Modelling of Soft Continuum Robotic Manipulators: Approaches, Limitations and Future Prospects

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Abstract. The continuous and soft robotic hand-like manipulators have gained more attention in recent years due to their high versatility and flexibility in the harsh environment. The three key types of modelling approaches employed in the presented study to perform soft robotics, discussed in the continuum mechanics model, the geometric models, and the data-driven or hybrid approaches, are these. The basic concepts and general modeling approaches to each category are described with the focus on the various strategies to describe the motion and the deformation actions of the soft manipulator arm. The potential further research areas are also explored, in particular the integration of the learning-based and the physical modelling techniques to improve the performance of the modeling. In general, this discussion contains a systematic overview of current modelling methods and the window into the future of the soft robotics modelling research.

Keywords: Soft Continuum Robotic, Robotic Hand-like Manipulators, Soft Manipulator Arm, Physical Modelling

1 Introduction

In robotics soft and continuum robotic manipulators are recently gaining popularity as a result of the natural flexibility as well as the adaptivity. In conventional fixed-link manipulators, the motors, reducer, sensors, actuators and other pertinent components are primarily concentrated on heavy loads or vastly accurate work. The fact that they are unable to understand the object on the end effector will seriously reduce the power of manipulation in the area that is not being conducted with new advances and practice to allow the use of their roles. Therefore, it is usually hard to deploy a rigid-joint manipulator without reorganizing the movements that it can perform. Continuum robots were conceptualized through the biological parts of organisms like the arms of an octopus and trunks of an elephant. In contrast to rigid-link manipulators, such elastic robots are being used that have the further advantage over hard redundant robots that they create little resistance to compressive forces, and thus are able to follow obstacles and with greater natural or elastic deformation.

This geometrical feature enables them to apply in confined or complicated environments, including low invasive surgery, pipeline inspection and handling of delicate objects. The initial

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research was mostly on geometric modelling, especially constant curvature assumption which reduces the shape of the robot into a circular arc to facilitate easier analysis [1]. Even though this approach minimizes the computational cost and allows simple motion planning, it does not allow the description of large deformation or external forces.

The aforementioned structural properties render soft robots the best to be applied in limited and/or high-density environments, including minimal interventions surgery, inspection of pipes, and handling delicate objects. The initial studies carried are primarily centred on geometric modelling particularly under the constant curvature assumption, to simplify the shape of a robot to circular arc to simplify analysis [1]. Even though this approach saves on calculation and allows simple motion planning, it cannot still simultaneously model large deformations, or external loads.

Over the past few years, many shape modelling methods have been formed to be applied to deformable flexible manipulators. The developments enable the flexible manipulators to strike a balance between the modelling ability and the computational power that are currently popular by the simplicity and adequacy of real-time control [1]. Nevertheless, such simplified assumptions can bring constraints to the accuracy of the modelling with complex deformation and external loading circumstances. Mechanics-based methods, which are based on the elasticity theory, were proposed to enhance physical consistency, allowing to better model continuous deformation, that is, taking into account both internal forces and external loads [2]. A more recent development is that learning-based methods are becoming popular because they are able to learn the law between actuation inputs and manipulator shape without necessarily involving known physical models.

Despite the fact that the morphological modeling techniques of deformable flexible manipulators have advanced tremendously in recent years, it is interesting to note that the current techniques vary significantly in terms of theoretical foundation, on the one hand their computational intensity and their real-world application on the other.

Having to make the trade-off between accuracy, real-time performance, and engineering practicability, there are still some difficulties in selecting the correct modeling method. Thus, it is time to organize and contrast the present mainstream techniques of modelling in a systematic fashion that will explain the iterations and area of application of various methods. This paper will present a summary of the morphological modeling of deformable flexible robotic arms and will look at the fundamental concepts and pros and cons of geometry modeling, and mechanics-based modeling, finite element modeling, and data-based modeling.

When deciding on a suitable modelling technique, there exist the problems of compromising between accuracy, real-time performance, and engineering feasibility. Hence, one should know what the various modelling techniques are and where they are applicable. This review paper seeks to give an overview of the morphological modelling methods that have been developed to deformable flexible robotic arms, the fundamentals of these geometrical modelling methods, the strengths and weaknesses of these methods and mechanisms of geometric modelling models, mechanics-based modelling geometry models, finite element modelling geometry models as well as those that employ data to model geometry.

2 Dynamic model of deformable robotic arm

The distinguishing feature of continuum soft manipulators is their capacity to be in a continuous state of deformation throughout their structure without joints and such rigid couplings between two parts. The biological systems that these manipulators are based on make theoretically infinite degrees of freedom. This allows a very high degree of flexibility and adaptability in complicated and constrained surroundings [3]. These types of manipulators are mostly of compliant substances like silicone or elastomers and driven either by pneumatic, hydraulic, or tendon. These properties will allow moving the complex motions including bending, twisting and elongation. Moreover, the high compatibility facilitates safe communication in harsh conditions and this makes them most appropriate to such procedures like minimally invasive surgery and medical robotics. Nevertheless, the deformation and non-linear materials that occur repeatedly makes it very difficult to model and control, hence necessitating sophisticated methods of accurate representation.

Segmented soft manipulators are constructed by assembling a series of discrete segments, each segment in the series is actuated by a distinct mechanism. Piecewise Constant Curvature (PCC) assumption can be used to approximate the overall shape of the manipulator and provide the convenience of simplifying the modelling and control [4]. A PCC robot is described as a mechanical system consisting of a chain of rigid sections which are deformable through a curvature constant.

As seen in Fig. 1, the PCC-based representation with reference frames $\{S_0\}$, $\{S_1\}, \ldots, \{S_n\}$ that are defined along the manipulator, and the relative transformations $\{T^i{}_{i-1}\}$ describing the kinematic relationship between adjacent segments [5]. The reason why such models are widely used is their simplicity and ability to provide real-time control. But the segmented manipulators can exhibit indications of lower smoothness and compliance when compared to continuum structures, which is caused by the segmented nature of the manipulator. Furthermore, in case of complex interaction and/or external loads, the segmented manipulators can exhibit inaccuracy because of their simplified assumptions.

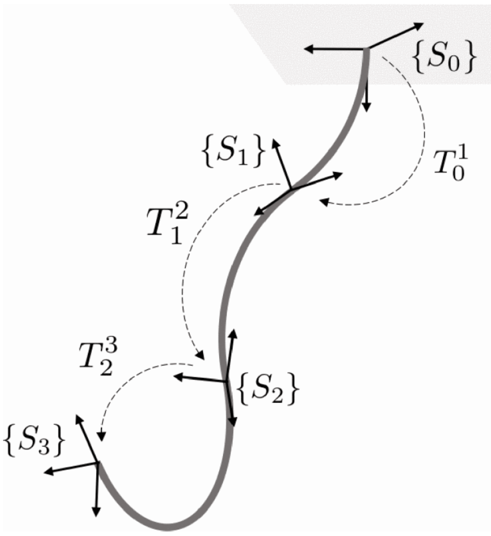

Fig. 1. 3D Piecewise Constant Curvature (PCC) soft manipulator, which is modelled as a constant curvature [6]

3 Modelling approaches for soft robots

Continuous deformation and high number of degrees of freedom make soft robots very challenging to model. The majority of the modelling approaches can be Vaguely categorized as being either continuum mechanics models or geometric models as well as data-driven or hybrid.

3.1 Continuum mechanics models

Models of continuum mechanics assume that of the form of the robot, it is a constantly deformed body and not a structure of restraints. The physical laws of elasticity and force balance are the foundations of these models; hence, these models can better represent deformation. Initial studies of continuum robots indicated that the line of the backbone thought of as a continuous curve is a better way of describing it [6].

The Newton Lagrange technique as developed by Tummers in Cosserat rod theory was applied to simulate a tendon driven continuum robot, as shown in Fig. 2 [7]. The Nantes Digital Science Laboratory Boyer et al. enhanced the research methods of continuum robots by integrating Cosserat rod theory and the optimal control theory in order to improve the approach of the first and second types of research, namely the static and dynamic methods respectively [8]. Ghafoori modeled the theory of Cosserat rod based on Cosserat rod theory where he used six link parallel continuum robot; this has the stability and strength of a parallel robot as well as the flexibility of a continuum robot [9]. To address the problem of coupling inelongation and bending, which is not easy to accomplish with a dynamic model, Xiaocheng Wang introduced a dynamic modeling approach based on the Cosserat rod theory to model a soft robot that can both be elongated and bent [10].

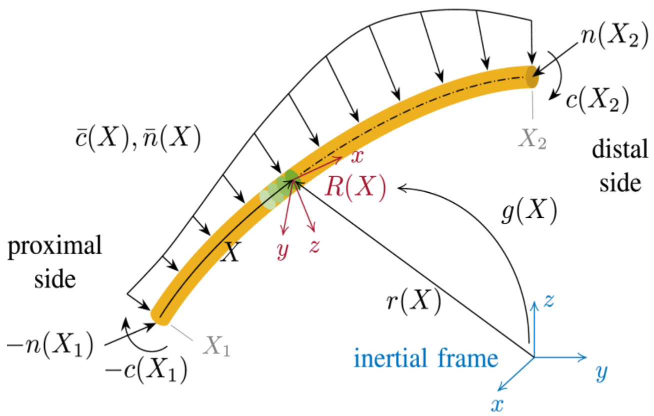

Fig. 2. Simulation of painting coverage of 3D CovDiffusion when painting various furniture [7].

3.2 Geometric models

The segmented constant curvature model is the most popular model of soft robots used in a geometrical modeling, that is, the soft robot is represented as a collection of arc-segments. PCC provides an easier description of robots that is often used in both robot modeling and control in comparison to the Cosserat rod theory. This technique refers to soft robots as spatial curves to define the relative rotational and translational motions of such robots, including two dimensional soft robots, which may be thought of as spatial curves, and represented as a series series joint configurations.

Cheng Hao proposed a kinetic equivalent model for continuum robots. It utilizes classic rigid links instead of the original model seen in kinematics, which effectively reduced complexity while improving numerical stability [11]. Wu Haoran and others from Beihang University designed a different sequence, based on the above-mentioned PCC model, which solved the inverse kinematics of continuum robots. This provides a new method of solving inverse kinematics in continuum robots [12].

DanielaRus proposed a 2D modeling universal framework for soft snake-like robots. This proposal can also be applied to curved soft robots that are driven by pressure fluids. By using the PCC model and enhancing the anisotropic friction function, the body shape over time can be described iteratively. When considering each segment of the robot as a joint and the short solid connectors between segments as links [13]. This framework is compatible with the dynamic modeling of existing rigid snake-like robots, providing accurate descriptions of the entire soft-snake-like system. Renda introduced the Bernoulli Euler beam mechanics based on the PCC model, which allows the prediction of deformation. Renda also proposed a segmented constant strain (PCS) model, which effectively ensures a geometric continuity in a robot. As shown in Fig. 3, PPC models are not able to cover all aspects of soft robots, an unconventional curvature model was developed [14].

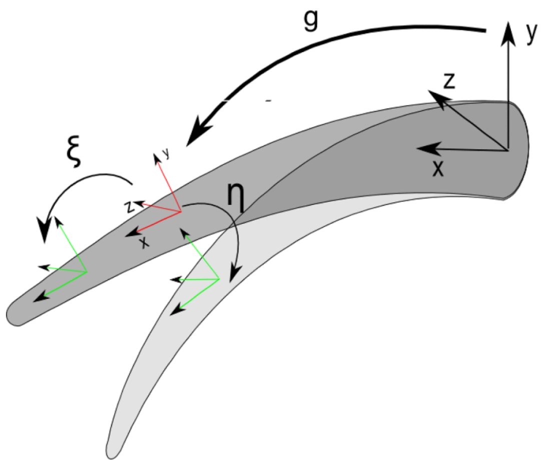

Fig. 3. Special curvature model of soft robot [13].

3.3 Data driven and hybrid approaches

In order to solve the problem of modeling soft robots requiring a large amount of mechanical and complex work, data-driven modeling has also been widely studied. A data-driven model is a method of constructing models using large external datasets. Morimoto proposed an integrated lightweight model free reinforcement learning network that can learn control strategies for continuum robot arms and has excellent sampling efficiency [15]. Bern used machine learning to learn a differentiable model of quasi-static physics for soft robots, and then performed gradient based optimization to find the optimal open-loop control input. This model can capture phenomena that do not exist in idealized physics based simulations [16].

A control system based on a deep deterministic policy gradient (DDPG) for continuous task space manipulation of soft robots has been proposed. The proposed RL controller can track and move the target accurately, and can adapt to the external changing load effectively. This method solves the problems of slow convergence and unstable effect when reinforcement learning is applied to the actual control of robots.

4 Limitations andfuture prospects

In spite of the fact that the soft robot modelling has seen a breakthrough over the past few years, it has certain limitations that influence how the models are used in the practice. These constraints are accuracy, computation costs and in real world scenarios performance.

Continuous-medium models are often of great precision, because they are founded on physical principles, and can recover the deformation of a robot during motion on quite a detailed level. This comes in handy for forces and interaction analysing. But in most cases a lot of information is required about material properties and system parameters which in practice are not always immediately available. Moreover, such models can be computationally expensive to solve and this presents a challenge to the real-time control.

In geometric modelling, the PCC assumption is typically used in an attempt to simplify the modeling of the soft robotics, making them more computationally efficient and easier to analyse the kinematics. Nevertheless, the real-world deformation is not as it would be in any idealized example as it is exposed to outside influences like forces, and a complex environment.

The model-free and hybrid ones provided an alternative to the other physical actions. Therefore, in uncertain systems, such approaches can deal with larger numbers of nonlinear behaviour issues. Nevertheless, they are dependent on the training dataset provided in the training process thereby making their performance to differ. It is possible that in certain cases it is hard to comprehend how the model could give such results with the given dataset.

Combinations between various modelling approaches would become more widespread in future. As a demonstration, physics-based learning may be used to augment and enhance the accuracy and flexibility of learning-based models. Sensing and data collection could be enhanced and this may also facilitate the update to occur during operation. The greatest challenge, however, that is dominant is the balancing aspect where accuracy, efficiency, and practical application are concerned in practice.

5 Conclusion

To summarize, this review has represented a synopsis of various modelling techniques of the soft and continuum robotic manipulators. It identifies the inherent properties along with the constant deformation and great flexibility concerning the traditional rigid-link systems. This review subsequently discussed the three primary modelling methods, in which one approach gives flexibility to the description of the soft robot, as well as in the control of the soft robot. This review also explains the major limitations of the said approaches, and challenges, such as the modelling accuracy, calculation expenses, and the versatility in the practical use. Regardless of these constraints and difficulties, studies continue to examine ways of working to understand better modelling techniques. In general, this review offers a consistent insight into the existing modelling methods and identifies future outlooks on the enhanced work with soft robots in the real setting.

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