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A review of continuum robot

Kenneth Ji[1,3,5], Yuyu Fang[2,4]

[1]Chengdu No.7 High school-China school, Chengdu, China
[2]Wuhan British- China school, Wuhan, China

[3]Kennethji2024@163.com
[4]fangyuyu@xymation.com
[5]corresponding author

Abstract. This paper comprehensively reviews continuum robots and their application in medical domains. Unlike traditional rigid robots, continuum robots possess continuous, flexible structures that enhance dexterity and adaptability. Their compliant nature allows safer human-robot collaboration, while their deformability permits navigation through confined spaces and conformance to anatomy. These advantages make continuum robots promising for medical applications like minimally invasive surgery. The paper discusses continuum robots' fundamental principles, including kinematics, dynamics, mechanical design, modelling, and control strategies. It highlights the unique benefits of continuum robots compared to rigid counterparts, especially for medical use. Challenges such as design optimization, accurate control and modelling, sensing, miniaturization, and technology integration are also addressed. Enhancing manipulation capabilities, developing miniaturized continuum robots, achieving autonomous operation, integrating imaging modalities, and validating safety and efficacy through clinical trials are suggested for future work. This review offers valuable insights into continuum robotics technology and its immense potential to transform medical interventions through precise, minimally invasive procedures.

Keywords: continuum robots, kinematics, dynamics, modelling control, medical application.

1. Introduction

This paper reviews the state of the art in continuum robots, focusing on their application and innovation in the medical domain. Continuum or soft robots are robotic systems with flexibility and compliance similar to biological structures. Unlike traditional rigid robots composed of discrete links and joints, continuum robots are composed of continuous, deformable structures, enabling them to navigate complex and constrained environments with enhanced dexterity and adaptability [1].

The fundamental principles of continuum robots lie in their kinematics and dynamics [2]. Kinematics describes the motion and configuration of the robot without considering the forces involved. Continuum robots exhibit a wide range of motion due to their flexible and continuous structure, allowing them to bend, twist, elongate, and even show complex locomotion patterns, such as crawling or slithering. The kinematic models of continuum robots are often based on the theory of kinematic mapping, which maps the robot's shape and deformation to its end-effector position and orientation.

The dynamics of continuum robots involve the study of forces, torques, and deformations exerted on and within the robot. The complex interactions between the robot's structure, actuators, and the

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environment give rise to intricate dynamics. Modelling the dynamics of continuum robots requires considering the material properties, such as elasticity, viscoelasticity, and hyperelasticity, and the distributed nature of forces and deformations along the robot's body. These dynamic models enable accurate control and manipulation of the robot's motion for precise tasks in various applications.

Compared to traditional rigid robots, continuum robots offer several distinct advantages. Their intrinsic compliance allows for safer physical human-robot interaction, making them suitable for delicate tasks and close collaboration with humans. The continuous structure of continuum robots enables them to adapt to various environments and navigate through confined spaces, reaching targets inaccessible to rigid robots. Furthermore, continuum robots can conform to complex anatomical structures, making them particularly promising for medical applications such as minimally invasive surgery, where precise and controlled manipulation within the body is essential for patient safety and recovery [4].

This paper presents a comprehensive overview of the basic principles underlying continuum robots. We discuss their fundamental concepts and characteristics, introducing their kinematics and dynamics. Additionally, we highlight the differences between continuum robots and traditional rigid robots, emphasizing the advantages of continuum robots in terms of flexibility, compliance, and adaptability in medical settings. Moreover, we explore the unique contributions and advancements in utilizing continuum robots for various medical applications, drawing upon the insights from analyzing the previous papers and research.

Through this comprehensive analysis, our paper aims to provide readers with a solid foundation in understanding the fundamental principles of continuum robots while highlighting the novel findings and advancements in their application and innovation within the medical domain. By focusing on the specific theme of continuum robots in the medical field, we contribute to the existing review literature by offering fresh insights into the state of the art, particularly in medical applications and innovations.

This paper provides a comprehensive review of continuum robots and their application and innovation in medical domains. The introduction discusses the background, motivation, and scope of the review. The core principles of continuum robots are elaborated in Section II, which analyzes their mechanical design, modeling techniques, and control strategies. Section III highlights the key challenges and difficulties encountered in developing continuum robots. Future research directions and suggestions to advance continuum robot technologies, especially for medical applications, are proposed in Section IV. The conclusion summarizes the key points and emphasizes the potential of continuum robots to transform medical robotics through their inherent compliance, dexterity, and adaptability. This review offers valuable insights into the state-of-the-art of continuum robotics, focusing on their unique capabilities and promise to enable new possibilities in minimally invasive medical interventions.

2. The core principle of continuum robot

2.1. Mechanical Design of Continuum Robots

Continuum robots have gained significant attention in various fields, particularly medical applications, due to their flexibility, safety, and potential for precise manipulation. The mechanical design of these robots plays a crucial role in achieving their desired functionality. Several advancements in the mechanical design of continuum robots have been explored in recent years.

One notable approach is based on Cosserat rods, as discussed by Burgner [1]. This approach takes inspiration from the natural flexibility and bending motion exhibited by animals such as snakes and octopuses. By utilising continuous arcs structurally, continuum robots based on Cosserat rods can achieve a high degree of flexibility and dexterity. The paper explores the statics and dynamics of these robots, providing insights into their mechanical behaviour and control. Additionally, applying optimal control theories enables precise control and manipulation of these continuum robots, ensuring their accurate performance in various tasks.

Furthermore, the paper on stiffness control of surgical continuum manipulators delves into another aspect of mechanical design. Stiffness control is crucial in surgical interventions to ensure safe and

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precise manipulation [3]. The research presented in explores strategies for controlling the stiffness of continuum manipulators, enabling surgeons to perform delicate procedures with enhanced dexterity and accuracy [3]. The paper discusses various techniques, such as variable stiffness mechanisms, active control of material properties, and compliant tools, which allow for adjusting the robot's stiffness characteristics. By dynamically adapting the stiffness, continuum robots can interact with their environment while maintaining stability and precision.

Integrating innovative mechanical designs, such as those based on Cosserat rods, and the development of stiffness control mechanisms contribute to the advancement of continuum robot technology. These advancements enable continuum robots to navigate complex environments, perform delicate tasks, and interact with the surrounding objects with enhanced adaptability and safety.

2.2. Modeling of Continuum Robots

Accurate modelling of continuum robots is essential for understanding their mechanical behavior and developing effective control strategies. Several modelling approaches have been investigated in the literature, considering continuum mechanics and geometric shaping hypotheses.

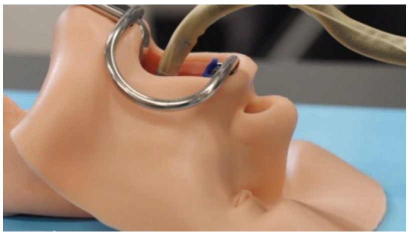

Figure 1. The continuous snake-like robot COBRA

Zhong's paper provides insights into the modelling techniques employed in continuum robots. The article discusses advancements in modelling approaches based on continuum mechanics, refined over years of research. These approaches involve the formulation and solution of partial differential equations that describe the deformation and motion of the continuum robot. Additionally, numerical analytic methods, such as finite element analysis, have been widely adopted to simulate and validate the proposed models. The integration of these modelling techniques allows researchers to gain a comprehensive understanding of the mechanical characteristics and capabilities of continuum robots.

Furthermore, the paper on cable-driven continuum robot perception using skin-like hydrogel sensors introduces a novel sensing mechanism for continuum robots [7]. By integrating skin-like hydrogel sensors into the robot's structure, the perception capabilities of the robot are enhanced. This advancement in modelling and perception techniques enables the robot to interact with its environment more effectively and perform complex tasks with improved accuracy and safety.

The combination of accurate modelling techniques and advanced sensing capabilities contributes to developing realistic simulations and control algorithms for continuum robots. By accurately predicting the behavior of these robots and incorporating real-time sensory information, researchers can optimize the performance, stability, and safety of continuum robots in various applications.

2.3. Control of Continuum Robots

Effective control strategies are crucial for achieving precise and coordinated motion in continuum robots. The control of these robots involves closed-loop and hybrid control methods that leverage sensor feedback information.

Yan's article provides an overview of various control approaches. The survey highlights the significance of closed-loop and hybrid control methods in achieving accurate and resilient motion control. Combined with sensor feedback information, these control strategies offer improved accuracy and adaptability to external disturbances.

Furthermore, the paper on the visual servoing of continuum robots explores the utilization of visual feedback for controlling the motion and manipulation of these robots [2]. As discussed by Zhang, optical servoing techniques enable the robots to interact with the environment based on visual cues, allowing for precise and real-time control [2]. The paper discusses different visual servoing methods, such as feature-based approaches and model-based approaches, highlighting their advantages and challenges in the context of continuum robots.

Integrating closed-loop control strategies, hybrid control methods, and visual servoing techniques enhances the autonomy and versatility of continuum robots. By continuously monitoring the robot's motion and environment and adjusting the control signals accordingly, researchers can achieve accurate and adaptive control of continuum robots in complex and dynamic scenarios.

In conclusion, continuum robots' mechanical design, modeling, and control have been active research areas. The advancements in these areas are highlighted in the referenced papers [1-7].

3. Challenges in the Development of Continuum Robots

This section will discuss the challenges and difficulties encountered in developing continuum robots, drawing insights from the eight research papers under consideration.

3.1. Design Variability and Optimization

The design variability and optimization of continuum robots are complex tasks that demand careful consideration. Each type of continuum robot, such as those based on Cosserat rods, layer-driven mechanisms, and cable-driven systems, presents unique design requirements. Selecting appropriate materials, actuation mechanisms, and sensor integration is crucial to achieving the desired performance [1,6,7]. Optimizing the structural parameters and kinematic configurations is essential to enhance the robot's capabilities [2].

3.2. Control and Modeling

Accurate control and modeling of continuum robots pose significant challenges due to their complex and nonlinear behavior. Developing suitable control algorithms that can handle the intricate dynamics of continuum robots remains an ongoing research focus. Closed-loop and hybrid control methods [4] offer improved accuracy and resilience when combined with sensor feedback. Continuum mechanics-based modeling approaches [1] and geometric shaping hypothesis [2] have made significant progress, but further advancements are needed to enhance computational efficiency and real-time performance.

3.3. Perception and Sensing

Enabling perception and sensing capabilities in continuum robots is crucial for safe and efficient operation. Integrating visual servoing techniques and skin-like hydrogel sensors can enhance the robot's perception abilities [2,8]. However, achieving robust and reliable perception in highly deformable and dynamic environments remains challenging. Advancements in sensing techniques and algorithms are required to accurately perceive the robot's surroundings and facilitate effective interaction with the environment.

3.4. Miniaturization and Scalability

Continuum robots offer the potential for miniaturization, enabling minimally invasive procedures in medical applications [3]. However, miniaturization introduces challenges such as fabricating miniature components, maintaining structural integrity, and ensuring precise control at a smaller scale. Additionally, scalability is a concern when continuum robots are scaled up for more extensive applications [2]. Ensuring that the performance and accuracy of the robot are maintained during scaling requires further investigation.

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3.5. Integration of Advanced Technologies

Integrating advanced technologies, such as machine learning and artificial intelligence, promises to improve the continuum of robot development. Data-driven modeling techniques simplify the modeling process and enhance anti-interference and generalization capabilities [4]. However, effectively integrating these advanced technologies into continuum robots poses challenges related to compatibility issues, availability of training data, and real-time implementation.

In conclusion, the challenges and difficulties in developing continuum robots encompass design variability and optimization, control and modeling, perception and sensing, miniaturization, and integrating advanced technologies [1-8]. Addressing these challenges through ongoing research efforts is essential to overcome obstacles and unlock the full potential of these versatile and adaptable robotic systems.

4. Conclusion

This paper has provided a comprehensive review of continuum robots, focusing on their application and innovation in the medical domain. The article discussed the fundamental principles of continuum robots, including their kinematics, dynamics, mechanical design, modeling techniques, and control strategies. A key point highlighted is that continuum robots offer unique advantages like flexibility, compliance, and adaptability compared to traditional rigid robots. Their intrinsic compliance allows safer human-robot interaction while their continuous, deformable structure enables navigation through confined spaces and conformance to complex anatomy. These characteristics make continuum robots highly promising for medical applications, especially minimally invasive surgery, where they can enable precise in-body manipulation and enhance patient safety. However, challenges exist in design optimization, control, modeling, perception, miniaturization, and integration of advanced technologies.

Further research should focus on enhancing manipulation capabilities, developing miniaturized continuum robots, achieving autonomous operation through algorithms, integrating imaging modalities, ensuring reliability and safety, and validating clinical efficacy. By addressing these research directions, continuum robots have immense potential to transform medical robotics and enable new possibilities for precise, minimally invasive interventions that improve patient outcomes. Their compliant, dexterous capabilities make them well-suited for revolutionizing robotic technologies in healthcare.

Continuum robots have shown promise in the medical field, but further research is needed to enhance their application and innovation. Here are key research directions and suggestions:

Enhanced Manipulation and Intervention: Improve manipulation capabilities by developing novel actuation mechanisms and control strategies. Integrate advanced sensing technologies for improved perception and feedback.

Miniaturization and Scalability: Explore materials, fabrication techniques, and control approaches to develop miniaturized continuum robots with improved functionality and scalability.

Autonomous and Intelligent Operation: Develop algorithms for independent decision-making, adaptive control, and learning from human-robot interactions to reduce human intervention and adapt to dynamic surgical environments.

Multi-Modality Integration: Integrate continuum robots with imaging modalities (MRI, ultrasound) for real-time visualization and navigation, enhancing accuracy and safety during procedures.

Long-Term Reliability and Safety: Study wear and tear of robot components, develop robust control strategies and implement effective fault detection and recovery mechanisms. Establish comprehensive standards and regulations for safe and ethical use.

Clinical Validation and Adoption: Conduct rigorous clinical trials to assess continuum robot-assisted procedures' efficacy, safety, and cost-effectiveness. Collaborate with medical professionals and regulatory bodies to ensure successful integration into routine clinical practice.

By addressing these research directions, continuum robots can revolutionize the medical field, enabling safer, more precise, and minimally invasive interventions to improve patient outcomes.

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