Master Thesis Research Proposal

Xiaowei Lin, ETH Zurich 21-947-072

Supervisors:
Prof. Pierre E. Dupont, Dupont Lab, Boston Children's Hospital, Harvard University
Dr. Giovanni Pittiglio, Dupont Lab, Boston Children's Hospital, Harvard University
Prof. Bradley J. Nelson, Multi-Scale Robotics Lab, ETH Zurich

April 2024

Introduction

In recent years, continuum robots have garnered significant attention from researchers, especially for their flexibility and potential applications in clinical settings like minimally invasive surgery [1]. However, this very flexibility presents a challenge in accurately controlling the catheter. Numerous efforts have been dedicated to investigating methods for achieving precise control of continuum robots. This includes developing better models as a feedforward approach and shaping sensing techniques as a feedback approach. Various modeling techniques have emerged to obtain a model for continuum robots, with the most prevalent ones being the piecewise constant curvature model, the Cosserat model, and data-driven models [5]. While the piecewise constant curvature model focuses on kinematics, the Cosserat model incorporates material properties, and data-driven models aim to capture non-linearities that other models may miss. However, often model do not accurately predict the robot behavior, necessitating the incorporation of feedback to augment model predictions of the robot's state and mitigate inaccuracies in modeling.

Sensing the shape of the robot is a recognized approach to provide appropriate feedback. Methods like fiber Bragg gratings (FBG), electromagnetic (EM) tracking, and vision-based methods are widely recognized. FBG sensing is getting attention for its ability to measure curvature accurately along the robot's length, though it's expensive due to the cost of fiber optic sensors (FOS) and optical interrogators [4]. EM sensors, while effective in certain clinical applications, are constrained to localizing a limited number of points along the robot's structure [3]. Vision-based methods, which use fluoroscopic imaging, endoscopy, or ultrasound, have drawbacks including cost, resolution limits, and the use of ionizing radiation [3].

In contrast to these methods, Magnetic ball chains, a recent innovation in continuum robot design [2], offer a unique approach to shape sensing. Consisting of a series of spherical permanent magnets enclosed within a flexible sleeve, the movement of the ball chain is controlled by an external magnetic field. Besides actuation, magnetic ball chains could be used as a sensing methodology. When inserted in the tool channel of a continuum device, they generate a magnetic field that depends on the shape of the device. This field is monitored with external sensors, and device position and shape is inferred.

Previous research has established the preliminary results for shape sensing using magnetic ball chains. We propose to optimize the shape-sensing technique by:

1. Optimize the sensor grid to get the best shape-sensing results.
2. Design and fabricate a sensor grid.
3. Design experiments to verify the goodness of the optimized sensor network.
4. Apply shape sensing in real-world applications.

Task Description

Optimize the sensor grid to get the best shape sensing results

The goal of this step is to find an optimized configuration of the sensor grid to improve the fidelity of the shape sensing output. It will include: investigating sensors required for different sizes of magnetic ball chains; given the sensors' specs and workspace requirement, constructing an optimization program that outputs the optimal sensor grid configuration in terms of the grid size, sensor position and configuration; and verifying the result in simulation.

Design and fabricate a sensor grid

The goal of this step is to design a sensor grid corresponding to the result obtained in step 1. It will include the mechanical design that places the sensors in their optimized configuration and the electrical design that drives the sensor and computes the shape-sensing result based on the sensors' readout in real time. It is better to design in a way that the configuration of the sensor grid can be adjustable. The electrical parts would be connected to a Raspberry Pi, which can be used to communicate with the robot controller in ROS.

Design experiments to verify the goodness of the optimized sensor grid

This step is to validate the performance of the optimized sensor grid by conducting real-world experiments to verify the simulation results. It will involve writing code for the experiment, which will require migrating the code into ROS using C++; collecting data for various shapes of the magnetic ball chain using the optimized sensor grid; data processing, analysis, and documentation; comparing the results to the simulation, and providing reasoning for any difference.

Apply shape sensing to real-world applications

Example applications can be developing a digital twin of the magnetic ball chain for visualization, demonstrating it by steering the catheter equipped with the magnetic ball chain in the phantom; and incorporating shape sensing into the control of a tendon actuated sheath for better control performance.

Project timeline

	April	May	June	July	August	September
Task1: Sensor grid optimization	■	■				
Task2: Sensor grid build-up		■	■	■		
Task3: Optimization verification			■	■	■	
Task4: Real-world application/improvement					■	■

Figure 1: Master Thesis research proposal timeline

Prof. Pierre E. Dupont, Ph.D.
Principal Investigator

Date: 04/05/2024

References

[1] Jessica Burgner-Kahrs, D Caleb Rucker, and Howie Choset. Continuum robots for medical applications: A survey. *IEEE Transactions on Robotics*, 31(6):1261–1280, 2015.

[2] Giovanni Pittiglio, Margherita Mencattelli, and Pierre E Dupont. Magnetic ball chain robots for endoluminal interventions. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*, pages 4717–4723. IEEE, 2023.

[3] Ardit Ramadani, Mai Bui, Thomas Wendler, Heribert Schunkert, Peter Ewert, and Nassir Navab. A survey of catheter tracking concepts and methodologies. *Medical image analysis*, 82:102584, 2022.

[4] Seok Chang Ryu and Pierre E Dupont. Fbg-based shape sensing tubes for continuum robots. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3531–3537. IEEE, 2014.

[5] Jingyu Zhang, Qin Fang, Pingyu Xiang, Danying Sun, Yanan Xue, Rui Jin, Ke Qiu, Rong Xiong, Yue Wang, and Haojian Lu. A survey on design, actuation, modeling, and control of continuum robot. *Cyborg and Bionic Systems*, 2022.