Analyze the Environmental Perception and Ontological Perception of Soft Robots

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Abstract. As the application of soft robots in complex environments continues to expand, their precise perception and their own state has become a key foundation for achieving safe, autonomous, and intelligent behaviors. This paper aims to systematically summarize the basic principles of environmental and ontological perception in soft robots, as well as the current development statecologicaly used sensor types and , such as pressure and tactile sensing, have been relatively mature and have demonstrated good application potential in fields like oceanography and healthcare. In contrast, ontological perception still faces challenges such as structural nonlinearity and complex deformation. In recent years, the development of flexible electrical, optical, and liquid metal sensors has provided feasible solutions for shape and curvature perception. Meanwhile, machine learning and multimodal data fusion technologies have effectively improved perception accuracy and system safety. The analysis provides a reference for the design and optimization of soft robot perception systems.

Keywords: Soft robot, sensor, artificial skin, robot perception system

1 Introduction

Robots compare positively with manual workers, as they consume little energy, are highly efficient and sustainable. They are commonly applied in industries, agriculture, medicine and other spheres since the 21 st century[1,2]. Soft robots are a recent trend and the subject in the robotics world that is gaining popularity. They are distinguished by the deformable flexible structure, i.e. being made of hydrogel or shape memory alloys, shape memory polymers etc. They are not rigid in form and are very flexible and responsive to the environmental conditions. There are lots of soft robots that can be based on the biological designs: human fingers, worms, octopuses, jellyfish, etc[3,4]. Their operation is close to that of biological forms and modes of driving and these robots tend to perform highly in real life tests. The flexibility of the soft robots enables them to work better in high pressure and narrow complex environments. Simultaneously, they are capable of the significant extent of their contact with other objects, and thus are applicable in the medical field.

There is currently a lot of research in the field of soft robots, including in the context of drive technology and material construction. But even in it, the spheres of perception, particularly the ontological perception of robots, it remains evident that there can be a lot more to be explored. As compared to conventional robots, soft robots are much stricter on position monitoring and

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shape control requirements, which require a sensor with improved functionality to be of higher quality in terms of their perception power. At the same time, to suit the needs of soft robots in deformation terms, sensors should have such properties like stretching, deformation, and bending, which is why flexible materials may serve as a source of sensor creation. Also, to meet different environmental and operational needs, several forms of senses, including optical sensors, electrical sensors, bar and pressure sensors as well as temperature sensors, all record wide growth opportunities.

The article at hand will dwell upon the perception possibilities of soft robots evaluating its principles and bringing forth subversive innovations. It has both the ontological perception and environmental perception in which it introduces in detail the associated technologies and the sensors. Also, it examines the use and future of soft robots.

2. Perception of soft robots in the environment

In the case of soft robots, capability to sense the world that surrounds them, with different characteristics of them, is paramount. This assists them in improving their body protection, adaptation to multifaceted working conditions, and completing multiple tasks. They can obtain a sensory awareness of the surrounding environment which is similar to that of the living organisms through different kinds of sensors[5].

2.1 Perception principle

The main concept behind soft robot environmental perception is to incorporate traditional sensor in soft structures in a flexible and distributed fashion. Perceptions can be made in various ways like tactile perception, pressure perception which is the simplest and most significant environmental perception. The perception of pressure is normally produced using electrical sensors which include resistors, capacitors and piezoelectric sensors. As the robot body suffers deformation or pressure, the characteristic materials of different electrical sensors will vary accordingly the properties, e.g., resistance, capacitance, and hence be able to measure them quantitatively.

The key elements of the body perception of a robot are curvature and shape perception but may be applied to the environmental perception. The issues may include the shape and the level of deformation of the robot in order to evaluate its interaction with the surrounding world.

Besides the above two sensing techniques, there are also sensing techniques on chemical properties like pressure, temperature, pH, and magnetism among others, which, in particular working conditions, can also be utilized.

2.2 Types of sensors applied

The scientific research results in the field of pressure sensors are certainly the most numerous and extensive in the present research on soft sensors. Guo et al. [3] used the interlayer hydrogen bonding effect to build MXene-FPDMS (MFP) sponges with high mechanical strength by using plasma treatment. The developed sponges are highly sensitive and accurate in production of pressure sensors with added sensitivity of up to 14.2 kPa -1, low modulus of 9.7 kPa and precision of up to 94+0.6. The pressure sensors can be improved further by employing deep learning algorithms.

Moreover, touch is also among the significant methods of perception of the external world. Roy et al. [4] used a supramolecular engineering approach to prepare a pseudo-sliding ring hydrogel by using polyacrylamide (pAAm), 2-cyclodextrin (2-CD) and poly(2-propyleneoxy)ethyl) trimethylammonium chloride (AETAc), bio-ionic liquid (Bio-IL). This biomaterial gives the sensors prepared using the same properties of mechanical toughness, conductivity, and stretchability, which makes it a good material to use as soft sensors. Moreover, the sensors that have been developed and created based on it are very effective in motion and tactile detection and are efficient, stable, and sensitive. Zhou et al. [5] exploited the large magnetoelasticity of soft polymer systems to develop a multimodal underwater robotic skin. This haptic device can distinguish objects with high accuracy like marine species and oceanic rubbish and has a low degree of waterproofing, which is suitable in environmental perception activities underwater.

2.3 Assistance from other types of technologies

In addition to various sensors, soft robots can also utilize other technologies to enhance their environmental perception capabilities.

Firstly, based on the robot's own model estimation and driving state, the robot can perceive the pressure changes around it and its own deformation. For example, in a soft robotic arm driven by air pressure, when grasping an object, the bionic fingers will stop deforming, so it can determine whether the grasp is successful based on the pressure change curve of its own driving arm.

In addition, the materials used to manufacture soft robots can analyze the surrounding environment through changes in their chemical properties during deformation, based on their special electrical or photothermal properties.

Lastly, equipping the robot body directly with visual perception devices such as cameras and analyzing the external environment of the body through machine learning algorithms is also an effective method of environmental perception.

3. Ontological perception of soft robots

Due to the complex and variable body structure of soft robots, in addition to their excellent external perception ability, they also need to be able to acquire information about their own shape, location, and various properties at any time, which is known as intrinsic perception ability. At the current stage, compared to environmental perception, research on the internal perception of soft robots is relatively lacking.

3.1 Perception principle

The core principle of soft robotic body perception is to deeply embed sensors as "proprioceptors" into the soft materials of the robot, directly converting material deformation into measurable physical signals. At the current stage, body perception is primarily achieved by measuring changes in the curvature and shape of the robot's body itself.

This article first introduces capacitive sensors. The principle is that the capacitance across a capacitor is related to its area and separation distance. The larger the area and the smaller the distance, the greater the capacitance. When a soft robot comes into contact with other objects, the area of the sensor changes, causing a change in capacitance that can be used to sense changes in its own curvature.

Perception based on fiber optic sensors is also a relatively mature ontological perception technology for soft robots. By engraving gratings on optical fibers, when the fibers are stretched or bent along with the soft robot, the period of the gratings changes, resulting in a shift in the wavelength of the reflected or transmitted light. By demodulating the changes in wavelength, strain, and temperature can be measured with extreme precision. Its characteristics include low cost of fiber optic materials, weak hysteresis, and the ability to avoid electromagnetic interference issues encountered by traditional electrical sensors. However, on the other hand, its sensitivity is relatively low, and the perceived signals are compounded, making it difficult to distinguish between them.

The sensing based on liquid metal sensors involves filling microchannels with liquid metal alloys and embedding these microchannels into the elastic body of a soft robot. When the robot deforms, the microchannels are stretched or bent, causing changes in their length and cross-sectional area, which in turn lead to significant changes in resistance. By measuring the resistance, the strain can be inferred. It is characterized by low cost and a relatively simple sensor structure. However, it also has disadvantages such as strong hysteresis and susceptibility to signal drift.

3.2 Applicable sensor types

Research on sensors in the field of body perception is generally at the forefront, utilizing advanced biomaterials to produce high-performance sensors. Liu et al. [6] proposed a novel multifunctional self-sensing driven gradient hydrogel, which exhibits excellent thermal sensing drive performance and photothermal efficiency when used as a photothermal sensor. Furthermore, it also combines the advantages of sensor perception sensitivity and stability. They also utilized this hydrogel material to fabricate a bionic tongue capable of self-sensing. When exposed to near-infrared light irradiation, the hydrogel's resistance changes significantly, allowing it to sense its own state. Not only that, but they also achieved remote interaction of the hydrogel sensor on the robot body, demonstrating the sensor's development potential in the field of robotics.

In addition to optical sensors, multimodal electrical sensors can also be utilized for proprioception in soft robots. Wang et al. developed an intelligent soft robot system equipped with multimodal triboelectric and capacitive sensors to achieve tactile perception and proprioception [7]. Specifically, their self-powered TENG sensor, equipped with a controlled buckling structure, can sense the bending of the robot body. The HB-TENG sensor, composed of nickel fabric and conductive silicone, can be integrated onto the robot's actuator unit due to its excellent extensibility and compatibility. It senses proprioception by measuring the bending and stretching length of the robot's body.

3.3 Assistance from other types of technologies

In addition to directly embedding physical sensors, the proprioception of soft robots is increasingly relying on data-driven technologies such as machine learning and deep learning, as well as biomimetic technologies. These technologies do not directly replace the role of sensors, but rather combine with sensor technology to achieve deeper proprioception [8].

Firstly, it is data integration based on machine learning. Its principle is to utilize machine learning algorithms to "learn" and integrate incomplete or multiple types of sensor signals into a complete ontological state. One approach is state reconstruction, which does not use or only uses a small number of low-cost sensors, such as capacitive sensors or resistive sensors, to take these easily measurable signals as inputs. Through a trained neural network model, it directly outputs the complete three-dimensional shape of the robot or the positions of key points. Another approach is multi-sensor data fusion and noise reduction. When a robot integrates multiple sensors, its data is often heterogeneous, asynchronous, and noisy. ML/DL models, such as recurrent neural networks (RNNs) and Transformers, can excel in fusing these multimodal data and filtering noise to obtain more accurate state estimations.

Next is the proprioceptive mechanism inspired by biology. Its principle is that many organisms, in addition to their own sensory organs, can also use feedback generated by movement to perceive their own state. In robot construction, this can be reflected in the interaction between driving and sensing functions.

4. Application of soft robot perception

As soon as the area of robotics began expanding and deepening, along with the larger and more sophisticated work situations in many contemporary industries, the sub-sector of soft robot perception received an incremental degree of focus. Whereas, most of the projects remain to be in their research and development and experiment phase, they have shown to be applicable in numerous intricate, hazardous or extremely accurate conditions.

4.1 Marine field

Rigid robots demand exceptional material requirements in the ocean and other forms of water bodies since they have to endure unlimited water pressure levels particularly in the deep-sea applications. Soft robots on the other hand have benefits because their shapes can be changed and therefore had wide application opportunities in the sea sphere.

Mao et al. developed an original multimodal tactile sensing hand in a soft robot that is inspired by the different organisms [9]. Tactile perception of such finger is attained via fiber optic sensors which are very sensitive to deformation of the body and changes in temperatures. In addition, it has anti-corrosion, high temperature and antinterference properties when transmitting sensing results over a long distance. Appearance-wise, its main body is designed (though it does not look) like a human finger, but bionic mouse whiskers and fish-fin-like features are also added to the surface of the robot in order to provide it with more sensing organs. This under water cabling soft robot has been found to excel in grasping experiments in water not only because it can sense the transparent things as indicated by its whiskers but also has a grasping force adequate enough.

The multimodal underwater robotic skin developed by Zhou et al. [5] has been provided with a morphology and material as well as capable of functioning underwater. Given that majority of the sensors types used are water or humidity sensitive, the magnetoelastic artificial skin they designed is chemically stable and thus waterproof. They came up with the waterproof tactile perception system that is created through the BMAS and gives the robot the capability to sense, recognize objects in the water. With up to 95% success of this system when classifying seven types of marine organisms and marine litter, robotic grippers and other soft robots based on this artificial skin are flexible in both robot applications in marine litter collection and marine resource exploration.

4.2 Medical field

Soft robots, by virtue of their physical body structure created out of soft material, bring safety and flexibility in performing sophisticated biological functions that cannot be introduced to normal medical staff and other robots. The most suitable case of their application is in the field of minimal invasive surgery, as small-sized robots have an opportunity to penetrate slender cavities of the human body to perform surgery. Moreover, soft robots demonstrate very high predictable performances to in-vivo imaging and specific target therapy.

Liu et al. [10] developed an intelligent soft quasi-organism equipped with sensor-driven integrated tentacles. This tentacle has tactile perception sensors, has self-state recognition, and it is able to identify motionless objects. The outer surface of the tentacle is a porous graphene that can serve as a resistance sensor because alterations in the length and surface area of the conductive pathways occurring during body deformations or extension of its length changes the resistance value of the tentacle. This is made possible by the perception system which is inspired by the neuromuscular system of sea anemones and is used to identify the objects of various shapes when they are grasping them. Eventually, when the performance of the object recognition algorithms is optimized, and the database is expanded, removing the necessity to be the least invasive during the surgeries of the implant, it is likely to prove its strong abilities in the area of minimally invasive surgery on the implant and other medical aspects.

The paper by Qiu et al. is a review of the use of soft robots with in-built sensors in healthcare [11]. They also presented medical soft robots which include: endoscopes, catheters, and ingestibles in the article. However, the structure of the human body can be extremely complicated and narrow, which contradicts the presentation of most important organs, including the gastrointestinal tract, and endoscopes, which are the traditional objects of exploration, cannot be used to explore and diagnose. It is because of this that soft robots can be able to complete exploration tasks painlessly and safely since they are flexible and soft. Besides, they also noted the significance of sensors in soft robots in surgery and diagnosis and enumerated some medical uses of sensors in soft robots, including pressure sensor, temperature sensor, bioelectric sensor, etc.

4.3 Other fields

In addition to medical and marine sectors, the only perception that soft robots possess has proven to be incredible in countless areas that are yet to receive their application. An example of this is on the use of soft robots during rescue and exploration missions, whereby they will be used to navigate through various obstacles such as rubble in buildings and cracks in the huge ruins that are caused by natural calamities like earthquakes and tsunamis. At the same time, they are also capable of using the sensors the robots have to detect the temperature, air pressure, and many other variables and find the survivors and important provisions. Moreover, another use of soft robots can be in the field of industrial inspection, agriculture food processing, and space exploration.

Di et al. [12] developed an inchworm-inspired crawling soft robot. Multi-molecular carbon nanotubes are used to make the sensory layer and the muscle layer of this robot. Carbon nanotubes change its conductivity when the bionic muscle stretches or contracts and therefore the resistance of the robot changes, which makes it a practical application as a sensor with proprioception. Moreover, the bionic muscle is capable of being propelled by an externally applied voltage, which enables crawling in the robot, and has some load-bearing strength, which is capable of supporting objects nearing five times its mass. The bionic technology of the robot, its proprioception capability and ability to carry loads make it possess the potential to move over complex terrain and not lose its integrity as well as deliver supplies.

5 Outlook

Soft robots perception technology is in a critical state moving out of a single-purpose cost to system intelligence. A literature review The current market research has indicated that although considerable progress has been made in terms of different types of flexible sensors (resistive, capacitive, fiber optic, magnetoelastic, etc.), most present systems currently utilize only one type of sensor. This single relative truth in the dimensions of perception creates information blind spots when it is exposed to complex real world environments, severely restricting the degree of autonomy in and adaptive capacity of the robots to autonomous decision making.

In the future, the trends of deep integration will be witnessed in the development of soft robotic perception systems in two primary ways. To begin with, multimodal fusion perception will turn out to be a typical set up. They will mimic the human skin system whereby future soft robots will incorporate various kinds of sensors, tactile sensors, proprioceptive sensors and even the temperature and humidity sensors. Integration is not merely a physical coexistence issue, but it consists of the collaborative design of various kind of sensors to create a multi-layered and comprehensive information on the environment. As an example, the system should incorporate pressure distribution information when holding fragile objects by responding to the pressure distribution aiming to regulate the grip strength and dynamic perception to prevent instability. This not only demands more performance and integration of sensors, but also creates new difficulties in real-time synchronization, calibration and fusion algorithms.

Secondly, the process of the development of the perception systems will be intertwined with the idea of embodied intelligence [13]. Through a thorough integration of machine learning and artificial intelligence algorithms into the materials, structures, and closed-loop control of soft robots; perception will cease to be a solitary act of gathering information, but will be an extremely well-coordinated unit with driving and control. This is intelligent perception that is capable of using the natural physical characteristics of soft structures as computation materials to perform real-time processing and prediction of information by reference to physics. This does not only significantly improve the performance of perception, but what is more important is that it can have a immense reduction on the reliance on large external labelled datasets.

6 Conclusion

This paper critically summarises the current research advancement in understanding the perception functions of soft robots, and two fundamental directions are targeted, namely; environmental perception and body perception. It thoroughly examines the perception principles, material choice, integration techniques, and performance of flexible sensors in other application scenarios.

The findings of the review reveal that the studies concerning the environment perception have attained fairly advanced level. Pressure, touch, temperature and chemical sensing flexible sensors have experienced considerable improvements on material performance, sensitivity and stability, and have been shown to have a high potential of application to ocean exploration, medical work, and difficult environmental duties. Conversely, proprioception is still a study issue in the domain of soft robots, and the primary issues are associated with extremely nonlinear properties of soft structures. Real-time systems with embedded sensing capabilities by use of electrical, optical, and liquid metal technologies currently demonstrate the capability to achieve, to some degree, curvature and shape awareness, but typically have the problem of signal lag and extreme system complexity. To overcome them, there is an increasing number of studies carried out using machine learning and multimodal data fusion approaches.

In the future, the trends of multimodal deep fusion and co-evolution of embodied intelligence in the development of soft robot perception systems will be observed. This line of research not only is of immense importance to the broadening of the scope of applications of the robots of soft type, but it is also a new direction of the study of the systems of robot perception and intelligent systems.

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