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An Elephant Trunk-Inspired Modular Variable Stiffness Soft Robot

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Abstract. The Elephant Trunk demonstrates unique advantages in complex environments thanks to its flexibility, high degree of freedom and versatile transport characteristics. In the industrial world, it is known as nature's universal robotic arm. However, the ability to achieve three-dimensional smooth movement and stiffness adjustment similar to that of the elephant trunk puts forward higher requirements on the structural design, drive integration and functional adaptability of the robot. Here I proposed and implemented a bionic elephant trunk robotic system that incorporates a modular architecture, soft actuators, and adjustable stiffness mechanisms, with 3D motion achieved by three 120 degrees soft bellows actuators working in concert, and thus possessing continuous deformation and spatial localization capabilities. In addition, in order to cope with the demand of rigid-flexible switching for different grasping tasks, the system introduces a variable stiffness mechanism based on skeleton-particle coupling, which is capable of state adjustment and structural toughening under external loads. In the end-operation environment, the robot integrates soft suction cups with adsorption functions. This effectively improves the stability of non-regular target attachment and grasping. The system is modeled using SOLIDWORKS software and the soft actuator is constructed using 3D printing and silicone injection moulding. Experimental results show that the robot exhibits excellent adaptability, load capacity, and locomotion in multi-scenario operations. It shows its wide potential in the direction of complex environment manipulation such as service robots.

Keywords: Elephant Trunk-inspired Robot, Soft Robot, Variable Stiffness, Modular Design, Silicone Injection Molding.

1. Introduction

In the recent few years, the appearance of soft robotics has changed the entire impact that robotics has had, and has greatly pushed forward the innovation in modern technology [1]. Soft robots are created via soft materials as well as silicone rubber, which is a malleable and flexible material. The innate features of soft materials in it has made it very safe and can employ their inherent mechanical properties for safe movement patterns [2]. Soft robots can also offer significantly safer interactions with humans and with a much better range of movement and maneuverability [3]. As a result of these 2 key traits, they have many applications in both automating industries and assisting in the rehabilitation of disabled people and can greatly improve one's quality of life.

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Although soft robotics have made many rapid advances to push the boundaries of the robotics field, there are still numerous issues that need to be addressed to improve their performance [4]. A notable and one of the most prominent directions in soft robotics research is stiffness tuning [5]. While the softness and compliance of soft materials can provide the robot with dexterous maneuvers without the need for complex algorithms, their lower stiffness also makes it difficult to maintain a relatively high payload while holding an object, leading to failure of the grasping task [6]. A lot of soft biological organisms in nature have natural stiffness adjusting mechanisms, such as elephant trunks and squid tentacles [7]. Animals such as these are able to adapt to their surroundings with low stiffness while simultaneously changing the stiffness of their "natural grasping mechanisms" depending on what they need to be used for. Thus, heavily inspired by biology, the introduction of stiffness adjustment capabilities into soft robots can help achieve a wider range of applications.

Various mechanisms for variable stiffness have been reported. Variations of stiffness in soft robots are usually caused by external stimuli, such as changes in air pressure. Jae Hyuck Jang et al. [8] presented an idea where a positive and negative air pressure linear brake is applied to jamming layers located inside of a pouch motor (pressurized using positive pressures). Hang Wei et al. [8] proposed a novel rigid and soft coupling variable stiffness module that employs a folded plate mechanism (FPM) to provide rigid multidirectional loading and combines it with particle jamming to achieve local variable thickness. Junfeng Li et al. [9] came up with an idea for the variable stiffness mechanism using polycaprolactone based on an integrated actuating cooling system. Mingzhu Zhu et al. [10] developed a design for variable stiffness soft gripper based on layer jamming. Ling-Jie Gai et al. [11] came up with the idea of using a cross fiber jamming mechanism with both elongation and bending stiffness tunable capability for soft bellow actuators.

In summary, most of the existing research work has been developed based on soft grippers or a single soft actuator, and very little research on soft robotic arms. This is due to the fact that there are still difficulties in achieving variable stiffness studies for soft robotic arms that bend in 3 dimensional directions [12]. To the best of our knowledge, conventional stiffening methods, such as layer blocking, only have 2D (planar) stiffening capabilities. However, soft robotic arms are pivotal in the field of robotics as carriers for a wide range of transmissions [13]. Therefore, it is crucial to develop a soft body robotic arm with a variable stiffness strategy with 3 dimensional bending to achieve a better load bearing performance.

In addition, another major drawback of soft robots/actuators is that they are prone to breakage during inflation, leading to failure, which greatly affects the work efficiency, especially in the face of large robots with complex and long production processes, such as soft robot arms, and the maintenance cost is extremely high in the event of breakage [14]. Although there have been some studies for soft robots developed after the breakage of the restorative work, such as the use of some chemical materials for the autonomous fusion of silicone, but still failed to solve the problem of maintenance difficulty and assembly complexity of soft robotic arms.

In this work, I developed a modular variable stiffness soft body bionic elephant trunk grasping robot. I utilized SOLIDWORKS 3D design software and the silicone injection molding process for fabrication. The robot realizes the bending function in 3-dimensional directions and significantly increases the load carrying capacity. In addition, I divided the robot into several modular segments for assembly, and its modular design facilitates the assembly of the robot and improves the efficiency of repairing the robot after breakage. In addition to realizing the ability to curl like an elephant trunk, I also installed a soft body suction cup structure at the end of the bionic robotic arm. Finally, I experimental verified the versatile grasping and transportation performance of the soft

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robotic arm and demonstrated autonomous grasping applications. I believe that my work will help promote the development of robotics.

The rest of this article is organized as follows. In Section II, the design and principle of the soft robotic arm is described. In Section III, the fabrication methods of the arm are introduced. In Section IV, the stiffness, and the motion performance of the stiffness-tunable soft robotic arm are verified. Finally, Section V concludes this article.

2. Design and principle of the soft robotic arm

2.1. Overall design of the soft robotic arm inspired by elephant trunk

I designed the robot to meet the following criteria.

• Firstly, I am going to make a soft bionic elephant trunk robotic arm, by imitating the elephant trunk's multi degree of freedom movement characteristics and adaptive grasping ability, to realize a safer and more efficient way of moving than the "rigid robotic arm".

• Secondly, in order to address the lack of load-bearing capacity of soft robots, I am going to implement the variable stiffness function of the bionic elephant trunk, which can be softly deformed to adapt to the shape of the object, and can also be stiffened to increase the weight-bearing capacity.

• Finally, I adopted a segmented modular design with standardized interfaces for quick disassembly and free combination of modules. This allows for a flexible configuration of the number of segments according to task requirements, and also allows for quick replacement in the event of damage.

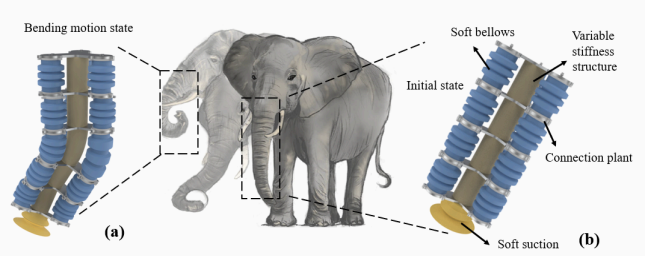

Figure 1. Design concept of the soft robotic arm inspired by elephant trunk. (a) Bending motion state of the robot. (b) Initial state of the robot. The robot is componets of soft bellows, variable stiffness structure, soft suction cup, and connection planes

The bio-inspired robotic arm's 3D model is as shown below (Figure 1):

In nature, the trunk of the elephant is a highly flexible and versatile biological structure that can move freely in three-dimensional space and perform a variety of tasks such as grasping, carrying, and exploring. The trunk not only has soft and controllable deformation ability, but also provides strong support and carrying capacity, when necessary, which is crucial for the elephant's foraging, survival and environmental adaptation. Inspired by this, to realize the demand for wide-range and high-flexibility movements of robotic systems in industrial and daily applications, this paper designs and develops a soft robotic arm using the elephant trunk structure as a bionic prototype.

The bionic soft robotic arm adopts a flexible modular design concept, and the whole is composed of multiple soft actuators, silicone bellows, suction cup end-effector, and other structural units in series, which can realize multi-directional natural movement capabilities, such as bending, extension and compression, and other multi-modal deformations. The modular structure not only makes the system easy to assemble and reduces manufacturing and maintenance costs, but also greatly

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improves the versatility and adaptability of the robotic arm. When a module is damaged during use, the user can quickly replace the damaged unit to avoid overall structural failure, which improves the reliability and maintainability of the system. At the same time, the design supports the flexible expansion or reduction of multiple segments, which allows the arm to adjust its length according to the task requirements to adapt to different spatial scopes and operating scenarios.

In terms of functional design, to achieve the transformation of the trunk's ability of "soft grip-rigid support", and to improve the arm's loading capacity and environmental adaptability, I constructed a 'backbone' with adjustable stiffness in the center of the trunk. structure with adjustable stiffness in its center. This structure is filled with a fine-grained material and integrates an internal structure like a ball-and-socket joint. When negative pressure (pumping) is applied to this area, the friction between the particles increases and the structure changes from flexible to nearly rigid, thus improving the arm's ability to support itself under load. This mechanism is like the 'jamming' principle, which provides adjustable stiffness control for the arm.

In addition, to further simulate the gripping function at the end of the trunk, a symmetrically closed suction cup structure is designed to be mounted on the end of any module. The suction cup is pneumatically controlled for adsorption and release and can be used to grasp objects of various shapes and materials, which effectively extends the end-effector function of the robotic arm. Overall, the bionic soft robotic arm has significant advantages in terms of flexibility, adjustable stiffness, modularity, lightweight, etc., and has good structural expandability and task adaptability. Its design is suitable for a variety of application scenarios, including industrial robot end-effector, biomimetic research platform, service robot manipulator arm, etc., showing a wide range of application potential and research value.

2.2. Working principle of the variable stiffness structure

The variable stiffness structure used in my study is constructed based on the particle jamming effect, as shown in Fig. 2(a) and (b). Fig. 2(a) shows a schematic diagram of the granular material in a loose and flowable state at atmospheric pressure, when the structure behaves flexibly; Fig. 2(b) depicts the working mechanism after applying negative pressure. Under the action of vacuum suction, the variable stiffness structure shrinks the outer silicone flexible membrane inward and presses the inner particles, thus inducing the tight stacking and friction enhancement between the particles, leading to a rapid increase in the overall structural stiffness. This process can be quickly recovered after the negative pressure is withdrawn, with good repeatability and adjustability.

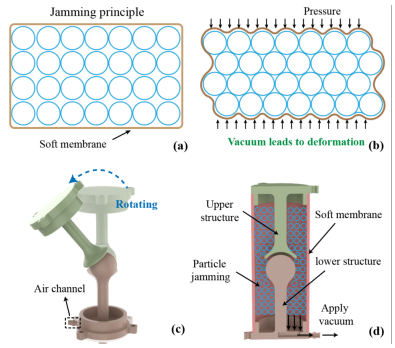

Figure 2. Design and principle of the rotating variable stiffness strucutre. (a) Under normal conditions (0 kPa), particles have fluidity. (b) Under vacuum conditions, particles are compressed. (c) Schematic diagram of rotational movement of the backbone structure. (d) The whole structure of the variable stiffness unit

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Given that the soft-bodied robot in this project needs to have the ability to flexibly bend and adjust in three-dimensional space, its integrated variable stiffness structure must also support multi-dimensional rotation and flexible deformation. However, conventional particle-jamming variable stiffness sleeves are often blocked, jammed, and prone to localized deformation in non-ideal situations when performing large-angle rotations.

To address these limitations, I draw on the bio-inspired mechanisms of the human shoulder and neck joints as well as the ball and socket structures such as the knee joint, and I introduced a spherical skeleton support system inside the variable stiffness structure. The structure has an upper and lower spherical add-on composition that maintains the overall 3D symmetry during axial compression and allows for continuous circumferential rotation around the central axis. When the particles are not vacuumed, the spherical skeleton moves in concert with the external soft silicone membrane to realize a high degree of deformation; while in the state of applying negative pressure, the particle jamming effect works in concert with the spherical structure to enhance the stiffness while ensuring that the overall structure still has good adaptability and stability. Specific structural implementation effects are shown in Figures 2(c) and 2(d). I reserved a dedicated ventilation line in the lower skeleton of the robot for connection to an external negative pressure pump.

I have performed a qualitative modeling analysis of the variable stiffness structure to explain the main influencing factors and acting mechanisms of its stiffness regulation. The equivalent stiffness K of the structure is mainly dominated by the particle obstruction mechanism, and its variation is affected by the synergistic effect of several key parameters, including vacuum pressure, friction coefficient between particles, filling density, and a particle contact model, which are expressed as follows:

$$K_{jam} = K_0 + \alpha \bullet \Delta P \tag{1}$$

while K0 is the initial stiffness without vacuum, α is the is an experimentally fitted constant reflecting the sensitivity of stiffness to pressure, ΔP is the applied vacuum pressure, Kjam is the equivalent stiffness in the jamming state.

Assuming that the stiffness between particles is established by the Hertzian contact theory, it can be approximated as:

$$K_{jam} \propto \varphi \bullet \mu \bullet (\Delta P)^n \tag{2}$$

while φ is the particle filling ratio, μ is the interparticle friction coefficient, and n is an empirical coefficient (generally taken as 0.5-1).

The stiffness adjustment multiplier η of the system is:

$$\eta = \frac{K_{jam}}{K_0} \tag{3}$$

2.3. Design of the modular suructure

Due to the large overall size of the bionic elephant trunk robot, there are significant difficulties in the building process and cost problems. Therefore, I adopted a modular design strategy to divide the bionic elephant trunk structure into multiple functional components, and build the overall structure by standardized excuses for assembly. Modularized design brings significant advantages, which are mainly reflected in the following two aspects. First, the modularized structure significantly improves the flexibility and convenience of processing and manufacturing. Each component can be

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independently processed, assembled and replaced, effectively avoiding the total scrap situation caused by local damage. Secondly, the design makes the robot system have good scalability and task adaptability. Users can freely adjust the length and function of the trunk structure according to the specific task requirements to meet diversified use scenarios. Each module is connected by tightening screws and can be disassembled and reassembled.

The modular structure shown in Figure 3 consists of four core components: the bellows, the variable stiffness unit, the rigid bracket, and the suction cup as the end-effector. The details of the structure are as follows: the total height of the bellows is about 95 mm, the wall thickness is 2.5 mm, and the height of the individual bellows structure is about 12 mm. The 2.5mm wall thickness is designed to prevent the bellows from breaking during inflation to a certain extent and to take into account the inflation efficiency (as shown in Figure 3B). The bellows is sealed by a sealing cap with an inflation hole (shown in Fig. 3C). The outer periphery of the rigid support is provided with three interface positions evenly spaced at 120-degree intervals (as shown in Fig. 3D) for the assembly connection of the bellows. By independently inflating the bellows at different positions, a multi-directional bending motion can be realized. The center area of the bracket is reserved for the installation of an adjustable stiffness structural unit to enhance the stiffness regulation capability of the overall structure. The connection mechanism between modules plays a crucial role in maintaining structural integrity. It is designed like a 3 headed boomerang with a height difference between the initial base and the end mounting point, so that the plastic pipe has room to be stuck in. At the end of the modular structure, a replaceable suction cup unit is designed to simulate the adsorption and grasping behaviors of an elephant trunk (shown in Figure 3E). Multiple molded bracket modules can be realized to close the end and connect with each other to build the elephant trunk structure with the desired length and flexibility by series connection. Depending on the application, the number of segments can be adjusted, increasing the length for extended reach, or reducing it for more precise tasks. Each module operates independently but can be seamlessly integrated into a larger system, enabling customized robotic arm assemblies that can work together as one.

The modular design not only optimizes the manufacturing and maintenance process, but also provides a good basis for the multi-task adaptation of the bionic flexible structure, demonstrating the potential for application in the design of flexible robot structures.

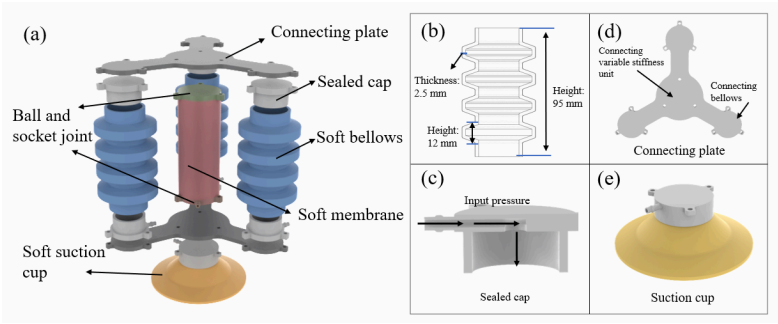

Figure 3. Schematic diagram of the modular structure of the bio-elephant trunk. (a) Exploded view of a single section. (b) Dimensions of the soft bellows. (c) Internal structure of the sealing end cap, especially the vent design. (d) Design of the connecting plate. (e) Design of suction cup structure

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3. Fabrication of the soft robotic arm

A synergistic approach of 3D printing technology and silicone injection molding was used for the fabrication of the soft bionic elephant trunk robot. In the process, I first prepared the core structure of the robot, including the mounting brackets, the shell, and the mold for subsequent silicone injection molding using Fused Deposition Modeling (FDM), an additive manufacturing technology based on the melting and extruding of materials, which is based on the principle of heating a hot-melt polymer material to a molten state, and then constructing the solid part layer by layer by building up the solid part in accordance with the pre-determined SOLIDWORKS model. The principle is that the heat-polymerized material is heated to a molten state to build solid parts layer by layer according to a predefined SOLIDWORKS model. As shown in Figure 4, I demonstrate and actually implement the 3D printing process. This method has a simple process, low cost, and is suitable for rapid prototyping.

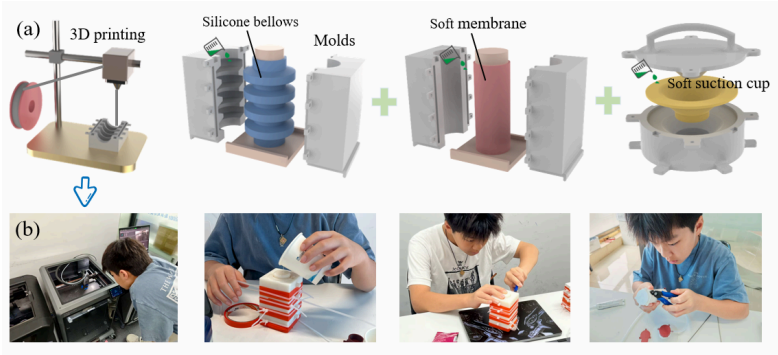

Figure 4. Schematic diagram of the molds for the fabrication process and the fabrication process. (a) 3D printing process and molds for bellows, soft silicone membrane, and suction cup. (b) Physical photos of my fabrication process

The bellows of the bionic elephant trunk robot, the flexible silicone membrane with variable stiffness, and the suction cups at the end are all prepared via the silicone injection molding process. In order to achieve a good balance between flexibility and load-bearing capacity, I selected silicone materials with different shore hardness. Specifically, the 15A Shore hardness silicone is used for the bellows to enhance its structural stability, while the flexible silicone membrane with variable stiffness is made of a softer 5A silicone to ensure good deformability. The end suction cup is made of a 10A durometer silicone for flexibility and adsorption. In the production process, I first pour the A gel and B gel in a 1 to 1 mass ratio to mix evenly, to ensure that the crosslinking curing reaction occurs between the silica gel. It is worth noting that silica gel tends to introduce a large number of air bubbles during the mixing process, and these residual air bubbles can significantly affect the structural finish and airtightness of the finished product, which is an especially sensitive aspect to pneumatically driven bellows. Therefore, I need to put the mixed silica gel into a vacuum defoamer for vacuum treatment to remove the air bubbles. Once this step is completed, the liquid silica gel is slowly poured into the molds pre-prepared by 3D printing. In order to prevent the silicone from leaking, I sealed the edges with zip ties and multiple layers of tape. The corresponding mold design and processing flow can be seen in Fig. 4. In order to speed up the curing process, I put the mold into a thermostat for heating after injection. After about 3-4 hours the silicone gel is almost cured. During the demolding process, I found that the silicone material would stick to the inner wall of the

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mold after curing, making it difficult to demold. For this reason, I first need to apply a petroleum jelly lubricant (vaseline) to the inside of the mold before injection.

Figure 4 shows a live view of my workbench during the soft robot fabrication process as well as a number of live shots of the completed soft actuators. After all the components were completed, I assembled the system following the following process: firstly, the bellows structure was inserted into the pre-fabricated end-cap interface and sealed and fixed using zip ties to ensure air tightness. Next, a rigid skeleton was embedded inside the flexible silicone membrane of the variable stiffness structure and filled with small granular materials such as rice to achieve variable stiffness regulation. Finally, the various types of flexible actuators are modularly assembled according to predefined mounting interfaces, and each module is fixed by screws.

4. Experimenal results

4.1. The soft actuator elongation experiment

I first experimentally tested the axial elongation and contraction properties of the flexible bellows. In the experiment, a proportional valve was used to apply positive and negative pressures in the range of 0-60 kPa to the bellows, respectively, and the length changes were recorded. To ensure the reliability of the data, each set of experiments was repeated five times to take the average value.

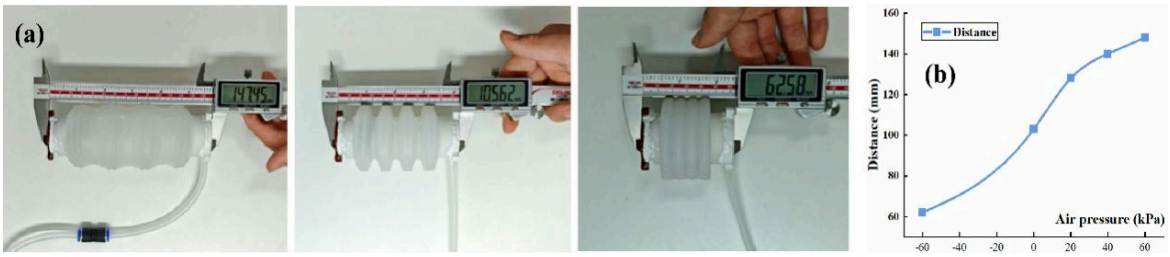

Figure 5. Soft bellows actuator elongation and shortening experimental test

The elongation characteristics of the bellows are shown in Fig. 5. The results show that in the initial state (i.e., 0 kPa), the length of the bellows is about 105 mm; when a positive pressure of 50 kPa is applied, its length can be elongated to a maximum of 147 mm; and when a negative pressure is applied, it can be contracted to a maximum of 62 mm.The deformation formation of this bellows is about 90 mm, which can provide a larger formation bending angle for the subsequent 3D spatial movement of the robot.

4.2. The variable stiffness experiment

I conducted stiffness adjustment performance tests on the designed variable stiffness structure to evaluate its load carrying capacity and deformation resistance. During the experiment, the variable stiffness structure was first bent to 90°. Subsequently, the maximum amount of negative air pressure it could generate was applied to the structure via an air pump to trigger the locking effect of the variable stiffness mechanism. In the stiffness-locked state, a force gauge was used to apply a tensile force along the bending direction of the structure so that it gradually retraced its steps back to the initial straight state, and the relationship between the force and the angle of retracement was recorded during this process. The experimental pictures and data are shown in Fig. 6. The results show that the maximum external force required for the variable stiffness structure to retrace to the

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initial straight line attitude is about 96N, which is higher than the own weight of the modular structure, indicating that the design is in line with the working conditions.

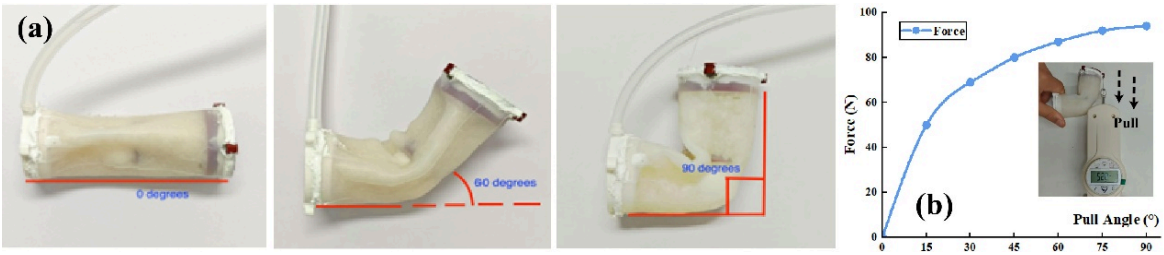

Figure 6. The variable stiffness structure and its jamming state. (a) Schematic diagram of variable stiffness bending locking; (b) data of locking force of variable stiffness structure under vacuum pressure

4.3. Platform construction of robotic arm motion performance test experiment

I built a scaffolding for mounting and hanging the robotic arm, as shown in Fig. 7(a). I then constructed a completed pneumatic drive circuit with more than a dozen individual air pumps and delivery lines arranged centrally to enhance the convenience of the system (see Fig. 7(b)). I began our experiments by demonstrating the three-dimensional bending capability of the bionic elephant trunk robot. I filled one side of the bellows with positive air pressure, as shown in Fig. 7(c), and the experimental test obtained that the maximum bending angle of the bionic elephant trunk can exceed 90 degrees. This can meet the needs of most handling tasks.

In addition, I verified the carrying capacity of the elephant trunk. In the experiment, the end of the trunk carries weights with a total mass of more than 300 g, and completes the rotation and circling motion in three-dimensional space under the load-carrying state, as shown in Fig. 7(d).

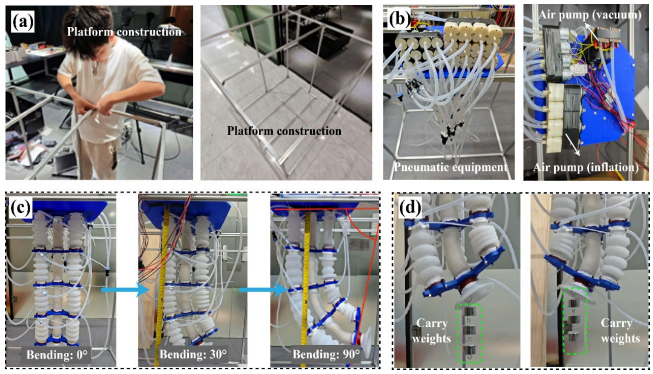

Figure 7. Experimental platform construction and motion performance demonstration. (a) Building a scaffold; (b) Building a pneumatic circuit; (c) Bending motion test; (d) 3D Bending effect after carrying a heavy object

4.4. Grasping, transport, and release experiments

Grasping and handling experiments were conducted to verify the operational capabilities of the bionic elephant trunk robot in real-world applications. In the experimental tests, the robot performed grasping, transporting and releasing operations on two square boxes (weighing 197 g and 498 g, respectively). The test method is: the end flexible suction cup of the robot first comes in contact with the target object and establishes stable adsorption, and then rotated and translated in three-

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dimensional space through the multi-degree-of-freedom drive. The objects were then transported to a specified position. The experimental results show that the robot exhibits stable adsorption in a series of processes such as grasping and transporting, reflecting excellent adaptability. Its strong transport ability is not only suitable for material handling in industrial production, but also has the potential to provide auxiliary operation for the disabled in daily life.

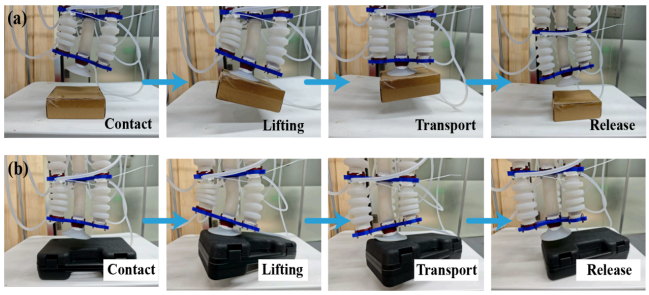

Figure 8. Demonstration experiment on lifting, transporting and releasing of a bionic elephant trunk robot

5. Conclusion and future work

The elephant trunk structure demonstrates unique advantages for manoeuvring and grasping tasks in complex environments due to its flexibility and high degree of freedom. However, the ability to experiment similarly compared three-dimensional pliable motion and stiffness adjustment puts higher demands on the robotic system. My research was heavily inspired by bionics, particularly the adaptability and flexibility of an elephant's trunk to develop a soft robot. The robot is made up of 3 key innovations: a soft body construction for safe human interaction, modularity for easy assembly and repair, and a variable stiffness mechanism to enhance load bearing capacity. The system introduces a variable stiffness mechanism based on skeleton-particle coupling that enables structural stiffening under external loading. In the end-effector topic, the bionic elephant trunk robot inherits a suction cup with adsorption capabilities.

Before developing this robot, I had to learn the SOLIDWORKS and KEYSHOT modeling softwares. For SOLIDWORKS, I followed tutorials on youtube and practiced designing little parts and gimmicks before I felt ready to start my formal robot designing. For manufacturing, I explored how to use a 3D printer as well as the process of making a soft robot using the silicone injection molding method. This process involved 3D printing molds, preparing the silicone mixture, and then carefully demolding the cured components after a period of time to avoid defects. I also further made rigid structural parts, such as connection plates and caps. To validate and test the robot's performance, I conducted multiple experiments assessing the bending range, load capacity, and grasping versatility. The variable stiffness mechanism worked well, and greatly increased the payload capacity from when compared without it.

I have the following insights and experiences from this work. Firstly, the manufacturing process of the modular soft robotic arm presented several difficulties, particularly in electrical integration and silicone fabrication. One major challenge was the complex wiring and the programming required for the buttons and control system on the Arduino. Soldering connections was also tedious, and the wires often became a tangled mess, which increased my risk of connecting the wrong wire and resulting in a short circuit. Another significant hurdle was the silicone injection molding process. While this method allowed for flexible and durable soft actuator segments, imperfections such as air bubbles, uneven curing or tearing during demolding occasionally led to defective and

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unusable parts due to structural integrity. Sometimes, the defects were more severe and required recasting which wasted valuable time and materials. The variable stiffness mechanism, while very effective, required a long time to put together, as the soft silicone membrane on the outside was hard to align and hold its shape when assembling it.

To enhance the future iterations of the robot, several improvements are planned. Firstly, the end effector design will be changed and improved to either a soft robotic hand with silicone actuators as fingers, or a rigid and stiff claw. Changing to either of these 2 can provide us with massive benefits, such as better grasping, more flexibility, and also having a wider range of uses. Secondly, more powerful and reliable motors will be integrated to address the current issue of insufficient force output, ensuring consistent performance under varying loads. Additionally, modular electrical connectors and less buttons could streamline assembly and reduce clutter, while automated pressure control systems might improve the simplicity of controlling the robot. For the fabrication process, alternative manufacturing techniques, such as 3D-printed molds or direct silicone 3D printing, could minimize defects and improve consistency. Furthermore, integrating self-healing materials or reinforced silicone blends may enhance durability, reducing the likelihood of damage during operation. These refinements aim to optimize both functionality and manufacturability, making the soft robotic arm more robust and adaptable for real-world applications.

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