Continuum robotics: variations, applications, and limitations

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Abstract. The article provides a comprehensive review of continuum robotics. In today's rapidly advancing world, the development of versatile robotic structures, such as continuum robots, is increasingly important. Unlike traditional rigid-link manipulators, which are widely utilized across various industries, continuum robots are relatively less developed. This review explores the diverse structural designs of continuum robots and examines their unique advantages and limitations when implemented in different applications and scenarios.

1 Introduction

Advancements in artificial intelligence and the recent ability to model complex structures have allowed different manipulators to become as functional and precise as they are today. Modern manipulators are highly advanced and capable of performing various tasks without further improvement. However, there are still areas that could be enhanced. Modern manipulators commonly have rigid links, meaning they are capable of functioning only within a fixed environment. They are widely utilized in various industries such as automotive, medical, agricultural, and military. These mechanisms have versatile applications, including assembly of different vehicles and devices, classification (sorting) of goods and waste, welding of structures, work in dangerous or hazardous environments, and medical procedures.

The idea behind most manipulators is to mimic the human hand and its joints. This type of structure is utilized in all industries and is extremely functional for specific tasks. However, it limits the maneuverability of the mechanism when applied to new tasks that are beyond its reach and capabilities. Hence, new ideas and structures are being introduced and tested to maximize the already high functionality and maneuverability. Continuum robotics are under development as a promising technology, though they currently lag behind robotic arms [1]. This work explores continuum robotics. Various structures of continuum robotics will be discussed to illustrate their potential if they reach a certain level of development. Applications of such mechanisms across various fields, including those currently served by robotic arms, will also be examined. Additionally, some advantages of using continuum robotics will be discussed, as well as limitations and issues with these technologies. The

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following continuum robotic structures will be covered: cable-driven, pneumatic and hydraulic, elastic rod-based, and magnetic.

2 Continuum robotics

As stated, commonly used manipulators have rigid links, connected by a relatively small number of degrees of freedom - typically six to seven. This number of degrees of freedom suffices for various complex tasks, with each joint capable of embedded movement. These types of manipulators have certain limitations, primarily related to operations in highly congested environments and the manipulation of objects using parts of the arm other than their specialized end effector. In nature, these issues are well addressed. Complex structures of different species exemplify how continuum robotics should perform; for instance, an elephant's trunk, a lizard's tongue, and octopus arms illustrate ideal continuum robotic functions. It is evident that continuum robotics derive their shapes, functionality, and structure from nature. With this capability, continuum robotics can firmly grasp objects of different shapes and sizes with their flexible structures [2, 3].

3 Various types of continuum robotics and their applications

3.1 Cable-driven continuum robots

Cable-driven continuum robots are mechanisms powered by cables. The structure consists of a flexible backbone made of highly bendable materials. The cables connect to or pass through moving platforms that form modules. By tensioning or relaxing the cables, which usually span the entire length of the structure, the body of the mechanism can be manipulated. The overall structure resembles a snake's body, mimicking its motion and capabilities (Figure 1) [4].

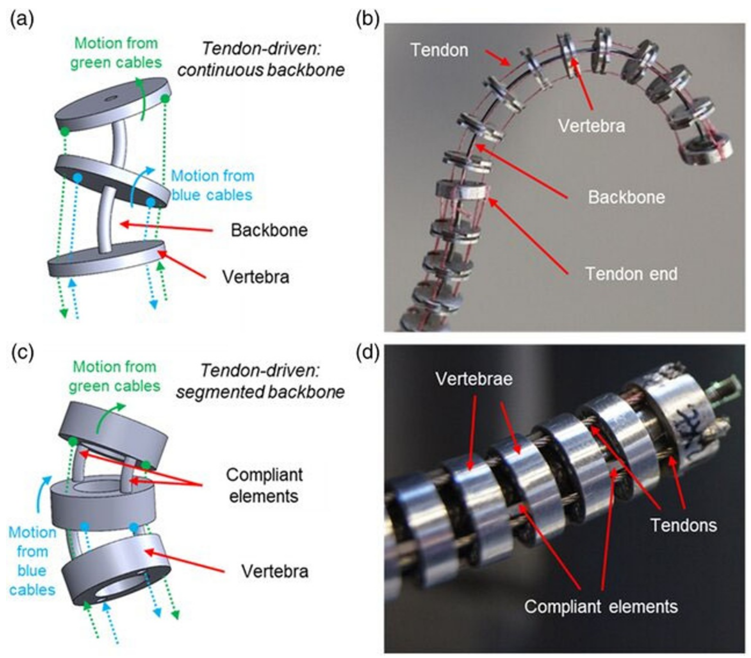

Fig. 1. Common representation of cable-driven continuum robots.

Cable-driven continuum robots have a high degree of freedom, introducing a wide range of motions. While this may be unnecessary in some cases, it is essential for others. This increased freedom results in smoother motion, making them ideal for complex, confined spaces. They are commonly used in applications requiring precision and control, such as surgical procedures and general medical applications [5].

3.2 Pneumatic/hydraulic continuum robots

Pneumatic or hydraulic continuum robots are similar to cable-driven robots but use different methods to actuate the structure. For instance, pneumatic continuum robotics uses air to transmit motion to specific parts of the structure, while hydraulic robots use water or various oils. These continuum robots have internal chambers that can inflate or deflate. When various chambers are pressurized, the structure can bend, twist, or extend in a desired direction. Similar to cable-driven systems, these robots can move smoothly through chosen environments. Due to their soft materials, they interact safely with the surroundings. They can also exert significant force, which is essential in high-load applications [6]. See Figure 2 [7].

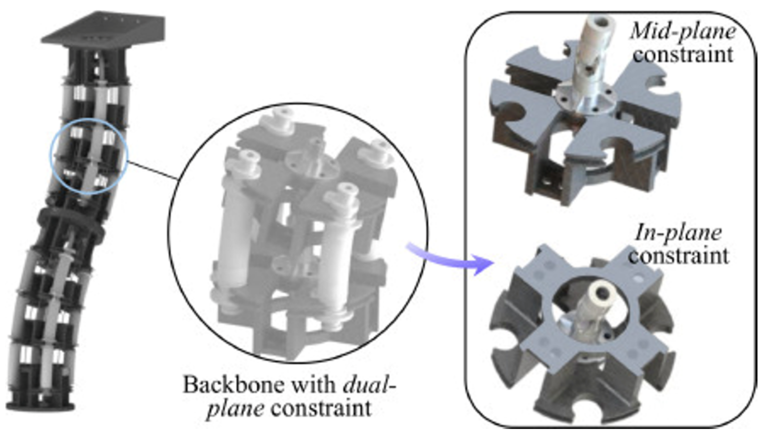

Fig. 2. Common representation of pneumatic/hydraulic continuum robots.

3.3 Elastic rod-based continuum robots

Elastic rod-based continuum robots are driven by elastic rods. Unlike cable-driven systems, which regulate motion through cable tension, this type of robot takes advantage of the natural bending and twisting of rods in response to external forces. The rods act as a continuous flexible element, allowing the robot's body to deform smoothly. Motion is achieved by applying forces to designated parts of the rods through external mechanisms such as tendons, magnets, or electroactive materials. This type of structure is comparable to plant stems that wrap around objects within reach. They adapt easily to the environment they are placed in. Although they have fewer degrees of freedom compared to cable-driven systems, elastic rod-based continuum robots are excellent for handling new environments and working in scenarios that require delicate, safe interactions [8].

3.4 Magnetically actuated continuum robots

All these robotic mechanisms are structurally similar but employ different methods to introduce motion. In magnetically actuated robots, movement is achieved through the use of magnets. By activating magnets, specific parts of the robot can be moved. While this type of mechanism has potential, it currently has more limitations than benefits. Due to the weak magnetic forces, it cannot be applied effectively in tasks requiring high force. Nonetheless, with future improvements, this technology may find more applications (Figure 3) [9, 10].

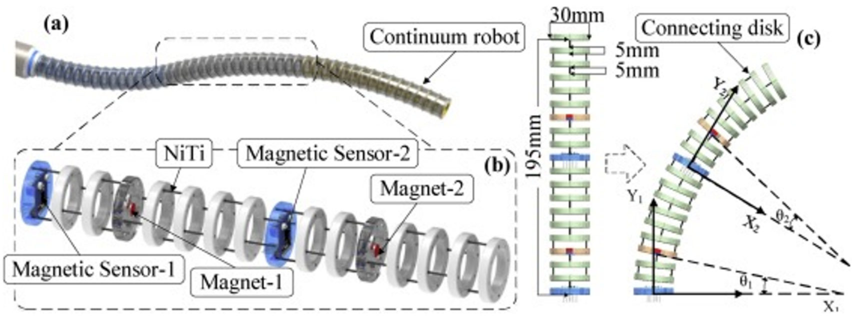

Fig. 3. Common representation of pneumatic/hydraulic continuum robots.

4 Advantages and limitations of continuum robotics

The most obvious advantage of these mechanisms lies in their flexibility. Thanks to advancements in the number of degrees of freedom, these robots can easily maneuver within their environments with greater accuracy and gentleness. Proper navigation is crucial, as these mechanisms would otherwise be ineffective in most cases.

They adapt well to complex and dynamic environments, mimicking the movements of snakes, octopus tentacles, and elephant trunks. This adaptability also facilitates complex object handling. For instance, while common mechanical robots typically grasp objects using forceps, continuum robots can curl around objects of any shape, securely grasping them for safe interaction. However, this adaptability mainly applies to lighter objects. Moreover, having multiple actuated modules increases their precision, but it also introduces navigational challenges. Despite the benefits, these mechanisms require further refinement for future applications [11-12].

5 Conclusion

In conclusion, this paper examined continuum robotics, focusing on the different variations of continuum robotics. It was essential to differentiate continuum robotics from commonly used robotic arms; hence, the paper discussed some conventional mechanisms. The paper aimed to define continuum robotics, emphasizing their unique appearance and structural complexity, which place them in a separate class within robotics. It illustrated the various forms of continuum robotics in terms of appearance and movement approaches. Applications, advantages, and limitations of continuum robotics were also discussed, considering functionality and flexibility.

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