Four-Page Thesis Synopsis

Development of A Soft Continuum Robot System for Surgical Blood Suction

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Empowering bio-inspired softness in robots for safer human-robot interaction

Bionics has long been a source of inspiration for developing more lively robots (Rus & Tolley, 2015). The *softness* and body compliance of the living creatures seem to be one of the common features that allow the living to better adapt to the complicated environment. Those examples include snakes, elephant trunks, tails of mammals, octopus tentacles, etc. Learning from nature, a new class of robots, namely, the *Soft Robots* with body softness and compliance has been proposed. Looking into how animals manipulate their soft bodies to work in sinuous, unpredictable environments can provide valuable innovation for emerging robotic applications in medical, rescue, and human-robot interaction.

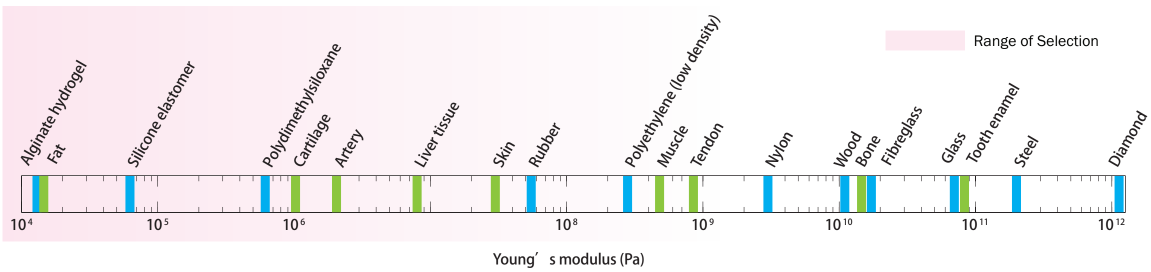

Fig. 1: The Young's modulus of some iconic engineering and biological materials. According to Rus & Tolley (2015), the soft robots shall be essentially composed of materials with moduli of less than 1 GPa, which are comparable with those of biological materials such as muscle and skin.

Different from the rigid-bodied robots that are usually made from hard materials (such as metals and plastics) with moduli ranging from 10^9 to 10^{12} Pa, soft robots are often composed of the soft-touch materials with moduli lower than 10^9 Pa (see Fig. 1). Soft robots are usually categorized as the subset of continuum robots (Webster III & Jones, 2010), as many continuum robots are assembled from multiple rigid and flexible components instead of soft materials (Fig. 2). Continuum robots share a lot of the same advantages as soft robots, but the latter demonstrate even greater advantages in terms of dexterity in constrained environments, safer human-robot interaction, miniaturization, and biocompatibility. All of these contribute to the attempt to the employment of soft robots in surgical purposes (Burgner-Kahrs et al., 2015), particularly, in R-MIS, which is the abbreviation of robot-assisted minimally invasive surgery.

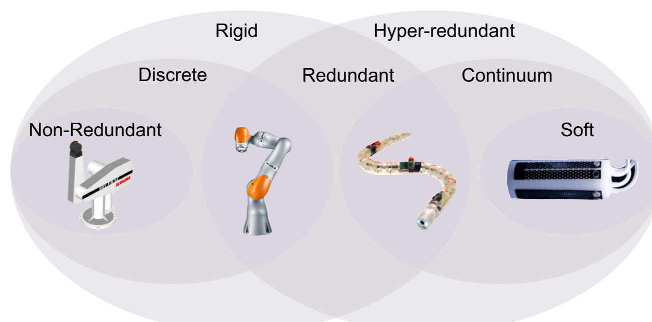

Fig. 2: Rigid and hyper-redundant robots based on the classification of materials and DOFs. Images from left to right: PUMA 560, KUKA LBR, modular continuum robot from Sensing Technologies Laboratory of Georgia Tech, and sensorized soft robot from CSAIL, MIT.

How soft robots may change the current R-MIS?

For the last decade, a number of works have been conducted by researchers and entrepreneurs to make the application of continuum robots feasible in R-MIS, which aims to complete a surgery as safely as possible while minimizing, or even totally avoiding any damage to peripheral tissue (e.g., the Natural Orifice Transluminal Endoscopic Surgery, also known as NOTES). Since the soft robots exhibit some unique advantages in being surgical tools (Cianchetti et al., 2018; Runciman et al., 2019), academics are also working on the *Soft-Robot-as-a-Surgical-Tool* (SaaS)[1], which would push the extra mile of surgical soft/continuum robots development.

[1] A new paradigm I proposed in this thesis.

Challenges on controlling a soft robot in R-MIS

According to a recent meta-analysis (Runciman et al., 2019), many interdisciplinary challenges of SaaS remain unsolved, especially when there is a unique requirement for a particular surgical procedure. This thesis chooses *surgical blood suction* as the initiative to explore a possible SaaS application.

In current practice, the residual blood at the surgical site can be evacuated by either a cotton gauze sponge or a suction apparatus connected to the negative pressure for continuous collection. The former approach uses a sponge to absorb the local fluid suffering from low efficiency. The latter approach involves the use of a manual suction tube. Without much flexibility, these tubes can become dangerous to the intracavity and organs.

To the best of the author's knowledge, the blood suction procedure has not yet been robotized. The efficiency and safety of blood suction can be improved by introducing a dexterous soft robotic manipulator as a blood aspirator. With the limited accessibility to the intra-cavity, where the incision ports (keyholes) are usually around 5–15 mm, a miniaturized soft continuum manipulator would be an ideal surgical tool for the automated suction task. The idea of using a soft robot to conduct the blood suction has neither been proposed nor verified elsewhere. Based on the requirements of surgical blood suction, some challenges are listed below: (a) manipulator design and actuation strategy, (b) accurate robot modeling, (c) tip positioning and path/trajectory tracking, (d) body motion planning, and (e) manipulator stiffness variability control.

Thesis overview and contributions

In this 3-year doctoral project supervised by Dr. Henry K. Chu, I have developed a proof-of-concept soft continuum robot system for blood suction *from scratch*. This thesis introduces the development of the SaaS for surgical blood suction, including robot design and fabrication, modeling, control, simulation, experiment, and application. I would like to make five claims that this thesis contributes:

- Design, exploration, and fabrication of the miniaturized cable-driven soft robot manipulators with two coupled segments, as well as the integrated robotic prototype for blood suction;
- Derivation of the constant curvature and establishment of mechanic-based compressible curvature model of the cable-driven soft robot;
- Development of the model-based control for the end-effector position, specified orientation, trajecotry tracking, and robot motion planning in the consideration of blood suction requirements. An RGB-D vision-enhanced control algorithm for trajectory tracking has been proposed. A Matlab-based 3D-simulator for the optimized motion planning of soft robots has been developed and open source;
- Development of the model-free control for the end-effector position and robot pose using learning and interactive visual servoing methods;
- Development of the hybrid of model-based and model-free control methods that adaptively controls the stiffness of the soft robot using the cable-tensioning approach.

What follows is the structure of the thesis, as diagrammed in Fig. 3. The logic goes like Why–What–How.

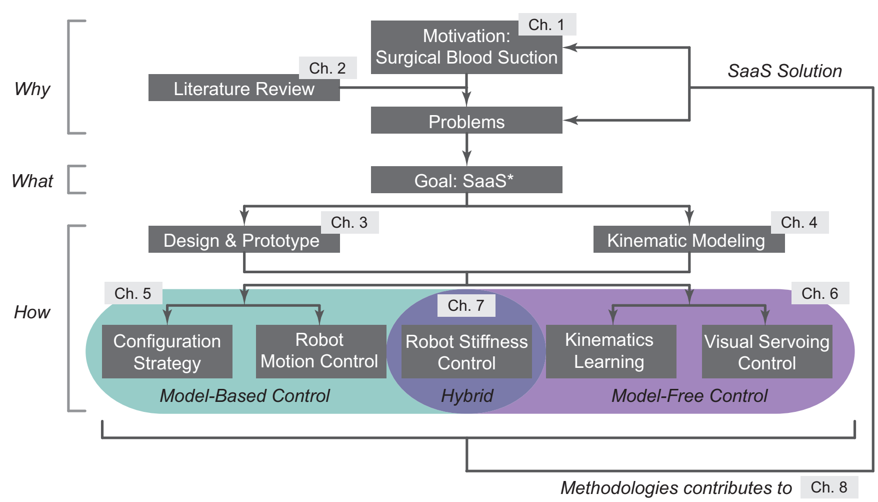

Fig. 3: Structure and contributions of the thesis, in terms of robot design, modeling, task space control strategies in model-based & model-free fashion, and stiffness control that hybrids the first two.

Part 1: Design, prototype, and modeling (Ch. 3, Ch. 4)

This project has developed two kinds of miniature cable-driven soft robots with two coupled segments. The first one was made from poly-dimethylsiloxane, also known as PDMS (which has been demonstrated in Lai & Chu (2019) and Lai et al. (2020)), and the second one was made from 3D-printed photopolymer. Both were bio-compatible and low-cost, with a diameter of 9 mm and capable of spatial motion. As the first generation prototype, the PDMS robot was made to be investigated the model-free control and application in the preliminary stage. The 3D-printed soft robot system was the second generation of this project (as shown in Fig. 4), which has been used in developing more sophisticated robot control methods based on the model. Fluid suctioning has been realized and tested on the 3D-printed version.

Fig. 4: CAD diagram of the prototype.

In the modeling part, firstly, the kinematics of a soft robot manipulator has been derived based on the trigonometrical representation. The derivation is detailed based on the Piecewise Constant Curvature (PCC) model. Both single and multisegment cases have been discussed. On top of that, a compressible curvature model, which is based on cable-driven mechanics, has been derived. This new model has been presented in Lai et al. (2022) and became the foundation of a self-developed simulator (Lai et al., 2021c). The model considers that a cable-driven soft segment is compressible, which provides different solutions of the end-effector pose because of the different cable actuation, even if the PCC configurations are identical. Both single and multisegment cases have been analyzed. The decoupled solution of cable actuation has been derived regarding the actuation coupling effect in the multisegment case.

Part 2: Task space control strategies (Ch. 5, Ch. 6)

Ch. 5 introduces two model-based methods to control a two-segment 3D-printed soft robot.

The first part proposed a Jacobian-based control method to control the robot. According to the requirement of surgical blood suction, an opposite-bending configuration scheme for the soft manipulator was adopted, ensuring the pointing direction of the robot tip remains normal to the work surface while performing a free space tip trajectory tracking task. Verified by extensive simulation, a point-cloud searching algorithm is developed to enable rapid task space searching for the manipulator. A 3D visual feedback system using RGB-D images was built, which can be used to enhance the accuracy with kinematic control. Experiment results confirm the feasibility of the proposed verticalized-tip scheme method to follow different trajectories. Different trials were also conducted to evaluate the performance of automated suction. An automated suction procedure was designed and performed. A comparison between the soft surgical and rigid tools was given, showing that the latter outweighed the former in terms of interaction safety, reachable workspace, and vertical tip configuration. The work in this part was published in Lai et al. (2021a). The second part of this chapter introduces a constrained motion planning approach incorporated with the compressible curvature modeling for a multisegment cable-driven soft robot under the segment coupling effect. This motion planning method contributes to the dexterous control of soft robots. Two optimization-based motion planning algorithms have been developed to extend the controllability and manipulability of a multi-DOF soft robot in trajectory tracking tasks in constrained conditions. Supported by the simulation and experiment, the method can be generalized to similar multisegment cable-driven soft robotic systems by customizing the robot parameters for prior motion planning. The work in this part was published in Lai et al. (2022).

Ch. 6 introduces two model-free methods to control a two-segment PDMS soft robot. In Sec. 6.1, a machine learning-based inverse kinematics solver was proposed based on a virtual-rigid link model. The simulation confirms that the solver can provide a simpler approach to compute the inverse solution in the configuration space for the robot control. The work in this part has been published in Lai et al. (2019). In Sec. 6.2, a visual servoing method is proposed. The method allows one to adaptively control a two-segment cable-driven soft continuum robot manipulator in bi-direction. With the developed interaction interface, the user can configure a two-segment soft robot by clicking the key points for the end-effectors of the segments. Supported by the experiment, the method was competent in both shape control and payload capacity. The work in this part was partially presented in Lai & Chu (2019) and published in Lai et al. (2020).

Part 3: Variable stiffness soft robots (Ch. 7)

In this part, a tendon-tensioning scheme to upgrade a normal dual-segment soft robot to a variable-stiffness version is presented. It is experimentally confirmed that the proposed scheme can variate the stiffness of a soft robot, i.e., providing an additional controllable DOF to the robot, without apparent change in configuration. In trajectory tracking, depth vision was employed to acquire the spatial deviation of the end-effector caused by an axial payload. The visual perception of the tip was treated as the closed-loop feedback for stiffness compensation. Utilizing our method, the manipulator can stabilize its instantaneous configuration by adaptively controlling its stiffness without losing compliance. Extensive experiments were conducted to verify the principle of the tendon-tensioning method, and the anti-disturbance performance was also evaluated through real-time trajectory tracking tests by adhering to different payloads to the robot tip. The results indicate a significant improvement in terms of load-bearing trajectory tracking compared to the pure open-loop version, with stiffness controllability of up to 130%. The positioning error can be reduced up to 50% when with an external payload of 30 gram-force. And it can be inferred that reduction would be more notable with heavier loads. This work shows that soft-bodied robots have great potential for application in future R-MIS manipulation for safer human-robot interaction. The work in this part was published in Lai et al. (2021b).

Discussion and closing remarks

This thesis is only a first step in enabling a science and engineering mix of promoting soft robots to play roles in the operation room. We acknowledge that much of our work was preliminary and required in-depth collaboration with physicians and surgeons in the future—if we want to impact current surgical robots. We, therefore, close with a discussion of the road ahead, including master-slave control, haptics, and multi-agent cooperation.

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