PhD Grants from the China Scholarship Council
– Details of the PhD proposal –

1. SUPERVISION

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2. TITLE

Magnetic Control of Continuum Microrobots for Medical Applications

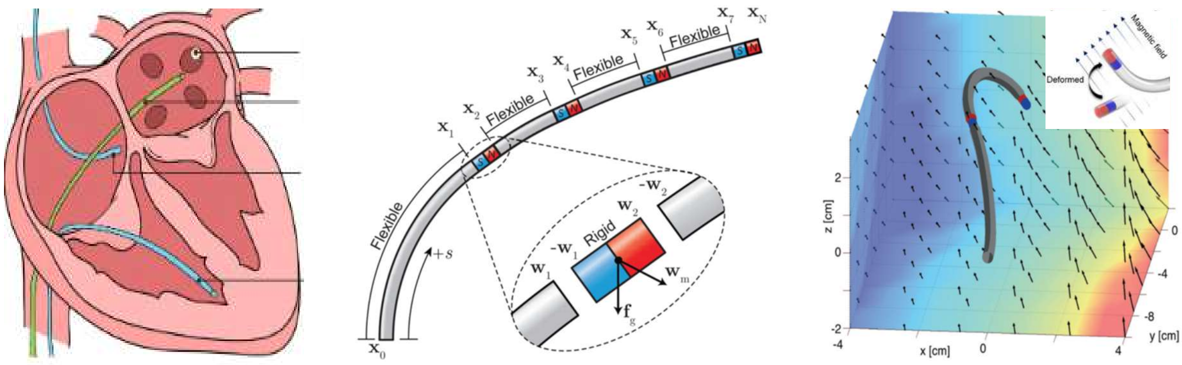
3. KEYWORDS

Mathematical modeling, magnetic theory, control of nonlinear systems, microrobotics.

4. SUBJECT

4.1. Introduction:

Robotic-assisted interventions facilitate minimally invasive procedures by reducing invasiveness and enhancing accuracy and dexterity. Presently, robotics is most commonly used in laparoscopic surgeries, but ongoing continuum manipulator research aims to bring the benefits of robotic assistance to a wider range of procedures. Current continuum manipulators, such as endoscopes, catheters, and steerable needles, rely on stiff constitutive materials to transmit forces and torques along the body, which can lead to unnecessary trauma when operating within soft tissue.



(a) (b) (c)

Figure 1: Magnetically guided soft catheters : (a) Catheter motion guidance for treatment of atrial fibrillation in the heart; (b) Magnetic catheter comprising four flexible, non-magnetic and four rigid, permanent-magnetic segments and (c) Principle of magnetic control: Magnetic catheters are deflected by the forces and torques generated by the interactions between embedded permanent magnets and the magnetic vector field.

One procedure in which magnetically guided catheters are used is in the treatment of atrial fibrillation (Figure 1a) by controlling and steering the catheter into the vessels to reach the heart.

Once in the heart the tip of the catheter is used to ablate the regions that cause atrial fibrillation. Currently, the most commonly procedures achieved by the clinician controlling the distal end through manual manipulation at the proximal end is based on feedback from fluoroscopic imaging. As shown in Figure 1b, the catheter is modeled as a flexible rod with M magnets along its length, which is parametrized by the station s along the arc length referenced to the proximal end of the catheter

Closed-loop catheter control will enable the clinician to shift his focus from the manipulation task itself to more sophisticated medical tasks, for example ensuring correct target trajectories and medical procedure conditions. The use of magnetic fields is of great interest since it can manipulate objects without contact. For catheters, this enables their manipulation without requiring mechanical guide wires or other internal structures as shown in Figure 1b-c. This allows magnetic catheters to be more flexible and smaller than mechanically manipulated designs, enabling access to difficult to reach areas.

4.2. State of the art:

Closed-loop position control of a magnetic catheter has been explored for the planar case. Ullrich et al. [1] proposed a solution using a magnetically guided flexible needle for capsulorhexis surgery (lens replacement) in the eye. The method successfully followed the circular trajectory required for the procedure, but the trajectory error showed systematic shifts, most likely due to their approximation of the needle deflection as a pinned rigid link. Tunay [2] presented a closed-loop control method for magnetically tipped catheters in a uniform magnetic field for use with Stereotaxis's system. This analysis utilized the Euler–Bernoulli beam modeling technique and assumes a constant curvature along the length of the catheter [3]. A similar beam modeling approach has recently been applied to an electromagnetic coil system developed by Magnetecs Inc. [4]. The primary drawback of these methods are that they are inherently planar and do not translate well to more complex geometries generated by applying both magnetic forces and torques to the catheter tip. The general modeling case of a catheter in an arbitrary magnetic field has also been addressed by Tunay [5] using Cosserat rod theory, but has not been applied to control. Cosserat rod theory has recently been applied to robotic control of continuum robots using pressure-drive, tendon-driven, and concentric-tube devices, but has yet to be applied to the control of magnetically tipped catheters.

4.3. Work to be done during the thesis:

The PhD work will focus mainly on the development of theoretical mathematical formulations related to modeling and control. The different steps are the following :

- Study existing references on magnetic microrobots dynamics modeling [6].
- Modeling of magnetic continuum catheter based on Cosserat rod theory [7a-b]. Continuum mechanics representation of the deformation of a long slender object will be developed taking into account variations in stiffness, cross-section, body loadings, and point loadings along the length of the catheter which is essential for calculating deflections under multi-magnet actuation.
- Development of Jacobian-based inverse kinematics method for control of the steerable catheter. Derivation of analytical closed-form solutions of the inverse kinematics will be developed taking into account the complexity of the kinematics [8]. A comparison

with Jacobian-based numerical methods will be conducted to validate the analytical approach.
- Self-sensing modelling and characterization to relate catheter model to the pose and force of the tip segment. Due to lack of position micro-sensors capable to be integrated in the catheter body, nonlinear reduced-order observers will be developed to estimate the pose and force of the tip segment [6].
- Closed-loop catheter control: Synthesis of a novel nonlinear sliding mode-based position and force controller with observer information as feedback [9]. Control simulations will be conducted on a four-segment magnetic catheter to explore various control stability conditions against modeling errors, blood perturbations, vessel friction, tip contact… during catheter motion guidance.
- Extension of the proposed modeling and control methodology to the multi-segment magnetic catheter configuration.

4.4. References:

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(b) Tang W, Wan TR, Gould DA, How T and John NW (2012) A stable and real-time nonlinear elastic approach to simulating guidewire and catheter insertions based on Cosserat rod. *IEEE Transactions on Biomedical Engineering* 59(8): 2211–2218.

[8] Sungwoong Jeon et al. (2018), A magnetically controlled soft microrobot steering a guidewire in a three-dimensional phantom vascular network, Soft Robotics, 2018.

[9] Sincic RS, Caton CJ, Lillaney P, et al. (2014) System architecture for a magnetically guided endovascular microcatheter. *Biomedical Microdevices* 16(1): 97–106.