

LMPA Epidermal Continuum Robot: A New Type of Programmable Stiffness and Environment Interaction Design

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Abstract: With the continuous development of robotics, the adaptability and flexibility of robots in complex environments have become a research hotspot. In practical application, the robot needs to face the changeable terrain, load and dynamic interactive environment, which puts forward higher requirements for the physical performance of the robot. This paper presents a variable stiffness robot epidermis design scheme, aiming to realize the adaptive ability of the robot in different task scenarios through the stiffness regulation of the epidermis. This study first conducted an in-depth analysis of the mechanical properties, and properties of epidermis materials, and comprehensively considered the properties of materials. Based on this, a variable stiffness epidermis structure based on intelligent material is designed, which can dynamically adjust its stiffness according to the changes of the external environment, thus achieving a balance between softness and rigidity. To verify the feasibility of the design scheme, this study performed a systematic analysis of the performance of the epidermis structures under different loads by modeling simulations. The simulation results show that the epidermis structure can effectively adjust the stiffness under a variety of complex working conditions, showing good adaptability. The research results in this paper provide a new direction for the intelligent design of robot epidermis, with broad application prospects, and are expected to play an important role in the future of robot technology.

Keywords: Robot skin, variable stiffness, environmental exploration, flexible structure

1. Introduction

With the wide application of robotics, the operational requirements of robots in complex environments are increasing. In recent years, many teams have achieved results in improving the robot's ability to explore the environment. Whether it is using an elastic rod to adapt to different terrain [1], or using 4D printing technology to make a snake robot [2] composed of ink, or improving the flexibility of the robot [3] through an origami structure, these achievements have made deep innovation for the environmental exploration function of the robot.

However, in order to better adapt to the complex curved environment, many teams optimize the structure of the existing robot through programmable stiffness robots, so that they can complete a specific target [4-7] by changing their own stiffness in different scenarios. For example, some studies use intelligent materials made of low melting alloys embedded in the robot structure to change the stiffness [8] of the robot through the properties of low-melting alloys. However, this design also poses some problems, limiting some of the robot's functions. If this design can be changed, it may be optimized for the variable stiffness robot design.

Based on the stiffness of intelligent materials at different temperatures, this paper proposes some programmable stiffness epidermis that can be attached to the robot surface, which can dynamically adjust the stiffness according to the task requirements, and has good response speed and adaptability. This research mainly focuses on the design of the epidermis of programmable stiffness robots, aiming to design the epidermis structure of the robot to change the stiffness without changing the main structure, and to provide new ideas for programmable stiffness robots and environmental exploration robots.

2. Advantage Analysis

In the design of existing flexible robots or programmable stiffness robots, the most common method used by researchers is to change its structure to make it have greater flexibility or complete the change of stiffness [9]. This design idea has its advantages. For example, the above functions can be widely adaptable and can be applied to most of the scenarios. But in contrast, its disadvantage is also very obvious. Compared with placing the programmable stiffness structure on the surface, the focus of the structure as the design may lead to complex structural design, increasing manufacturing and maintenance costs. At the same time, the internal integrated materials may be limited by other components of the robot and unable to give full play to its stiffness regulation capacity. Moreover, this design has limited environmental interaction capacity, and may not be flexible enough in direct contact with the external environment to achieve complex surface deformation and adaptability. It is worth mentioning that the increase in weight and volume are also important factors in this design idea to affect its mobility and flexibility.

On the contrary, designing a robotic skin that can change the stiffness limits a part of the usage scenarios, but its advantages are large enough. First, using smart materials as skins can simplify the internal structure of the robot and reduce the difficulty of manufacturing and maintaining them. When the robot is damaged, it can easily remove or replace the skin rather than repair the internal structure. Secondly, the robot skin can directly contact the external environment, which can not only realize more complex surface deformation and adaptability, but also effectively protect the internal structure of the robot. If some sensors are installed, it can also realize the exploration of the external environment. Moreover, the robot's epidermis may not significantly increase the weight and volume of the robot compared to the internal integration, thus maintaining its lightweight and flexibility. Finally, more importantly, the robot skin can be adapted to more robot structures, increasing the function of the robot, and making additional requirements such as collection and transportation simpler.

In summary, placing the structure of variable stiffness on the epidermis to achieve the stiffness requirements of the robot in different environments has some advantages. If researchers can develop better materials in the future, the study can be further optimized.

3. Stock Option

Through the design of existing robotic skin and the reference of natural biological skin, I summarize some possible properties of robot skin structure:

(1) Sufficient sensitivity: The robot skin needs to have high sensitivity to sense small pressure, temperature and tactile changes. For example, through a flexible dielectric elastic body-based drive, a highly sensitive motion control is suitable for the tactile sensing [10] of the robotic epidermis.

(2) Extension and flexibility: The skin of the robot should have good extension and flexibility to adapt to the movement of the robot. This is usually achieved by using flexible materials such as silicone rubber, polymers or nanocomposites.

(3) Self-healing: In order to improve the durability and service life, the robot skin needs to have the self-healing function. This can be achieved by special chemical composition or microcapsule techniques, such as the malrecovery [11] by laser-assisted technology.

(4) Wearability and air permeability: In medical or wearable device applications, the robot skin needs to have good air permeability and thin characteristics to ensure the comfort of wearing for a long time. Through the microporous design and the use of thin materials, air and moisture can be allowed through, reducing the irritation to the skin [12].

(5) Biological compatibility: The material of the robot skin needs to be compatible with human skin to avoid causing allergies or other adverse reactions. This requires the use of well-certified biocompatible materials. For example, the robotic skin developed by Japanese scientists uses a collagen gel for adhesion, which is naturally sticky and biocompatible.

(6) Multilayer structure: Robot epidermis can use a multi-layer structure similar to biological skin, such as epidermis, dermis and subcutaneous tissue layer. The epidermis layer is responsible for quickly sensing the slight touch, the dermis contains most of the sensing elements, and the subcutaneous tissue layer senses the overall deformation. This structure can better mimic the function of the human skin.

(7) Environmental adaptability: The robot skin should have good environmental adaptability and can remain stable under different temperatures, humidity and mechanical stresses.

(8) Antimicrobial and chemical stability: The robot epidermis needs to have certain antibacterial capabilities to prevent microbial attachment and infection.

(9) Salvability and sustainability: To reduce environmental impact, materials for the robot skin surface should be recyclable.

Given that the content of this study focuses on the design of the epidermis of the environment, some features applicable to electronic skin are not given high priority. Based on the above characteristics, this paper uses silicone rubber as the main design material of the epidermis as a high-performance material, which has many advantages and limitations in the application of robot epidermis. The following are some characteristics of silicone rubber organized in this paper: (1) Durability and long life: Silicone rubber has excellent aging resistance, high and low temperature resistance, ultraviolet light resistance and chemical corrosion resistance, and can remain stable in extreme environments. This means that the robotic skin can be used for a long time, reducing the frequency of replacement due to material aging. (2) Flexibility and elasticity: Silicone rubber has good flexibility and elasticity, and can adapt to the movement needs of the robot. This feature makes it suitable for epidermal applications that require frequent deformation, such as robotic joints or wearable devices. In this study, this property was able to fit well for frequent deformations due to changes in stiffness. (3) Recyclability and environmental protection: silicone rubber has good recyclability, and can be recycled after waste. In addition, its low energy consumption and low emissions in the production process also meet the environmental requirements. (4) Weather resistance and chemical corrosion resistance: silicone rubber can maintain performance in long-term exposure to ultraviolet, ozone or humid environments, and is suitable for robot applications in outdoor or complex environments. In the process of environmental exploration, we will often encounter a relatively harsh environment, which can well maintain our own structure and function.

Of course, silicone rubber also has disadvantages such as limited mechanical strength, poor self-healing ability, and insufficient oil resistance. However, in overall comparison, silicone rubber still has significant advantages in the application of robot skin. Through further material modification and composite technology, silicone rubber is expected to become an ideal material for robot skin.

After selecting the main component material of the epidermis, a material that can meet the variable stiffness should also be selected. In this paper, the low melting point alloy is selected as the core material. As a functional material, a low melting point alloy can quickly switch between solid and

liquid states, and its elastic modulus can vary in the range of 0 to nearly 10^{10} Pa. This feature enables the robot skin to dynamically adjust the stiffness in different working states, to meet the needs from soft compliance to firm support. At the same time, the melting point of low-melting-point alloy is usually lower than 300°C , and the solid-liquid phase transition can be realized with only a small amount of energy near room temperature. This enables the robot skin to quickly adjust stiffness to complex environments under low energy consumption. In addition, the high conductivity and thermal conductivity of low melting point alloys as well as self-repair and shape memory functions can steadily improve the reliability and durability of the system, maintain stable performance during multiple phase transitions, and adapt to the dynamic task requirements.

Crucially, low-melting alloys can combine with flexible materials (such as silicone rubber or elastomers) to form a composite material with adjustable stiffness. This composite material combines the high strength of the metal and the compliance of the flexible material, and is suitable for the robot skin that requires both rigidity and flexibility. Therefore, starting from silicone rubber and low-melting-point alloy, this paper designs a skin structure suitable for an environmental exploration robot to have the property of adjustable stiffness.

4. Design Modeling Simulation

The robot epidermis structure designed in this paper is cylindrical, which can effectively reduce the deformation and stress concentration of the epidermis during movement. The center leaves space for the use of robots of different types or sizes. The bulge of the cylindrical surface is filled with a low melting point alloy inside, and the outside adopts a silicone rubber design to meet the design requirements of variable stiffness.

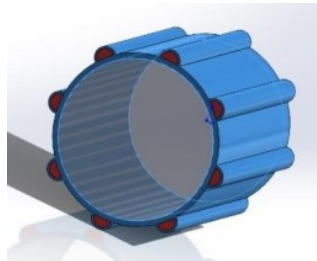


Figure 1: Robot epidermis structure model

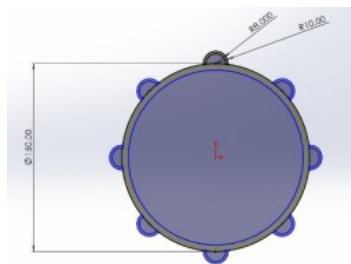


Figure 2: Section size

Figure 1 is a radial part of the epidermis structure, where the blue part is made of silicone rubber, and the red part is filled with low melting point alloy. Take the epidermis structure with a diameter of 150mm as an example (Figure 2), the silicone rubber layer is only 2mm thick, which can effectively reduce the resistance of the robot when rotating.

In order to more intuitively understand the variability of its stiffness, this paper conducts a finite element analysis of the above structure. By applying the same torque of 200 N/m to the overall

structure, it can be found that the force deformation of the whole structure is obviously different in the different stiffness (different temperature) states of the low melting point alloy. The maximum deformation when the stiffness is large (Fig. 4) is 0.679m, while when the stiffness is low (Fig. 3), the maximum deformation is 1.595m. This shows that the epidermal structure can realize the regulation of the overall stiffness by changing its internal stiffness.

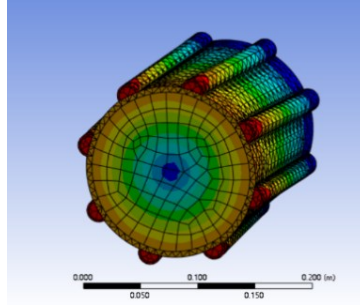


Figure 3: Epidermal deformation at low stiffness

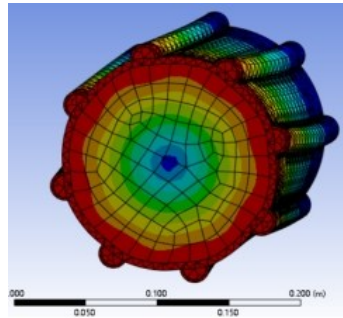


Figure 4: Epidermal deformation with high stiffness

It is worth noting that, due to the characteristics of the robot structure, the overall stiffness of the robot is not only determined by the epidermis, but also affected by the specific structure of the robot. In this paper, the FEA analysis assumes that the robot structure is solid and cylindrical. In practice, the robot structure will be different, which should be analyzed by specific structure.

5. Conclusion

This paper presents a novel robot skin design scheme with variable stiffness, which is successfully realized through the development of material selection and stiffness regulation mechanism design in different task scenarios. By comparing a variety of smart materials, low melting point alloys were selected as the main material of epidermis in this study. It has good stiffness regulation ability and rapid response characteristics, and can meet the dynamic needs of the robot epidermis. Mechanical properties analysis shows that the material exhibits excellent stress-strain performance under different driving conditions, which provides a reliable theoretical basis for epidermis design. Despite the achievements of this study, there are still some limitations, and the adverse effects of epidermis structure design on stiffness and how to adapt it to different shapes of robots are still the problems to be solved.

However, the variable stiffness robot epidermis has a broad application prospect in many fields. In the future, with the continuous development of materials science and driving technology, the variable stiffness epidermis is expected to be widely used in more fields, further promoting the development of robotics technology.

References

- [1] Wang W., Wei L., Liu F., & Wang G. (2023). Research on compliant legs of bionic hexapod robots. *China Mechanical Engineering*, 34(17), 2089-2094.
- [2] Ou X., Huang J., Huang D., et al. (2025). 4D-printed snake-like biomimetic soft robots. *Bio-Design and Manufacturing*, 8, 55-67.
- [3] Pang, W., Xu, S., Wu, J., Ren, H., & Zhang, Y. (2022). A soft microrobot with highly deformable 3D actuators for climbing and transitioning complex surfaces. *Proceedings of the National Academy of Sciences*, 119(49), e2215028119.
- [4] Mulvey, B. W., & Nanayakkara, T. (2024). HAVEN: Haptic And Visual Environment Navigation by a Shape-Changing Mobile Robot with Multimodal Perception. *Scientific Reports*, 14, 27018.
- [5] Tang, S., Yao, J., & Yu, Y. (2025). Design and mechanical analysis of a novel modular bionic earthworm robot with upright functionality. *Scientific Reports*, 15, 3829.
- [6] Zhang, Q., Fang, H., & Xu, J. (2021). Yoshimura-origami Based Earthworm-like Robot With 3-dimensional Locomotion Capability. *Frontiers in Robotics and AI*, 8:738214.
- [7] Yue, L., Wei, Q., Cheng, H., Liu, J., & Jin, H. (2022). Research Review of Tip-growth Soft Robots without Environmental Resistance. *Science Technology and Engineering*, 22(6), 2159-2169.
- [8] Zhang, J., Wang, B., Chen, H., Bai, J., Wu, Z., Liu, J., Peng, H., & Wu, J. (2023). Bioinspired Continuum Robots with Programmable Stiffness by Harnessing Phase Change Materials. *Advanced Materials Technologies*, 2023, 2201616. <https://doi.org/10.1002/admt.202201616>
- [9] Xu, L., & Han, S. (2021). A Review of the Research on Soft Robots Based on Shape Memory Alloy. *Science Technology and Engineering*, 21(12), 4760-4768.
- [10] Li, Y., Peine, J., Mencattelli, M., Wang, J., Ha, J., & Dupont, P. E. (2022). A soft robotic balloon endoscope for airway procedures. *Soft Robotics*, 9(5), 1014-1029. <https://doi.org/10.1089/soro.2020.0161> **[^47^]
- [11] Plantin, J.-C., Lagoze, C., Edwards, P. N., & Sandvig, C. (2016). Infrastructure studies meet platform studies in the age of Google and Facebook. *New Media Society*, 20(1), 293-310. <https://doi.org/10.1177/1461444816661553> **[^47^]
- [12] García-López, J. S., & Yelinek, J. (2019). Emotions in storybooks: A comparison of storybooks that represent ethnic and racial groups in the United States. *Psychology of Popular Media Culture*, 8(3), 207-217. <https://doi.org/10.3916/C62-2020-01> **[^49^]