Exploring the Progress of Soft Robot Applications in Extreme Environments

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Abstract. As robotic technology extends to complex scenarios, soft robots are gradually replacing traditional rigid robots in certain applications within extreme environments, leveraging their core advantages of high deformability and exceptional adaptability. This paper systematically analyzes the current applications and technological advancements of soft robots in extreme temperature, high-pressure, and high-radiation environments. It focuses on key breakthroughs such as the "rigid + flexible" collaborative operation mode, novel actuation mechanisms like magnetic or solar-driven systems, and optimized radiation shielding materials. The study also examines core challenges, including the insufficient stability of flexible sensing technologies and difficulties in signal processing. Finally, it explores the potential applications of emerging technologies such as liquid crystal elastomer fiber actuators and liquid metal materials.

Keywords: Soft robots; Extreme environments; Application advancements

1 Introduction

Under the wave of global technological innovation and industrial upgrading, the demand for extreme environmental operations is becoming increasingly prominent. From deep space exploration and deep-sea resource development to nuclear facility maintenance, minimally invasive medicine, and other fields, unprecedentedly strict requirements have been put forward for the environmental adaptability, flexibility, and safety of operational equipment. Traditional rigid robots are limited by the inherent rigidity of their structures. In complex working conditions such as extreme temperatures, high pressures, and high radiation, they generally suffer from insufficient degrees of freedom, poor environmental adaptability, and high operational risks, making it difficult to meet the requirements of precision and high reliability operations. In this context, soft robots with flexible materials as the core, strong deformability, and flexible movements have emerged. By simulating biological motion mechanisms, they can achieve stable operations in irregular spaces and extreme physical and chemical environments, gradually becoming an important development direction for extreme environmental operation equipment.

In recent years, scholars at home and abroad have conducted extensive research on the application and technological optimization of soft robots in extreme environments, achieving a series of breakthrough results. Qiu Z et al. upgraded pneumatic soft actuators to achieve spatial deformation, further enriching the driving methods and application scenarios of extreme

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environment soft robots [1]; In terms of material innovation, Zhang et al. developed temperature adaptive elastic conductive fibers, significantly improving the working stability of soft robots in extreme temperature ranges [2]; Zhang et al. systematically reviewed the progress of soft robots in space applications and pointed out that the "rigid + flexible" collaborative operation mode can effectively compensate for the operational limitations of traditional space robots, providing a new technological path for deep space exploration tasks [3].

This article aims to systematically review the application status and technological improvement achievements of soft robots in three typical environments: extreme temperature, high pressure, and high radiation. The following chapters will respectively elaborate on the specific application scenarios and core technological breakthroughs of soft robots in different extreme environments, deeply analyze key challenges such as insufficient stability of current flexible sensing, and finally look forward to future development directions such as liquid crystal elastomer fiber actuators and intelligent material fusion, providing reference for technology research and application expansion in this field.

2 Application and improvement of soft robots in extreme temperatures

2.1 Outer Space Operations

Outer space is a typical extreme temperature environment, with temperatures in the permanent shadow zone of the lunar polar region dropping as low as -250 ℃, far exceeding the low temperature of liquid nitrogen. The temperature in the daytime illuminated area can rise to 121 ℃, with a temperature difference of over 200 ℃ between day and night.

Space robots significantly reduce the risks and costs in space missions, while traditional space robots have lower degrees of freedom due to the use of rigid structures, which limit their performance in missions. Soft robots, on the other hand, can complete more complex tasks with their better flexibility and higher robustness.

It is not difficult to find from existing research that the advantage of soft robots is not to replace traditional rigid robots, but to complement and upgrade them. For example, in scenarios such as large equipment handling, the load-bearing advantage of rigid robots is still irreplaceable, but in subsequent precise debugging and narrow space operations, soft robots can leverage their flexibility and expertise. This "rigid + flexible" collaborative operation mode can further reduce the comprehensive risks and costs of space missions, and this direction is also worth further exploration and research.

2.2 Technical Improvements

Kulkarni, Mayura et al. analyzed the implementation of soft robotic devices, including actuators and sensors that meet these requirements [4]. In addition to the structure of these devices, they also explored expanding the application of soft robots in extreme environments through optimized design and control systems. Fig. 1 shows a soft robot suitable for extreme environments.

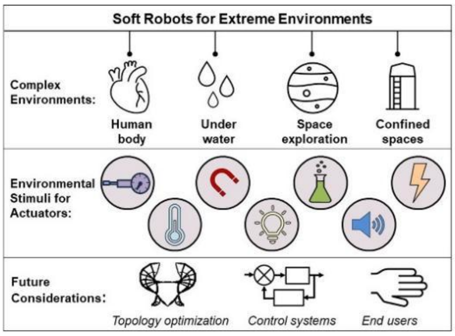

Fig. 1. Soft robots suitable for extreme environments [5]

They proposed that fluid-driven mechanisms can be used for soft robot actuators in space applications, as they have adaptability and can generate high output forces with low energy. Palmieri et al. proposed a deployable soft arm made of pneumatic inflatable chain links that can be stored in small packages to reduce weight and volume during transportation [5]. They also proposed that solar-powered soft robots can be used for aerospace applications due to their efficient energy systems. Mirvakili et al. developed a solar-powered soft robot consisting of a pressure chamber containing low boiling point liquid [6]. One end serves as a heat sink, and the other end is connected to a silicon-based soft robot. After exposure to white light, the absorbing film will increase the liquid temperature, thereby increasing pressure output and forcing driving.

3 Application and improvement of soft robots under high-pressure conditions

The high-pressure environment imposes strict requirements on the pressure resistance, flexibility, and adaptability of equipment, and soft robots, with their flexible materials and deformable structures, can adapt well to such special scenarios, demonstrating unique application value in medical, industrial, and other fields. Among them, high-pressure related scenarios in the medical field (such as high-pressure environments in specific chambers within the body, pressure adaptation requirements in minimally invasive surgery, etc.) are important directions for soft robots to leverage their advantages.

3.1 Medical

Zhang Yin et al. designed a soft robotic arm with multiple degrees of freedom for use in atrial septal defect (ASD) surgery [7]. The multi-module soft robotic arm they developed consists of four different units: a bending unit, a rotating unit, a stretching unit, and a grasping unit. The multi-module flexible soft robotic arm they proposed is used for minimally invasive surgery, allowing it to reach the designated surgical area during the repair of atrial septal defect. Additionally, the grasping unit can stably fix surgical instruments.

Wang Yadong and his team have developed a cordless soft robot that mimics earthworms [8]. The core of the robot is a three-stage actuator consisting of a "front radial center axial rear radial" section, which also integrates flexible pressure sensors, wireless miniature cameras, and four miniature air pumps. By controlling the expansion and contraction of the actuator through

Bluetooth, the robot can achieve controllable motion (speed 0.75mm/min) in a gut like environment. It can not only monitor environmental pressure in real time, but also accurately identify foreign objects through the Fast RCNN algorithm.

Although both types of robots are used for human cavity operations, there are significant differences in the requirements of their application scenarios. Cardiac surgery requires higher precision and sterility of instruments, so Zhang Yin's team's design focuses more on the collaborative cooperation of multi-degree-of-freedom mechanical structures; The intestinal environment itself is irregular, and the comfort level of the test subject needs to be considered. This led Wang Yadong's team to adopt a deformation mechanism that mimics earthworm peristalsis, combined with wireless sensing technology. The two form a design logic difference of "structural adaptation scenario" and can complement each other. If the visual recognition capability of Fast RCNN is integrated into the robotic arm for cardiac surgery, it is expected to achieve precise localization and real-time feedback of defect areas. If cordless drive technology is applied to minimally invasive surgical instruments, it can further reduce the invasiveness of surgery.

3.2 Application improvement on underwater operations

Another high-pressure related application scenario is underwater operations. The underwater environment is a typical high-pressure extreme scenario. For every 10 meters increase in ocean depth, the water pressure rises by one standard atmospheric pressure. The water pressure in deep sea areas can reach hundreds or even thousands of atmospheres. For example, the water pressure in a 1000-meter-deep sea is about 101 MPa, which is equivalent to withstanding 100 kilograms of pressure per square centimeter.

Alshehhi, Aysha A. Samra, and others introduced a new hybrid soft rigid robot called Trident, which was developed by connecting three soft modules and integrating tendons [9]. This multifunctional robot can not only swim, but also grasp underwater objects. They provided a detailed introduction to the design and manufacturing process of the robot, and conducted detailed experimental analysis on its performance. This innovative design cleverly combines the flexibility of soft materials with the strength of rigid structures, providing a multifunctional solution for fields such as underwater exploration, environmental monitoring, and ocean research.

Figure 2 shows the key structural design and physical form of the Trident hybrid soft rigid robot, which includes three core parts: Fig. 2 (A) illustrates the geometric parameters of the robot's flexible components; Fig. 2 (B) shows the component composition of the robot, including 3D printed hooks, disks, and nylon tubes with built-in tendons; Fig. 2 (C) shows the physical prototype of the Trident robot, with a blue flexible body and rigid interface design, visually presenting its morphological characteristics suitable for underwater operations.

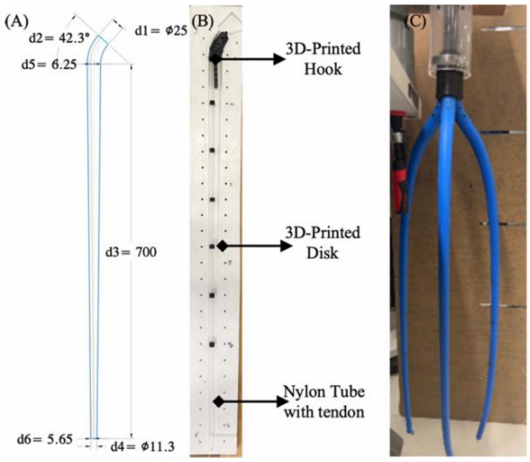

Fig. 2. Branched flagellum design: (a) Geometric structure of the Flagellum. (b) Flagellum mold with internal components. (c) Completed branched flagellum

4 Application of soft robots under high radiation conditions

4.1 Testing and Maintenance of Nuclear Power Plants

Soft robots are gradually gaining recognition for their outstanding performance in extreme environments. Radiation shielding is a major issue in the design of soft robots for nuclear environments.

Zheng Tengfei and others proposed an effective soft robot design and developed a new type of radiation shielding material, which enables robots to perform multiple tasks in complex pipelines of nuclear power plants while possessing sufficient radiation shielding [10]. They used a mixture of silicone and lead powder with excellent radiation shielding capabilities to design and manufacture a soft robot prototype consisting of multiple pneumatic actuators and a resin frame. This method can also be extended to the application of other soft robots in nuclear environments, and has the potential to improve the safety and efficiency of nuclear power plant operations.

4.2 Exploration of Outer Space

Spacecraft are exposed to high radiation environments in space and face the risk of space debris impact, while existing robotic arms are difficult to cope with dynamic, non cooperative target operation requirements. The lightweight, high flexibility, and strong adaptability advantages of soft robots make them stand out.

Li Pengchun developed a self-growing soft robot to meet the operational requirements of dynamic spatial targets, which achieves long-distance multi-degree of freedom motion through pneumatic drive and distributed steering joints [11]. He developed variable stiffness technology by drawing on the structure of eel scales to enhance load capacity, and adopted composite weaving technology to ensure spatial adaptability. At the same time, intelligent control methods were used to complete ground simulation experiments such as target capture, providing technical support for the autonomous operation of space flexible equipment.

He deeply integrates the three core requirements of "motion expansion," "performance enhancement," and "environmental adaptation." Compared to traditional soft robots that simply pursue motion flexibility, its variable stiffness design greatly enhances practical operational value and is more suitable for long-distance target operation scenarios. It has important practical significance and potential application value for ensuring the long-term stable operation of spacecraft.

5 Challenges and Prospects

Although significant breakthroughs have been made in the field of soft robotics, flexible sensing technology is still in its initial exploration stage and still needs to overcome many challenges. From a practical application perspective, this type of technology still has obvious limitations, and the performance of flexible sensors is highly susceptible to temperature, humidity, and chemical environment changes, posing challenges to stability. In addition, sensors need to follow the robot to complete stretching, bending, deformation and other actions, without interfering with the robot's free movement, while maintaining flexibility throughout the sensing process. This special requirement makes the signals collected by sensors exhibit nonlinear and high-dimensional characteristics, as well as a large amount of irrelevant interference information, which poses significant difficulties for subsequent signal processing and analysis [12].

From the perspective of technological development trends, soft actuators inspired by biological motion mechanisms are becoming a core research direction in the field of soft robotics due to their excellent environmental adaptability and operational safety. Among them, liquid crystal elastomer fiber actuators (LCEFAs) are considered to have great potential for development. They can achieve reversible linear motion and accurately complete preset actions such as stretching, rotation, bending, and expansion, with both adaptability and functionality [13].

In terms of intelligent material applications, Yuan Ruibo et al. proposed a magnetically driven liquid metal geometrid-like soft robot, whose core material liquid metal combines excellent flexibility and strong magnetism. Under the drive of an external magnetic field, it can achieve motion through its own deformation, not only adapting to complex environmental conditions, but also completing reciprocating crawling movements [14]. Moreover, gallium-based liquid metals have a low melting point, which allows for flexible control of stiffness through temperature changes, enabling them to perform various load-bearing tasks and expanding the application scenarios of soft robots.

6 Conclusion

As an emerging direction in the field of robotics, soft robots have unique advantages in extreme environmental operations due to their flexible structure and adaptability to the environment, making them an important supplement to traditional rigid robots. This article summarizes three typical scenarios: extreme temperature, high pressure, and high radiation. It is found that in extreme temperature environments, with the "rigid + flexible" collaborative operation mode and adaptive driving technologies such as solar energy and fluids, precise operation in narrow space and stable operation in a wide temperature range can be achieved; In high-pressure environments, relying on the deformation adaptation characteristics and hybrid structure design of soft materials, it demonstrates irreplaceable advantages in tasks such as flexible movement of human body cavities, complex underwater terrain shuttle, and object grasping in medical minimally invasive scenarios; In high radiation scenarios, through the research and development of radiation shielding composite materials and innovation in variable stiffness technology, we have successfully adapted to high-risk operations such as pipeline inspection and spatial dynamic target operation in nuclear power plants. Despite significant progress, soft robots still face core technological bottlenecks that constrain their expansion towards high-precision and high stability applications. In the future, the research and application of new soft actuators represented by liquid crystal elastomer fibers, as well as intelligent materials such as magnetically driven liquid metals, will provide new paths for improving the motion accuracy and load capacity of soft robots; The cross-fusion of technologies in different scenarios is expected to further broaden its application boundaries.

Overall, the application of soft robots in extreme environments is still in a rapid development stage. With the deep integration of materials science, sensing technology, and control algorithms, their potential for application in aerospace, medical health, marine engineering, nuclear industry, and other fields will continue to be released. In the future, they are expected to become the core equipment for extreme environment operations through the development model of "functional adaptation scenarios, technological complementarity and collaboration, promoting technological innovation and efficiency upgrading in related industries.

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