Paper Critique

A stiffness- adjustable hyperredundant manipulator using a variable neutral-line mechanism for minimally invasive surgery

EN 601.656 Computer Integrated Surgery II

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1. CIS II Project Overview

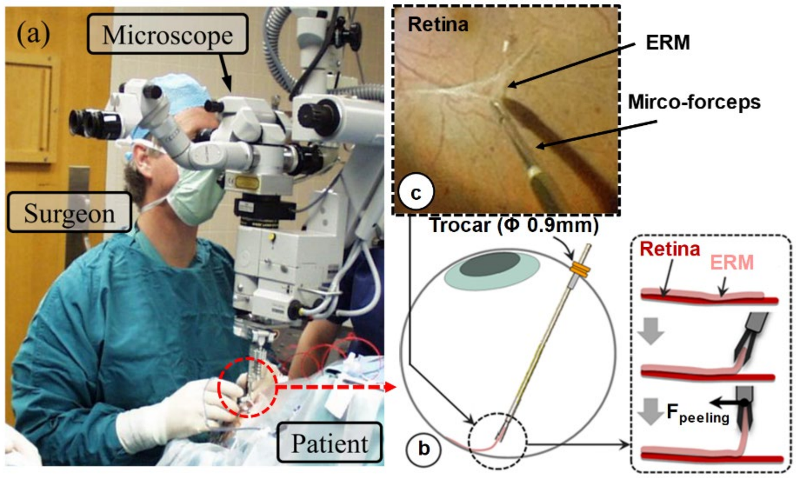

Figure 1 ERM peeling

Vitreoretinal surgery requires advanced surgical skills at or over the limit of surgeons' physiological capabilities due to space, force and motion limitations of the surgical tools. For instance, epiretinal membrane (ERM) peeling surgery shown in Figure 1, where a micron-scale membrane on the retinal surface is removed, requires the forces exerted by the surgeon to be less than 7.5 mN [1] to not cause tissue damage.

This project aims to move towards solving the clinical challenges mentioned above by providing the surgeons a cooperatively controlled robotic system with 2 DOF snake-like manipulator I^2RIS and a 5 DOF Steady Hand Eye Robot that has the capabilities of 1) tremor-free tool manipulation, 2) increased dexterity to ensure safe access to target from suitable directions, and 3) force sensing at the tool tip and sclerotomy. To be more specific, this project will integrate control of two existing robotic systems (I^2RIS and SHER) so that a surgeon can control the system to complete desired trajectories.

2. Paper Selection

The paper I have selected is:

Y.-J. Kim, S. Cheng, S. Kim, and K.Iagnemma, "A stiffness- adjustable hyperredundant manipulator using a variable neutral-line mechanism for minimally invasive surgery," IEEE Transactions on Robotics, vol. 30, no. 2, pp. 382–395, 2014

This paper, which we will refer to as Kim's, is relevant since the two DOF I^2RIS robot we are basing our project off of adopts the neutral-line mechanism designed for minimally invasive surgery in this paper. The paper also discussed the properties and working mechanisms of the proposed snake robot, which helps the team to better understand the mechanical design and control of I^2RIS. The method of link-by-link analysis in this paper also provides guidance on the kinematics and force distribution analysis of I^2RIS robot that our project include.

3. Summary and Key Result

Kim's proposed a hyperredundant tubular manipulator with a variable neural-line mechanism and adjustable stiffness. The paper presented a complete design and development of snake-like manipulators with 2 DOF with design optimizations. It also analyzed the relationship between control input, movement of wires, and output, bending angle of the manipulators. Kim's also added a feature of controllable stiffness to the manipulator. Validations of the systems were also performed

4. Introduction and Background

Snake like manipulators are receiving high attention due to interests in MIS, which has the benefit of low trauma and minimal scarring. And snake-like manipulators have the advantage of having flexibility, safety, dexterity and potential for minimization. Having its stiffness be tunable is also beneficial since high stiffness would allow high payload operation and exact positioning, while low stiffness would allow safe movement without harming internal organs. Therefore, in the scope of this paper, Kim's goal is to develop a snake-like manipulator with adjustable stiffness.

5. Paper: Theory

5.1 Basic Mechanics

The snake-like manipulators presented in Kim's have rolling joints between modular links, where the joint has arc-shape contact surfaces as Figure 2 shows. Two pairs of wires control 2 DOF. And the position of the neutral-line (center line) varies according to the pose of the proposed mechanism. Through the geometry of the manipulator and link-by-link analysis, it is found that there is a fixed relationship between input wire length and output angle.

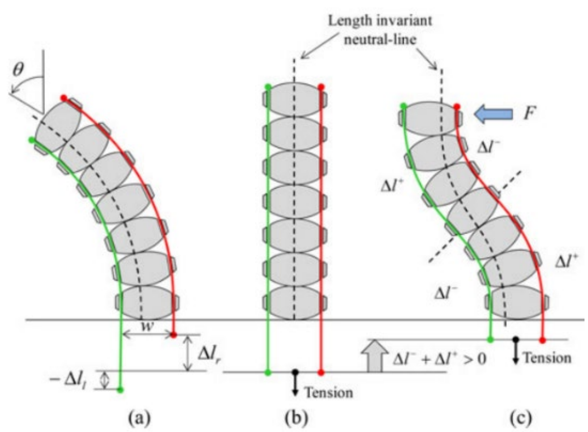

Figure 2 One-dimensional Variable Neutral-link Manipulator

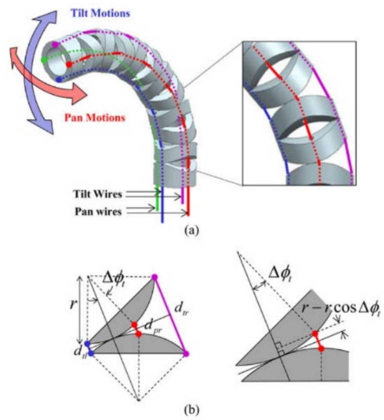

Figure 3 Pan and Tilt Motion and Close-up view

5.2 Deflection under External Force

In order to quantify the stiffness of the manipulators, Kim's first find out the pose change of the manipulator with an external force. The manipulators are approximated as revolution joints at small angle of deflection due to external force. And problem of finding the pose change can be simplified to finding ϕ with $argmin(\Delta l_t + \Delta l_p)$. Through geometry of the robot and link-by-link analysis, it is also found that there is a fixed relationship between displacement d and pose ϕ_i's indicated as Figure 4.

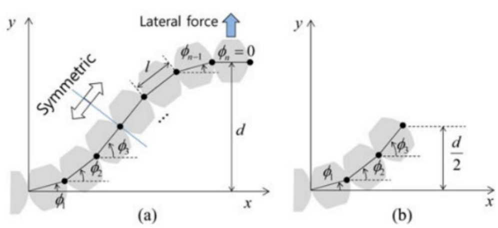

Figure 4 Deflection Model of 1-DOF Manipulator

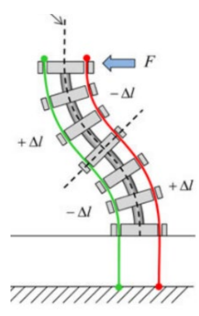

Figure 5 Revolute Joint Approximation

5.3 Stiffness and Wire Tension

Using virtual work concept and results from 5.2, an approximately linear relationship between tension and manipulator stiffness is found from calculation and simulation. It is also found that increasing joint number doesn't significantly affect the stiffness performance. Figure 6 shows the force-displacement curve at different tensions. Note that the shape of force vs. displacement because the manipulator lies outside of the Taylor series expansion and other approximations used during the calculation. But the force vs. displacement is linear with small deformations.

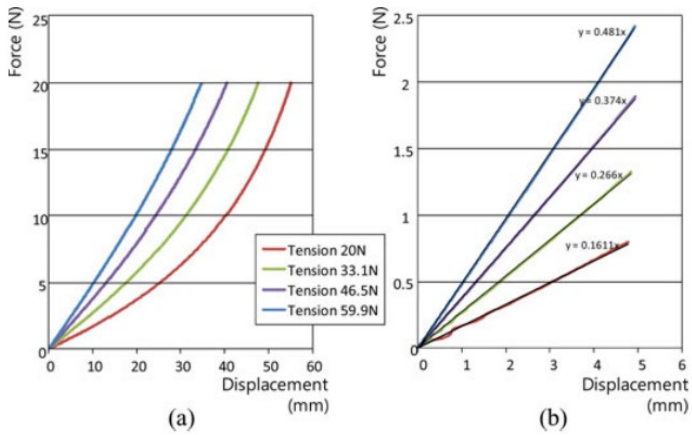

Figure 6 Simulated Force vs. Displacement with Different Tensions

6. Paper: Experimentation

6.1 Design Implementation

A fan-shaped level connected to two wires is confirmed through calculations to be able to generate a proportional relationship between actuator motion and manipulator motion. A lead screw and motor are used to adjust pretension of the wires. Winding of the wires around the lever amplifies the wire motion. A more detailed assembly of the actuation is shown below.

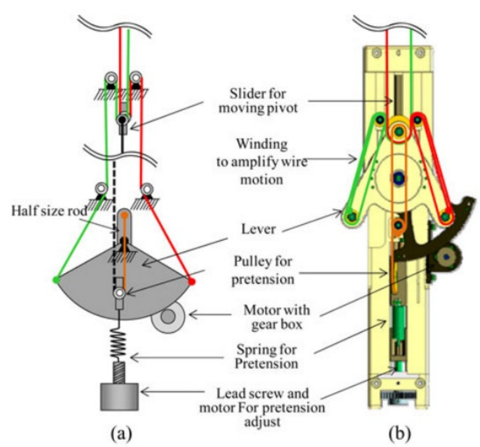

Figure 7 Main Component of the Actuation

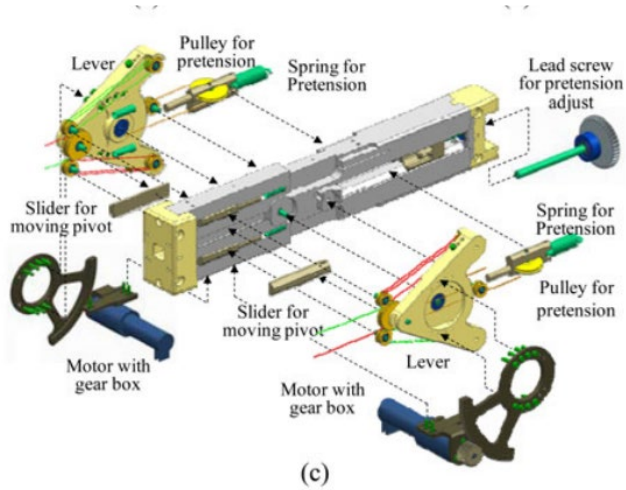

Figure 8 CAD Assembly of the Actuation

6.2 Validation

Maximum bending angle agrees with calculated maximum, which confirms the calculated relationship between input and output. The approximately linear relationship is also confirmed by Figure 9. In terms of stiffness of the system, it is found that the real robot manipulator has high stiffness than the simulated system, possibly due to internal friction between links and wires.

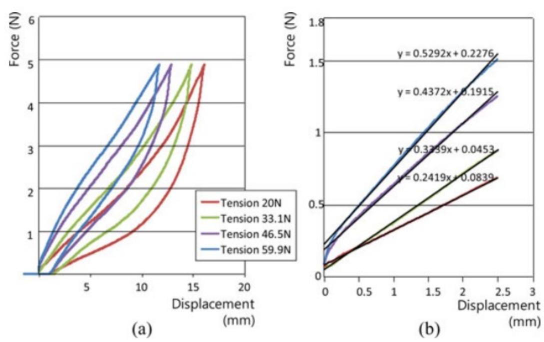

Figure 9 Stress-strain Graph

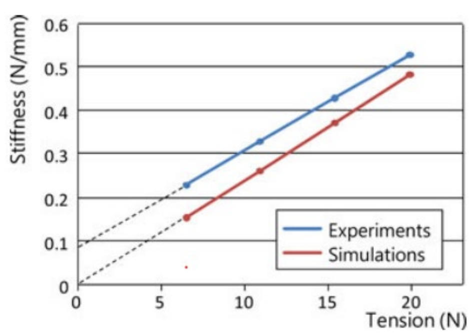

Figure 10 Stiffness vs. Wire Tension

7. Assessment

7.1 Pros and Cons

Kim's clearly explained the geometry model of the manipulator design and link-by-link analysis of relationship between system parameters with supporting figures. There is also a thorough discussion of the difference found between experiments and simulation results.

The motion of the manipulator is of great interests since the manipulator is designed to perform certain tasks for MIS. However, the effect of stiffness on commanded motion is ignored. There is also a lack of comparison between motion of the simulated system and the real one.

7.2 Future Work

Some of the future work Kim's can perform is the improvement of the system design. The next step could be to simplify the actuation mechanisms and experiment with variations of the shape of the snake links. Another direction for future work is to explore the application of the snake robot system and implement control algorithm with force sensing so that the robot can perform certain tasks.

7.3 Relevance

This paper is highly relevant to our project since it helps with the understanding of the I^2RIS robot geometry, which adopts the same the neutral-line mechanism. We can also adapt the input(motor rotation)-output(pitch/yaw) relationship model developed in this paper to our system. The method of link-by-link analysis is quite useful when analyzing kinematics and force distribution model for I^2RIS. The Hysteresis indicated in the paper also indicates the need for error estimation when we are applying control algorithm to our real robot system. We might also be able to use validation method presented in this paper.

8. References

[1] P. Gupta, P. Jensen, and E. de Juan, "Surgical forces and tactile perception during retinal microsurgery," in *International Conference on Medical Image Computing and Computer Assisted Intervention*, vol. 1679, 1999, pp. 1218–1225

[2] Y.-J. Kim, S. Cheng, S. Kim, and K.Iagnemma, "A stiffness- adjustable hyperredundant manipulator using a variable neutral-line mechanism for minimally invasive surgery," IEEE Transactions on Robotics, vol. 30, no. 2, pp. 382–395, 2014

* This review references source[2] for all figures and section 3 – 6.