \Delta l_{t1}, \ldots, \Delta l_{tn}]^T \\ &= l_b\,\kappa \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_n \end{bmatrix} + l_a\,\epsilon_a \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} + l_t\,\frac{1}{K_t} \begin{bmatrix} T_0 \\ T_1 \\ \vdots \\ T_n \end{bmatrix} \\ &= \mathbf{D}^T\,\mathbf{L}_0\,\mathbf{q} + \mathbf{L}_t\,\mathbf{K}_t^{-1}\,\boldsymbol{\tau}.\end{aligned}$$

Fig.5 Spring model of the snake and tendons

Eq.2 Tendon length change computed from tension

Apart from kinematics model, the authors proposed the idea of building a 3-D vision based measuring system to obtain the configuration of snake manipulator, but didn't specify any approach, which motivated me to search for relevant documentation, which leads to the third paper.

***Third Paper*:** This paper introduced a computer vision approach to reconstruct the configuration of a catheter using image from two camera perspectives. In each camera image, an algorithm is used to obtain the tip point and central line of the catheter. With the obtained central line points, authors successfully generated 3-D configuration of the catheter.

The central line point extraction algorithm could be divided into three big steps. The first one is making binary mask of the catheter and crop the region of interest. The second step is using edge detection to find the edge of region in interest, select three points, fit a optimal circle, take the circle center as tip point. The third step is to use concentric circular arc centered at the root point to propagate along the length of the catheter and find a series of center line points. Essential steps are demonstrated as follows,

*Fig.6 From **binary mask** to cropped **region of interest** to prior estimation of **tip point***

*Fig.7 From **tip edge** to **feature points** to posterior estimation of **tip point***

For the 3-D reconstruction algorithm, the firstly compute the 3-D coordinates of center line points in the camera frame from their pixel locations, then fit a 3-D quadratic function (ellipses) to these points. From camera calibration, the transformation matrix from one camera to the other could be obtained, and two elliptical cones (camera focal point as the cone tip) were constructed, whose intersection in the world frame are identified as 3-D coordinates of catheter central line points. Based on the fitted curve of central line, authors were able to computed bending angles of the catheter. They conducted series of experiments to validate this approach, one of the experiment results are shown as follows,

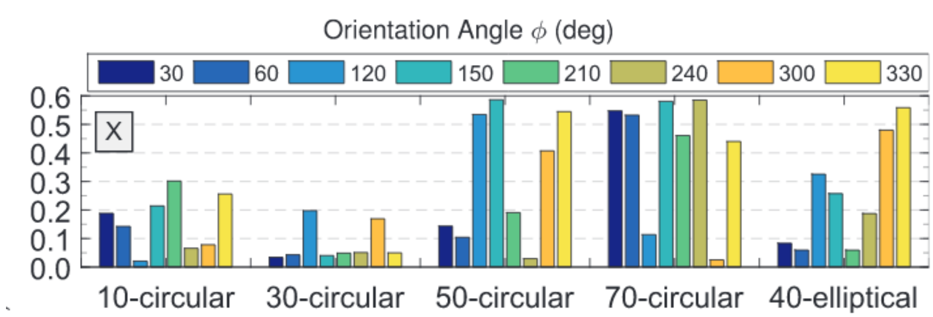


Fig.8 Error value of catheters with different cross-section when bent from 30 to 330 degrees

Comments and conclusion:
The kinematics model in the first paper could be applied into experiment and obtain validation data to see its effectiveness. If the mapping works with acceptable error, it will be coded into IRIS control algorithm. Similar stiffness analysis will also be conducted if force sensor is available to find a proper pretention level for tendons. Model established in first paper based on the assumption that there's no elastic deformation in both snake centerline and the tendon; also the curvature of snake is assumed to be uniform, which is not a good assumption in real experiment.

Kinematics model proposed in the second paper is more advanced and well supported by simulation results. However implementation of such a kinematics model requires considerable computational power and skills in embedded system, which is not accessible in current stage of project.

The computer vision solution of configuration detection is worth trying if we can obtain two cameras with good resolution to acquire images of sub-millimeter subjects. It will improve our current human eye measurement (resolution: 5 degrees) a lot.

Lesson learned: This presentation I made is not a satisfactory one. Apart from being nervous and speaking incoherently, my own understanding of the paper content is also lacking, especially for the second one with involves difficult math. Although it's a good paper I could have abandoned it and focus on the first and the third paper. Also, rehearsal for a talk before large audience is very necessary, which I didn't really pay attention to. Thanks Dr. Taylor who spent minutes to rectify what I did wrong. I wish things could be improved in final presentation, this is a valuable experience for me.

Bibliography
[1] Kim, Yong-Jae, et al. "A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimal Invasive Surgery" IEEE Transaction on Robotics, VOL. 30, NO. 2, April 2014.

[2] Camarillo, David B., et al. "Mechanics Modeling of Tendon-Driven Continuum Manipulator" IEEE Transaction on Robotics, VOL. 24, NO. 6, April 2008.

[3] Dalvand, Mohsen Moradi., et al. "Fast vision-based catheter 3D reconstruction" Institute of Physics and Engineering in Medicine, Phys. Med. Biol. 61 (2016) 5128-5148.

Application and feedback:
This report is written after weeks of the presentation I made, some of the methods are tried, some get accepted and modified, while others are abandoned.

The kinematics proposed in the first paper didn't work well in lab. Some reasons are considered: the nitile tendon used in IRIS is elastic and will be stretched under tension. Also the cylindrical components of snake would deform under compression, which makes error larger. The last reason may be a starting point with insufficient pretention, in which case although motor rotates for a certain amount there's no bending in the snake. Our current solution to the kinematics mapping is pure empirical.

For image processing techniques used in the third paper, we implement a simpler version. Instead of detecting the center curve, the bending angle is computed by the slope of the straight indicator mounted at the top of IRIS snake. The tip and root points are detected with hough transform. An example is shown as follows,

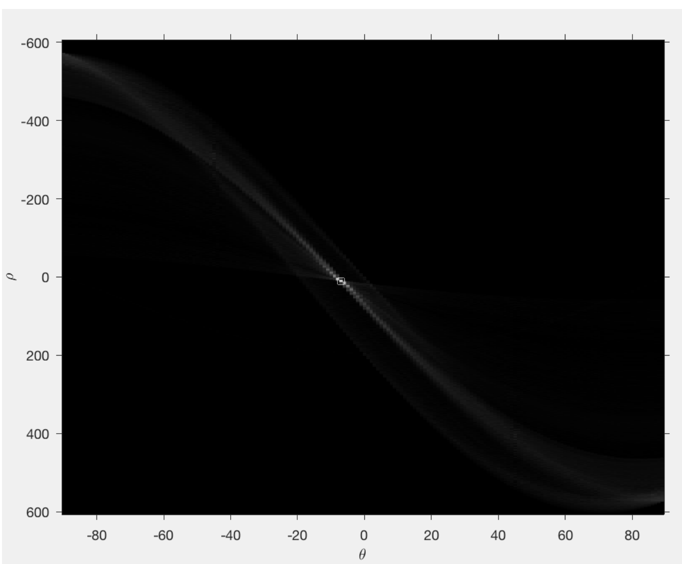


Fig.9 Hough transform detected one major line feature

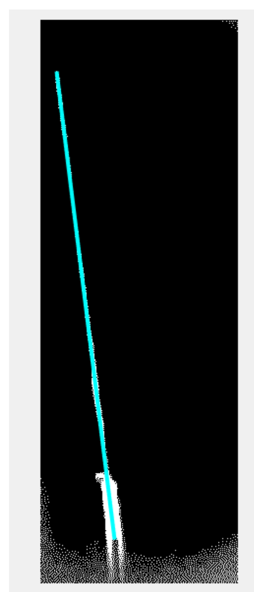


Fig.10 Bending detected as 5.38 degree