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Adaptive Soft Pneumatic Robot Inspired by Locomotion of Snake

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Abstract— Pneumatic soft robots have garnered widespread attention for their flexibility and adaptability in various applications. However, existing soft robots generally struggle to effectively navigate diverse terrains, especially when it comes to climbing obstacles. This paper introduces an adaptive pneumatic soft robot designed based on snake-like locomotion, which effectively addresses this issue. The robot utilizes four corrugated tubes as its soft actuators, complemented by silicone-made feet with bidirectional friction anisotropy, enabling it to adapt to various terrains and exhibit climbing capabilities. Experiments demonstrate that the robot can traverse different surfaces such as sand, gravel, and slopes, and can climb obstacles up to 20 centimeters high. Additionally, it features a self-regulation mechanism that allows it to recover from accidental overturns. This study presents a soft robot design with multi-terrain adaptability and self-recovery capabilities.

I. Introduction

In recent decades, soft robots have garnered significant interest due to their elasticity, enabling them to adapt to various environments without complex mechanisms [1] [2] [3]. These robots leverage soft materials and biomimetic designs to perform functions rigid robots struggle with, such as navigating confined spaces or traversing uneven terrain [2]. The flexibility and adaptability of soft robots allow them to change their shape and movement strategies, similar to deformable tentacles of octopus [4], to handle a broader range of tasks, obstacles, and environmental conditions. However, despite these advantages, many existing pneumatic soft robots face challenges in effectively traversing diverse terrains [5]. Traditional design often lack the multifunctionality needed to handle different terrains [6], such as a multifunctional soft stackable robots made from modular pneumatic artificial muscles by netting-rolling-splicing can move by crawling, rolling and pipe climbing [7], but they cannot traverse terrains with steps. This limitation has driven research towards more adaptive and multifunctional soft robots to overcome these terrains.

Snakes exhibit remarkable diversity in their movement, changing their body shape and utilizing lateral undulation, concertina, sidewinding, and rectilinear motions to generate propulsion and glide through various environments in nature [8] [9] [10]. One of the earliest snake-like robot designs by investigating snake biomechanics was proposed in 1971 [11], and subsequently, it has been deployed in numerous fields, such as the modular snake robot ACM-R5, for inspection and rescue tasks in complex and confined environments [12]. Similarly, inspired by snake locomotion, we developed an adaptive pneumatic soft robot capable of moving across various terrains. The emergence of numerous artificial actuators has enabled soft robots to exhibit diverse modes of movement [13] [14]. By mimicking snake locomotion with artificial soft actuators, our robot achieves enhanced mobility and adaptability: it utilizes the concertina locomotion strategy for straight-line movement and turning, and the sidewinding locomotion strategy for propulsion on 5 cm thick sandy terrains. This design improves its mobility performance on flat surfaces, 20-degree inclines, obstacle courses with 12 cm gaps, and gravel terrains.

Although snake-like robots demonstrate effectiveness in specific environments, they often face challenges in navigating highly complex or irregu-

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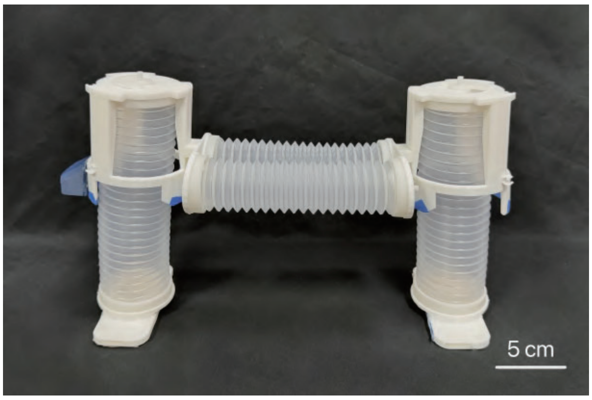


Fig. 1: Adaptive soft pneumatic robot inspired by snake locomotion in this work.

lar terrains, such as difficulties in surmounting high obstacles [15] [16]. To overcome these limitations, we introduced a novel morphological design that transcends the conventional snake-like structure. The proposed pneumatic-driven robot consists of four corrugated tubes, offering superior extensibility and resilience [17] [18], and two silicone-based, bidirectional friction footpads. This design achieves climbing via extending two longitudinal corrugated tubes, enabling the robot to climb stairs up to 20 cm high (twice its body height). Additionally, the robot features a self-righting mechanism, enabling it to recover from falls, which is crucial for autonomous operations in unpredictable environments. This design has been practically validated, as our robot won first place in the 2024 RoboSoft Soft Robot Locomotion Competition and was selected as the Best Manipulator Award winner. These results highlight the potential of our robot for applications in complex terrains.

This paper is organized as follows. Section II introduces the design and characterization of the robot. Three different gait cycle model of the robot are analyzed in Section III. Section IV demonstrates the locomotion performance of the robot on different surfaces and obstacles.

II. Design and Characterization

A. Soft Actuator

To realize high adaptability both radially and axially in the body of the robot, we utilized readily available corrugated tubes, enhanced with resin-printed parts, to create soft pneumatically actuated chambers, as shown in Figure 1 with the four corrugated tube actuators. The corrugated geometry increases extensibility and reduces bending resistance compared with tubes without it, significantly improving the flexibility of the robot and fulfilling more complex movement strategies.

To investigate the response of this bellows-type soft actuator under different pressures, compression tests are conducted by a tensile testing machine (MTS, C42, LSB.500), as shown in Figure 2. The experimental results showed linear behavior of 1.6k N/m and 2.6k N/m stiffness coefficients for 1.01 kPa and 1.60 kPa pressurized actuators, respectively. Different mechanical performances can be achieved by controlling the internal pressure of the soft actuator for robots.

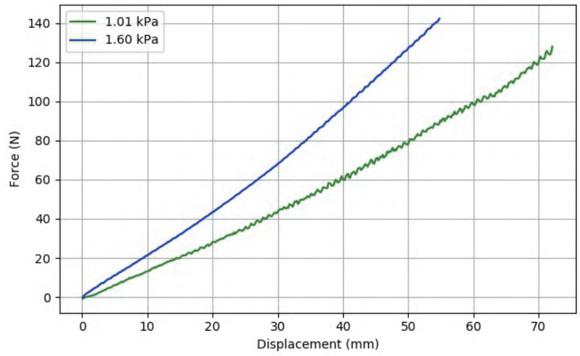


Fig. 2: Experimental results of the soft actuator driven by different pressures under compression tests.

B. Silicone Footpad

We designed a footpad structure with bidirectional friction anisotropy at the bottom of the robot (the robot's foot in Figure 1) to assist its movement. As shown in Figure 3, the high friction areas are made of silicone, while the low friction areas are made of ordinary 3D-printed PLA material. By controlling the extension and retraction of the actuator, silicone and PLA respectively contact with the ground axially. In cases of stair climbing, the radial flexibility of the corrugated tubes allows the footpad to tilt. The tilt direction determines the magnitude and direction of the frictional forces. Figure 4 exhibited great anisotropy between silicone of 1.25 and PLA of 0.24 friction coefficients with a customized experimental setup for the foot structure.

C. Four-Channel Robot Design

The robot body consists of four bellows. Two thinner bellows are arranged in parallel to form the waist, allowing it to flexibly bend left and

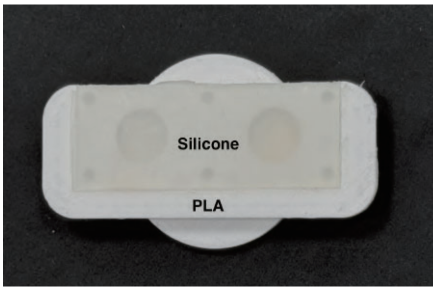


Fig. 3: Bottom view of the silicone footpad.

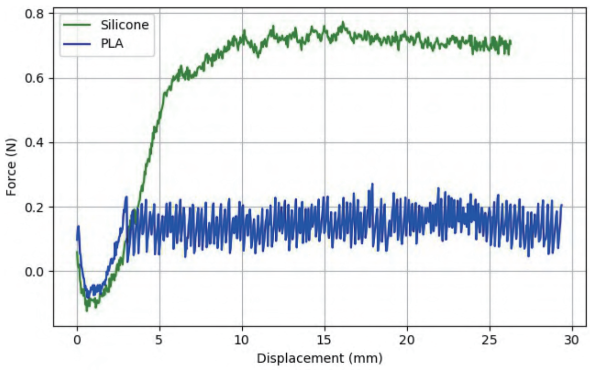


Fig. 4: Friction coefficient tests for silicone and PLA materials of the footpad on a wooden board.

right, while the other two thicker bellows are vertically aligned as the head and tail, each of which connects with a silicone footpad at the lower end. In their normal state, these footpads are either retracted within the body or slightly extended. When climbing step obstacles, they inflate and extend to lift the robot. The robot's head is designed with a small protrusion to aid in climbing.

Moreover, all components are designed to be detachable with rotary buckles, which significantly improves assembly and repair efficiency. Except for the soft actuators, all other components are 3D printed from PLA to lower the fabrication cost and simplify the manufacturing process.

D. Pneumatic Control System

We adopted the Arduino Uno as the control board for the robot and used a PLC amplifier to manage the control of the solenoid valves. The entire pneumatic control system includes 8 solenoid valves, which are divided into two groups. Each group of four valves is fixed on a manifold, connected to the inflation and deflation ends of the air pump, respectively. By connecting the air paths controlled by the solenoid valves on different manifolds, we created four air channels controlling the inflation and deflation of four bellows.

To facilitate easier control of the robot's posture, we also integrated a PS2 remote control module, enabling remote control of the robot's four actuators. Human operators can use this remote control system to arbitrarily operate the robot's four soft actuators, improving the robot's flexibility and adaptability and enhancing its capability to operate in complex environments.

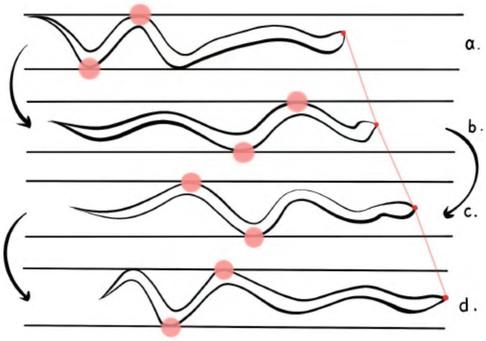
III. Gait Analysis

A. Concertina

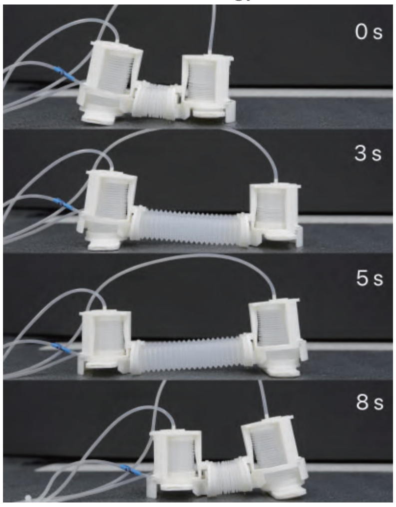
The concertina motion is a common locomotion strategy of snakes to generate forward motion through periodic contractions and relaxations. It first compresses the front part of its body into a wave peak, then pushes this peak forward while pulling the rear part forward [19]. This strategy allows the snake to move through narrow and complex environments, as shown in Figure 5a. In our robot, the silicone footpad on the front and rear produce these snake-like wave peaks. as shown in Figure 5b, by slightly inflating the actuator at the tail in A, the silicone footpad extends from the body, serving as the wave peak in the accordion gait, pushing the robot forward in B. In C, the actuators at the head and tail of the robot are respectively inflated and deflated, with the silicone footpad at the head extending from the body to act as the wave peak, pulling the robot forward in D. When turning is required, the robot can steer its body towards the shorter side by creating a length difference between the two parallel corrugated tubes.

B. Sidewinding

Sidewinding is a specialized snake locomotion method commonly observed in deserts and other soft or low-friction environments [20]. This gait involves the snake's body moving sideways, leaving parallel tracks on the ground. Unlike other movements, sidewinding reduces the contact area between the body and the ground, thus minimizing efficiently on soft terrain [19]. As shown in Figure 6a, in sidewinding locomotion, the snake's body forms several curved wave peaks, each sequentially contacting the ground and propelling the snake forward. Our robot mimics this sidewinding motion on sand by alternately inflating and deflating the corrugated tubes to create alternating wave peaks and valleys, propelling the robot move forward, as illustrated in Figure 6b.



(a) Schematic diagram of the snake's concertina locomotion strategy.



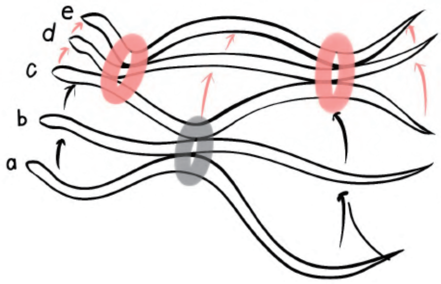
(b) Illustration of the forward locomotion gait cycle of the robot inspired by concertina locomotion.

Fig. 5: The robot biomimicing the concertina motion of a snake while moving forward.

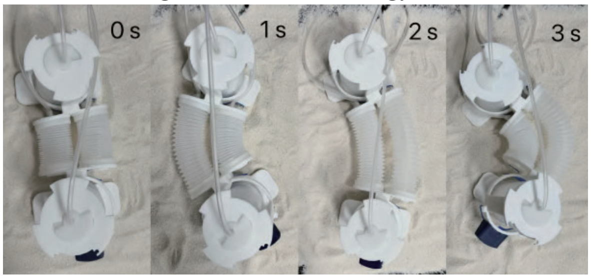
C. Elevation

Due to the design of the two longitudinal bellows located at the head and tail, the robot can function beyond the typical snake-like locomotion mode. As shown in figure7, the two longitudinal bellows can extend upward and lift the robot 20 centimeters from its initial position, which endows the robot with a climbing ability to overcome obstacles up to 20 centimeters in height. In addition to its capability for planar movement, the robot's enhanced ability to navigate more complex and uneven terrains significantly improves its adaptability in challenging environments.

Figure 8 presents a simulation in Matlab where the robot approaches and climbs a step obstacle. In the simulation, the robot first adopts an accordion gait to approach the step obstacle, then extends its longitudinal bellows to lift itself up. Utilizing the structure of its head, the robot climbs onto the step, continues to use the accordion gait until the tail reaches the step, and ultimately the entire robot ascends the step.



(a) Schematic diagram of the snake's sidewinding locomotion strategy.



(b) Gait cycle illustration of the robot mimicking the sidewinding locomotion.

Fig. 6: The robot biomimicing the snake's sidewinding gait on sandy terrain.

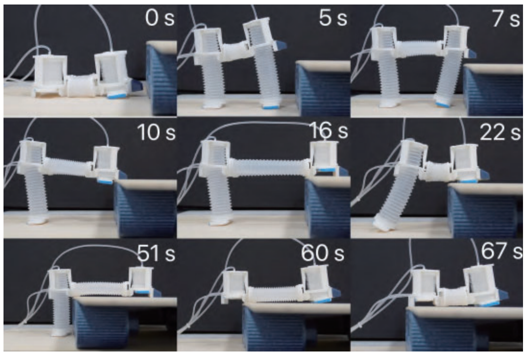


Fig. 7: The process of climbing obstacle.

IV. Experiment

We tested the robot's performance in real-world scenarios, including crawling on wooden slopes, free turning, moving on various surfaces, and self-righting after a fall. The robot successfully completed these operations autonomously or under human control.

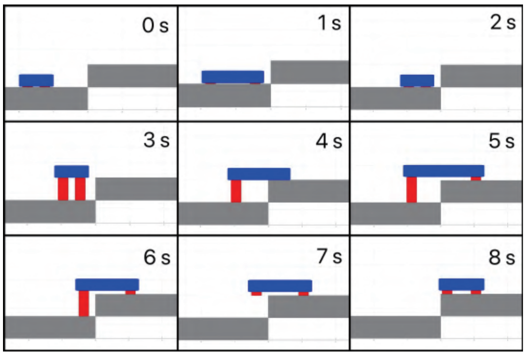


Fig. 8: Matlab simulation of elevation gait.

A. Slope Navigation

Our robot can navigate slopes of up to 20 degrees using a snake-like concertina gait. The friction force provided by the silicone footpads and great frictional anisotropy between silicone and PLA allow it to move on slopes as long as the front and rear footpads do not simultaneously detach from the body, as this would cause accidental sliding down the slope.

B. Turning

As discussed before, the radial flexibility of the two parallel corrugated tubes on wrist allows bending by creating a length difference between them. This feature, combined with the snake-like concertina gait, enables the robot to turn. As shown in Figure 9, step A, the robot extends the rear footpad while retracting the front footpad and elongates the right actuator. In step B, the robot retracts the extended rear footpad and extends the front footpad to reach position C. By repeating this process, the robot can achieve a desired turning angle.

C. Running over a variety of surfaces

We tested the robot on various surfaces, as shown in Figure 10. The robot successfully navigated gravel, sand, sponge, and uneven boards. On complex surfaces like gravel, the robot in autonomous locomotion successfully avoids accidental stuck through remote control intervention from a human operator and proceeds to move.

D. Self-Righting

When navigating complex surfaces, tipping over is inevitable. Our robot has a self-righting capability to cope with this situation. As shown in Figure 11, the robot is tipped over in position A and extends the actuators of both feet at their

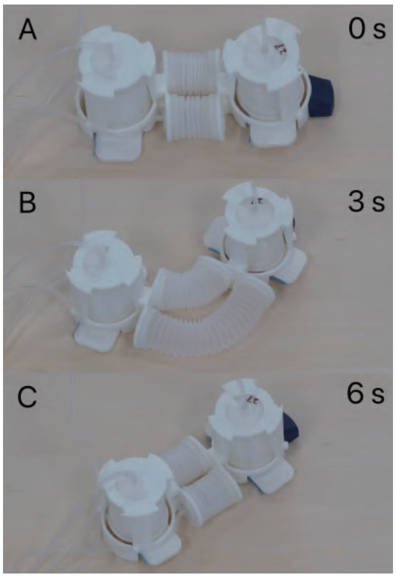


Fig. 9: The robot turning on a wooden board.

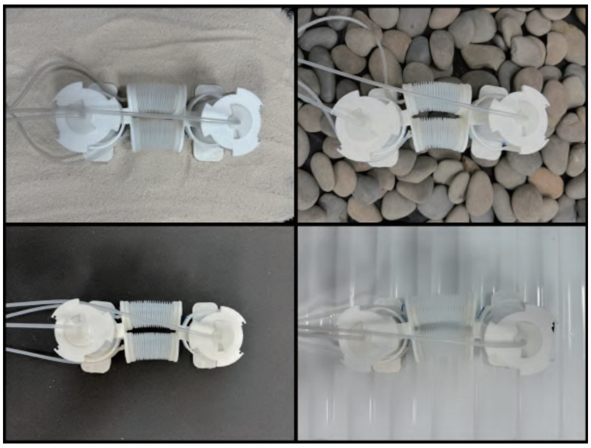


Fig. 10: The robot turning on a wooden board. The robot moving on different surfaces.

maximum length. In position B, the robot extends the actuator underneath its waist, lifting itself to a certain angle. Then,the robot retracts the actuators of both feet to their shortest length in position C, landing on its footpads. Finally, the robot returns to its initial state. This feature showcases the robot's strong self-adjustment ability, ensuring its recovery in complex terrains.

V. Conclusions

The bio-inspired adaptive pneumatic soft robot designed in this study demonstrates significant advancements in multi-terrain adaptability and mobility. By utilizing corrugated tubes and silicone footpads, the robot effectively mimics various snake locomotion gaits in planar motion, such as

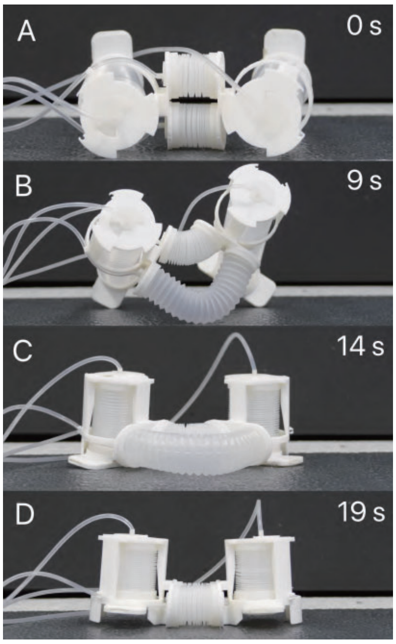


Fig. 11: The robot's self-righting after tipping over.

concertina and sidewinding, and can also move spatially to overcome obstacles. Demonstrations successfully validated the robot's abilities in navigating complex terrains, climbing obstacles, and self-righting, showcasing its potential applications in search and rescue and environmental monitoring. The innovative design and successful implementation highlight the promising future of the proposed robot in challenging and unpredictable environments.

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