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Analysis and prospect of soft robot drive control technology

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Abstract. Soft robots have become an emerging field of research with the advancement of science and technology. It has the advantages: flexible, soft and fast. It has good results within narrow space work and has great research potential in disaster relief, exploration and medical treatment. It has a theoretically infinite number of degrees of freedom, but degrees of freedom and actuators do not always correspond in a straightforward one-to-one manner, making it difficult to achieve accurate, control-accurate modelling. It is worth exploring how modelling techniques and sensor control techniques can be optimized to improve control accuracy and achieve human-machine interaction. In addition, most actuators currently use a single drive method, which leads to the limitations of redundant degree of freedom control. Combining multiple drive methods while ensuring drive control accuracy and drive force is also a future research direction. In this paper, the current state of control and drive research in soft robots will be introduced. Then three control modelling methods - modelled, modeless and hybrid control will be discussed in detail. Three common drive methods will be mentioned - fluid drive, SMA drive and EAP drive. A prospect on the control methods and drive mode of soft robots will be given. This paper is useful for robotics research.

Keywords: soft robots, automation, control.

1. Introduction

Traditional rigid robots can be found in many fields, including industrial, logistics, and agriculture. They have the advantages of good rigidity, stability, and reliability. Although rigid robots have been utilized successfully across many different fields, they have a number of shortcomings and restrictions. They are less convenient and secure to use in many industries due to their rigid structure and lack of flexibility [1].

There is a breakthrough in the study of robotic system and a field called soft robotics has emerged as 3D printing technology and novel intelligent materials advance. Robotics research on soft robots has gained popularity recently [2].

The body of soft robots is built of flexible or soft materials, and the material's degrees of freedom can be freely adjusted to meet requirements. The soft robot has huge potential in applications of biotechnology, emergency management, and healthcare, making up for the limitations of traditional robots in confined spaces.

While this is a thriving and emerging field, it also faces challenging obstacles. Traditional methods of modelling rigid robotic arms have not been able to adequately represent soft robots due to their high

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degree of flexibility and lack of rigid joints, and the complexity of soft robots' geometries has made it extremely challenging to model and control their kinematics and dynamics, particularly inverse kinematics. The shape and deformation characteristics of soft robots place greater demands on the selection and configuration of sensors, requiring a combination of sensors for modelling and control. To increase safety and lessen the strain on the user, automatic control of soft robots requires to be implemented [3].

In this paper, recent research status on soft robots will be introduced. Their kinematic modelling and control methods such as hybrid control, model-based control and model-free control is discussed. The actuation classification and driving mode will be provided, basically in three directions, fluid drive, SMA drive and EAP drive. Prospects on future trends and research direction of soft robots will be provided.

2. Research status

The basic idea behind soft robotics is to take advantage of the qualities of soft materials to provide machines intrinsic flexibility, variable stiffness, and extremely dexterous movement in unstructured situations. The systems that result from this work can make a number of infamously challenging activities simpler. Comparing with the rigid material, soft materials' flexibility and compliance enable secured interaction between humans and machines.

Currently, the main modelling approaches are continuum models, geometric models and data-driven models. The segmented constant curvature modelling approach is currently the most commonly used assumption for continuum robots. Inverse kinematics studies of soft-bodied robots are difficult to determine the deformation curvature through a specific location. In response to the problem that the end position of the soft robot cannot control the overall shape, Wang's research team [4] has proposed visual servo and shape control algorithms to enable the soft robot to basically achieve the desired overall shape, how to better control the soft robot is still a major challenge in the field of soft robotics.

Model-based control, model-free control, and hybrid model control are the three categories of current control techniques. Model-based control performs better in terms of motion precision but is strongly dependent on accurate continuum robot modelling and accurate sensor perception. Model-free control techniques are data-driven control techniques that rely on neural networks to comprehend the robot's model and generate effective control. Mixed-model control methods generally combine neural networks and physical models, using neural network models to compensate for non-linear factors in order to achieve effective control accuracy. Additionally, remote control techniques are frequently used in the medical industry. The status of the robot can be evaluated by the user's visual perception with the use of intraoperative images, and the robot's mobility can then be adjusted appropriately [5]. For example, a flexible robotic arm system for low risky heart surgery was developed by Deng Tao et al. from Shanghai Jiaotong University. The flexible robot arm, which draws inspiration from the physiological design of the trunk of elephants, carries out certain duties primarily by pulling on a pulling wire encased in silicone that creates a certain amount of deflection and bending [6].

There are two types of drive mechanisms in use today: internal drive mechanisms and external drive mechanisms. Internal drives are typically represented by pneumatic robots since the expansion of the internal elastic cavity results in deformation [5]. In 2016, The first entirely soft robot, Octobot (shown in Figure 1), in the world was developed by Professor Wehner of Harvard University using injection moulding, soft lithography, and multi-material embedded 3D printing. It is powered by a chemical reaction of a 50% concentration of hydrogen peroxide solution in the presence of a platinum catalyst, driving alternating telescopic movements of the tentacles with the help of changes in pressure within the two sets of tentacles, thus achieving a breakthrough in the development of soft robots [7]. External drives are represented by magnetic continuum robots, where different drive mechanisms give different characteristics to the robot. Research on soft-bodied robots can be applied not only to marine exploration and environmental monitoring, but also to the medical field. The most commonly used continuum robots today are tendon driven. These robots are widely used for multitasking of various surgical instruments, with bending angles typically around 106 degrees and with a placement precision of about 2.0 mm.

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However, conventional tendon-driven continuum robots are constrained by typical production techniques and are complex to scale down to smaller sizes. Numerous cutting-edge materials have been created and used to execute robot actuation in order to obtain tiny structures for continuum robots [5].

Figure1. Schematic diagram of Octobot [7].

3. Control methods

3.1. Model-based controllers

3.1.1. Model-based static controllers. The most popular control method now employed for continuum/soft robotics is model-based static controllers. Since more complicated models require more processing effort and are design-specific, the majority of model-based controllers rely on the constant curvature approximation. However, one of the most effective and practical techniques for statically regulating homogenous, low mass manipulators is the verification of constant curvature models for fully soft robots, which is frequently utilized for the control of various continuum/soft robots. More complex approaches have not significantly improved performance due to their higher processing costs and requirement to estimate more parameters. Recent comparisons between other model methodologies on the same platform have also shown this. The model-free approach provides an alternative approach to generate more accurate, design-specific models that are more sophisticated without requiring prior knowledge of the underlying structure. Although error convergence is not guaranteed (unless a perfect forward model is available), more reliable and quick controllers can be delivered by closed-loop configuration space controllers or joint space controllers. In theory, a closed-loop task space controller is considered as the most accurate control. Tendon-driven devices are more challenging to simulate in terms of actuation, whereas pneumatic manipulators require more sensors [8].

3.1.2. Model-based dynamic controllers. The development of continuum/soft robotic arms with model-based dynamic controllers is still in its early stages. The majority of dynamic control methods now used concentrate on control in joint space, with very few exceptions even in this instance, the controller for a planar homogeneous robotic arm must be built as open-loop due to the computing cost. This would be the best option if the feed-forward controller were flawless. Ideal candidates for controlling these continuum/soft manipulators with low gain accuracy are model predictive controllers. However, due to the computational complexity of the most recent dynamic models, their application is presently

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constrained. Model-based dynamic control approaches should be taken into account as computing power, sensor capabilities, and intelligent controllers all increase [8].

3.2. Model-free controllers

3.2.1. Model-free static controllers. The fact that parameters in configuration space and/or joint space don't need to be defined and are independent of the manipulator's shape is one of the model-free approach's primary advantages. As a result, sample data and a lot of sensory noise can be used to build arbitrarily complicated kinematic models. As a result, systems that are extremely nonlinear, inhomogeneous, susceptible to gravity, or function in surroundings with little structure benefit more from model-free methodologies. However, for tiny manipulators that function effectively in well-known situations, model-based controls are still more precise and dependable. Furthermore, stability analyses and convergence proofs are challenging to demonstrate, due to their black box character. Static/dynamic controllers presumptively presume minimal or no dynamic coupling among components. Static/dynamic controllers presumptively presume minimal or no dynamic coupling among components. As discussed at the start, static/motion controllers rely on steady-state assumptions, which restrict soft robotic arms from moving precisely and quickly. Therefore, for quicker, more adaptable, effective, and smoother tracking when coupling effects exists, controllers that take into account the dynamic behaviour of these manipulators are essential [8].

3.2.2. Model-free dynamic controllers. Dynamic controller development can be made comparatively easy considering model-free techniques of continuum/soft manipulator dynamic control. The simplicity of modelling precision and limited sensory needs are the evident advantages of model-free approaches. Due to training requirements or stability issues, there are just a few practical uses, and this sector is still in its early stages of development. Nevertheless, it's a strategy to take into account. Combining model-based and model-free techniques, hybrid controllers are also a potential option as more potent algorithms for training recurrent dynamic networks are developed [8].

3.3. Hybrid model control

Hand-eye visual /shape hybrid control is a hybrid control technique, derived from the D-H (Denavit-Hartenberg) parametric method, the Frenet-Serret framework method. The method does not require knowledge of the 3-dimensional coordinates of the spatial feature points, but only provides the ideal soft robot shape for control and the intended pixel coordinates of the feature points in the final camera plane, by building a kinematic model of the soft robot, combining depth-independent interaction matrix adaptive hand-eye vision control and soft robot shape control. Theoretically, the arm of a soft robot can be bent into various shapes after completing a specific task. Given a certain feature point in space, a soft robot with a camera at the end can, by controlling that feature point, cause that feature point to reach a particular location in the camera plane and cause the robot to take a particular shape. The model takes full advantage of the properties of soft robots. It can be applied to a multi-stage continuum of soft robots to perform more specific tasks [4].

4. Driving methods

The control method relies on the driver to achieve, the common driver has the following several.

4.1. Fluid drive

Fluid drive is widely used to drive soft robots of various structures. It is a way of imitating the movement mechanism of some molluscs in nature by building different shapes of fluid channels, such as ribs, cylinders and folds, into the body of the robot made of super-elastic materials, or by adding restrictive layers of material at special locations. When a fluid such as gas or liquid is introduced, the change in volume of the fluid in each channel is controlled to drive the deformation of the soft robot in different positions such as contraction, expansion, bending, etc. to achieve movements such as crawling and

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swimming and to interact well with the outside world. Although fluid-driven soft robots have the advantages of high deformation capacity, fast response time and high-power density, it is difficult to miniaturise the drive equipment and requires complex structures such as external circulation pipes, air compressors and hydraulic pumps, as well as high requirements for sealing [9].

4.2. SMA drive

SMA is a smart material having shape memory properties based on the principle of thermoelastic and martensitic phase transformation and its inversion, which can change its shape and mechanical properties under certain conditions and is widely used in fields such as medicine and aviation. The benefits of SMA include its light weight, simple layout, and quick response time, but its energy consumption is high and the temperature is difficult to control, and the heat needs to be dissipated when the next drive is carried out. This results in low drive efficiency [10].

4.3. EAP drive

EAP is a new type of intelligent polymer material that can have the ability to change its internal structure under the action of an applied electric field to produce various forms of mechanical response such as stretching, bending, binding or expansion, and has strong electrical and mechanical properties to achieve a variety of functions such as driving and sensing at the same time. EAPs can be divided into two main categories: electronic EAPs and ionic EAPs, depending on their actuation mechanism [11].

Electronic EAP is a smart material that directly outputs displacement and stress under the action of direct current and has a good electrical actuation effect. The ionic EAP consists of two electrodes and an electrolyte. The ionic migration or dispersion allows these materials to produce excitation and induced bending displacements at low voltages, with excellent flexibility and high electromechanical conversion efficiency, easy to shape and less susceptible to fatigue damage. They can therefore replace conventional materials in applications such as microelectromechanical systems (MEMS), flexible devices and bionic robots [11].

5. Application

5.1. Gripping

Soft-bodied robots can change their shape according to the shape and size of the object and therefore have a great advantage in the gripping of irregular objects. Compared to rigid grippers, soft bodies are safer, less costly, simpler and more adaptable to space, and have good prospects for use in gripping operations.

5.2. Field marine exploration

The soft body robot itself can be continuously deformed, with theoretically infinite degrees of freedom. It can both change its own motion modality and has incomparable advantages for operating in non-structural environments with restricted space, such as earthquake rescue and military exploration. The bionic fish suction cup robot jointly developed by Beijing University of Aeronautics and Astronautics and Harvard University in 2017 draws on the special structure of a fish head. The robot enables swimming, adsorption and detachment operations underwater [12].

5.3. Medical rehabilitation

Soft-bodied robots have an important role in helping stroke and hemiplegic patients achieve rehabilitation activities. By pre-programming the bionic structure, the soft robot can be made to replicate human joint movements so well that it can interact with patients more safely and perform complex movements like grasping. 2014 P. Maeder-York et al. at Harvard University developed a soft robot glove. Because its material is soft and stretchable similar to that of a human hand, it follows the natural movement path of healthy fingers and allows patients with nerve damage to grip objects independently.

At the same time, soft robots have a wide range of prospects in surgery because of the softness of the material and the low damage to human organ tissues [13].

6. Conclusion

Soft robots are a multidisciplinary intersection of biomaterials, mechanical mechanics and computing. They have the advantages of being resilient, small in size, able to adapt to unstructured and complex environments, and can perform well in many confined spaces. With the flexible structures to shine in engineering, livelihood, medical, military and service industries, they have become an integral part of people's lives. Soft-bodied robots is an emerging area of research. It also has many areas worth exploring.

This paper introduces the current state of research in soft robotics, with examples from modelling, control and actuation. The control methods of soft robot are discussed, including model-based, model-free and hybrid approach. Model-based control is the most widely used control method, relying on an analytic model to derive the controller. Empirical methodologies or machine learning techniques are used by the model-free control, and although its stability has yet to be tested, it is still a worthwhile research direction because of its flexibility. Hybrid combines model-based and model-free approaches and is currently under investigation. Drive classification is explored, focusing on fluidic, EAP and SMA drives. In order to ensure the motion precision, the combination of modelling technology, sensor control technology and driving method is the future research direction.

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