Recent advances on application of continuum robots in minimally invasive surgery

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Abstract. Continuum robots have emerged as pivotal tools in advancing minimally invasive surgery (MIS), offering enhanced flexibility and precision compared to traditional rigid instruments. This review categorizes continuum robots based on structural designs and actuation strategies, highlighting their ability to navigate complex surgical environments with minimal invasiveness. The integration of advanced sensing technologies for shape and environmental perception is examined, underscoring their role in improving surgical accuracy and patient safety. Specific applications in bronchoscopy, gastrointestinal endoscopy, and orthopedic procedures demonstrate the diverse capabilities of continuum robots in clinical settings. Despite challenges in material stiffness and sensor miniaturization, continuum robots show promising potential to reshape the landscape of MIS through continued innovation and research advancements.

Keywords: continuum robots, minimally invasive surgery, medical technology.

1. Introduction

With the continuous advancement of medical technology, minimally invasive surgery (MIS) has increasingly become the mainstream approach. MIS requires only a small incision in the affected area, through which small instruments and miniature cameras are inserted into the body. The camera captures internal images and displays them in an enlarged format on a screen, enabling the surgeon to perform the operation with enhanced visualization. This approach significantly reduces patient trauma and shortens recovery time [1,2]. However, the flexibility and precision of surgical instruments in complex surgical environments remain critical concerns [3,4].

Continuum robots, known for their exceptional flexibility and dexterity, are particularly well-suited for navigating complex and confined environments. These robots have proven invaluable across various fields, including medical procedures, inspection, maintenance, and search and rescue operations [5,6,7]. Their ability to adapt their shape and follow non-linear paths facilitates precise manipulation and extended reach in difficult-to-access areas. The compliant nature of continuum robots ensures safer interactions, minimizing the risk of injury or damage. Furthermore, their scalable and customizable design, along with advanced actuation and sensing mechanisms, enables them to perform a wide range of tasks effectively, particularly in scenarios where traditional rigid robots face challenges.

This review aims to explore the application of continuum robots in minimally invasive surgery, focusing on the different types of continuum robots, their perception systems, and specific applications within this field. By evaluating the current state of research, identifying existing challenges, and

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highlighting future directions, this review seeks to provide a comprehensive overview of the potential of continuum robots to advance the field of minimally invasive surgery.

2. Literature Survey

The development of continuum robots can be traced back to the 1960s. Hirose et al. designed a snake-like robot in their research project [8]. In the late 1990s, continuum robots gradually began to be widely studied, leading to the publication of numerous review papers thereafter. Figure 1 illustrates the number of papers retrieved per decade using the search terms "Continuum Robots" on Google Scholar. The relevant literature has dramatically increased in 1990s, and in 2010s to a peak of approximately 18,000. This trend indicates a growing interest in the application of continuum robots.

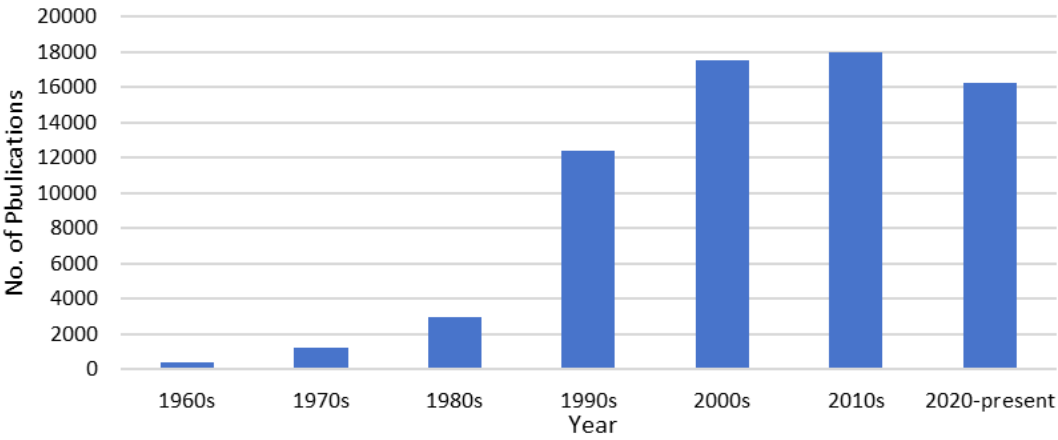

Figure 1. The number of papers searched using "Continuum Robots" per decade

3. Background on Continuum Robots

3.1. Types and classification of continuum robots

Nowadays, continuum robots can be classified based on their structural design and actuation strategies [9]. In the medical field, commonly used continuum robots are single backbone robots, these robots feature a central backbone that runs through the entire length of the robot. Additionally, there are also multibackbone continuum robots, composed of a series of rigid bodies and flexible elements [10]. From the perspective of actuation methods, continuum robots can be classified into intrinsic and extrinsic actuation. Intrinsic actuation is embedded within the robot's backbone, allowing direct control over the internal skeleton's shape and simplifying modeling and control. However, it tends to increase the robot's overall size. On the other hand, extrinsic actuation is typically fixed at the robot's base. This method is advantageous for reducing the robot's size since it does not require motors to be placed inside the robot. However, it consequently makes the robot's modeling more complex [11].

3.2. Traditional surgical instruments and their limitations

Traditional surgical instruments are typically composed of rigid links and rigid joints, which have the advantage of bearing significant loads. However, they are generally bulky and have severely limited degrees of freedom, which greatly affects their manoeuvrability and range of applications. In contrast, the flexible design of continuum robots overcomes the rigidity drawbacks of traditional surgical instruments. This flexibility allows them to operate more effectively within the complex and confined internal environments of patients during minimally invasive surgeries [12]. Additionally, compared to traditional rigid surgical instruments, continuum robots offer the advantages of smaller size and higher degrees of freedom. These attributes enable them to perform complex operations through smaller

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incisions during minimally invasive surgeries, thereby reducing postoperative pain and recovery time for patients.

4. Perception System of Continuum Robots

To enhance the performance of continuum robots in practical applications of minimally invasive surgery, researchers have designed various sensing methods. The sensing methods of continuum robots can be categorized into two main types: shape sensing and environmental sensing. Shape sensing can be further divided into electrical, magnetic, and optical characteristic sensing, while environmental sensing can be categorized into electrical and optical sensing [13].

4.1. Shape perception

During the operation of a continuum robot, its shape changes, and shape sensors determine the robot's shape based on electrical, magnetic, or optical characteristics. The deformation of the robot causes changes in these three characteristics. In terms of electrical characteristics, elastic materials with good conductivity or elastic materials infused with conductive substances are commonly used as the main components of the sensor [14,15], This material can accurately sense the posture changes of the continuum robot and provide reliable data in the form of electrical feedback. The advantage of electrical characteristic sensing is that the materials required to make these sensors are relatively inexpensive. However, the downside is that other electrical devices nearby might interfere with the sensor's signals, and contact with other conductive objects could affect the sensor's performance.

Magnetic characteristics are also commonly used to detect the motion and position of robots, playing an important role in continuum robots [16]. A magnetic sensing system typically places magnets or permanent magnets inside the continuum robot. Magnetic field strength sensors located at various parts of the robot detect the changes in the magnetic field caused by the robot's movements, thereby determining its position [17]. The advantage of this method is the miniaturization of the sensing equipment. However, the extensive use of ferromagnetic materials in the robot may interfere with the normal operation of other sensors, potentially leading to erroneous data readings.

Optical sensing is achieved by adding multiple optical fibres inside the continuous robot, then measuring the changes in the intensity of reflected light which travel through the fibres, the length of each channel can be determined [18]. Algorithms then use this data to calculate the current shape of the continuum robot [19]. For continuum robots, optical characteristic sensing systems are the most common due to their advantages of being lightweight, highly flexible, and having minimal interference both generated and received. However, the drawback is that the cost is relatively higher compared to the other two methods.

4.2. Environment perception

Environmental sensing is designed to detect contact and collisions between the continuum robot and surrounding objects. It can be divided into two types: one uses changes in electrical characteristics, and the other uses changes in optical characteristics to sense the robot's positional changes.

For environmental sensing based on electrical characteristics, a soft, conductive material is often used to wrap around the continuum robot [20], when the continuum robot touches a part of the human body, changes in resistance values due to the piezoresistive effect can detect the contact position. Additionally, this soft material layer can serve as a shock absorber.

In optical characteristic environmental sensing, similar to electrical sensing, a layer of soft material is wrapped around the robot. However, in optical sensing, this layer includes a row of embedded optical fibres [21]. When the continuum robot makes contact with an object, the optical fibres are compressed and deformed, causing the distance light travels to shorten. This change allows for the detection of contact with objects.

When the path of the continuum robot is clearly planned within its operating environment, collisions with objects can be avoided, making environmental sensing less necessary. However, when path planning is insufficient and understanding the surrounding environment is required, environmental

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sensing becomes essential. Therefore, the adfvantages and disadvantages of environmental sensing depend on the specific application and use case.

5. Continuum robots for minimally invasive surgery

Continuum robots offer high degrees of freedom, strong operability, and ergonomic design, allowing them to navigate flexibly within the patient's body, avoid obstacles, and reach the targeted treatment area. Therefore, they have broad application prospects in the field of minimally invasive surgery. Different types of continuum robots are used in various surgeries. This section briefly introduces the application and distinct characteristics of continuum robots in minimally invasive surgeries such as bronchoscopy, gastrointestinal endoscopy, and orthopaedic procedures.

1. Bronchoscopy: Bronchoscopy is an effective method for treating various lung diseases. However, traditional rigid surgical instruments are limited in their ability to navigate the narrow and complex airways, making it difficult to accurately and safely reach the lesion. To address the specific needs of bronchoscopy, researchers have developed continuum robots designed for this purpose, enhancing the safety and precision of targeted treatments [22]. These robots are characterized by the incorporation of a clear imaging endoscope and a precise navigation system that guides them into the respiratory tract.

2. Gastrointestinal endoscopy: Given the specificity and complexity of gastrointestinal endoscopic surgery, continuum robots are extensively used in this field, including in laparoscopies, gastroscopies, and colonoscopies. Continuum robots used in gastrointestinal endoscopic surgeries can be categorized into two types based on their operation modes: insertion-assist operation and master-slave remote control operation. Insertion-assist operation continuum robots typically have lower degrees of freedom and are used for auxiliary tasks such as image transmission. In contrast, master-slave remote control continuum robots usually possess high degrees of freedom, with a wide reachable working range at the end effector, allowing for precise execution of complex surgical procedures [23].

3. Orthopaedic endoscopy: In orthopaedic minimally invasive surgeries, continuum robots need to interact with both soft and hard tissues of the human body and perform surgical operations. During this process, there is a risk of accidentally contacting surrounding tissues. Therefore, continuum robots used in orthopaedic minimally invasive surgeries typically require high control precision and effective obstacle avoidance capabilities [24]. Additionally, they need to be flexible to efficiently and safely complete the surgical procedures.

6. Challenges and Limitations

6.1. Materials challenges

Continuum robots are often constructed using flexible materials to better adapt to complex environments. However, this design choice typically results in a lower overall structural stiffness. As a consequence, the robot's structure can undergo significant deformation when subjected to substantial external forces or when generating low output forces, leading to a notable impact on control precision [25]. Balancing flexibility with adequate structural stiffness is therefore a critical challenge currently faced by continuum robots.

6.2. Perception system challenges

The integration of sensing systems in continuum robots plays a crucial role in accurately reflecting internal conditions during medical procedures. However, incorporating additional sensors inside the robot can limit its flexibility and pose challenges for miniaturization [26]. Externalizing sensors offers a potential solution to mitigate these impacts to some extent. Achieving a balance between functionality and miniaturization is a significant ongoing challenge in developing continuum robots suitable for minimally invasive surgery, particularly in the context of sensing systems.

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7. Summary

This review provides an in-depth examination of continuum robots in the context of minimally invasive surgery. It categorizes these robots based on structural design and actuation methods, emphasizing their flexibility and adaptability in navigating complex surgical environments. The review also explores various sensing technologies integrated into continuum robots for shape and environmental perception, crucial for enhancing surgical precision and safety. By discussing specific applications in bronchoscopy, gastrointestinal endoscopy, and orthopaedic procedures, the review underscores the transformative potential of continuum robots in modern surgical practices despite ongoing challenges in materials and sensor integration.

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