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Multi-material 3D printing of caterpillar-inspired soft crawling robots with the pneumatically bellow-type body and anisotropic friction feet

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ABSTRACT

Due to large shape-changing ability and high adaptability, soft crawling robots become a promising candidate in applications with unpredictable terrain and complex environments. However, designing and fabricating of soft crawling robots with hybrid soft and rigid components are still elusive. Here, we present a novel caterpillar inspired pneumatically-driven soft crawling robot, which can be directly 3D printed with multiple materials and without complex assembling process. To mimic the biological structure and morphological locomotion of caterpillars, we design the soft crawling robot with a pneumatically driven bellow-type body, 12 anisotropic frictional feet, and two end caps, and introduce a passive synergy locomotion model between the crawling robot's body and feet. By selecting different cross-section shape of the feet, we characterize the moving performance of soft crawling robots. Finally, we integrate a pneumatic closed-loop control system to drive the soft crawling robots with a periodic gait and demonstrate their motion capability in a curve plastic tube.

1. Introduction

Animals can take advantages of their flexible bodies and anisotropic frictional feet or skin to efficiently move in various environments [1–5]. For example, caterpillars utilize the anterograde wave of dorsal deformation and the controllable prolegs and thoracic legs to propel themselves moving unidirectional [6,7]. Mimicking biological structures has recently inspired rich development of soft crawling robots [8–11].

Among the reported developments, we can find that the combination of a stretchable body and anisotropic frictional feet or skin plays a significant role in the locomotion of crawling robots [10–15]. Therefore, one of the key issues in soft crawling robots is to design and control the synergy between the deformation of the body and directional friction of feet to achieve desired behaviors and functionalities (e.g., locomotion), which can be roughly classified into two categories. The first category is to active control the body and feet independently. Through a synergy control strategy, the robot can achieve a directional locomotion such as presented in [16]. The other category is to design a passive coupled mechanism of body deformation and directional friction force of feet or skin. In this case, only one actuation source without complex control strategy can enable the robot to crawl efficiently as reported in [11,15].

On the other hand, it is still a challenge to fabricate the soft crawling robots with multiple components effectively and simply. Casting techniques are the most common way to fabricate the soft robots by replica molding process [17–19]. However, this approach may be laboriously intensive and limited by manual fabrication of hybrid soft and rigid materials. Alternatively, additive manufacturing (also termed as 3D printing) has drawn much attention for rapid fabrication of soft robotic systems, including combustion-powered jumpers, multilegged robots and stiffness-tunable actuators [20–25]. Recently, shape-memory alloy and motor tendons actuated 3D printed soft crawling robots have been developed and show a significant advantage in the simple and fast fabrication [8,14,15,26]. However, the pneumatically-driven 3D printed soft crawling robots has not been demonstrated.

In this paper, we develop a novel caterpillar inspired pneumatically-driven soft crawling robot, which can be directly 3D printed without complex assemble process. The soft crawling robot is composed of a pneumatic bellow-type body, 12 anisotropic frictional feet, and two end caps. To further mimic the morphological locomotion of caterpillars, we introduce a pas-

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sive synergy locomotion model between the crawling robot's body and feet. By selecting different cross-section shape of the feet, we characterize the moving performance of soft crawling robots. Finally, we integrate a pneumatic closed-loop control system to drive the triangular shape feet robot with a periodic gait and demonstrate the excellent motion capability in a curve plastic tube.

The remainder of this paper is organized as follows. Section 2 presents the design and fabrication of the soft crawling robot based on the morphological locomotion of the caterpillar. Section 3 characterize the motion of the robots with different structural feet. The closed-loop control system and demonstration of its adaptive moving ability are detailed in Section 4. Finally, conclusions are drawn in Section 5.

2. Design and fabrication of the soft crawling robot

2.1. Bioinspiration from the caterpillar

The crawling locomotion of caterpillars has provided rich inspiration in the development of crawling robots due to the advantageous of the low complexity and energetically efficient. Caterpillars consist of a soft cylindrical body, a pair of stiff-jointed thoracic leg, 2–5 pairs of prolegs and a pair of terminal proleg [27] (Fig. 1(A)). It is capable of moving forward through the anterograde wave of dorsal deformation and alternate controlled feet. In the crawling gaits (shown in Fig. 1(B)), the gut of the caterpillar shortens and slides forward during the terminal prolegs' swing phase, resulting in a shift forward of the animal's center of mass (CoM). In this sense, both legs of each pair in the bottom of the body are lifted simultaneously to move forward. When it comes to the end of the terminal prolegs' swing phase (phase 4 in Fig. 1(B)), the gut of the caterpillar extends and keeps sliding forward with legs of each pair in the front of the body lifted simultaneously [26]. Thus, the caterpillar can achieve a forward gait. By mimicking the structure and the crawling locomotion of the caterpillar, we present a design and fabrication method for a novel soft crawling robot, which will be detailed in the following.

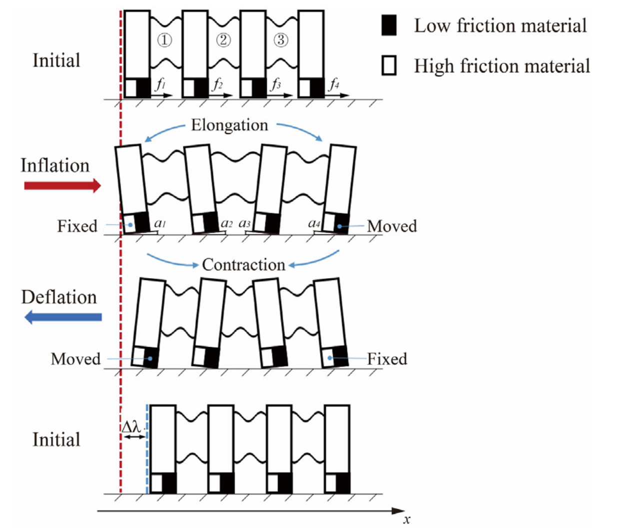

Fig. 2. Passive synergy locomotion model of the soft crawling robot.

2.2. Bioinspired passive synergy locomotion model of the soft crawling robot

Based on the crawling locomotion of the caterpillar, a pneumatically driven crawling locomotion model is developed with a passive synergy control strategy between the body and anisotropic friction feet (shown in Fig. 2). The soft body is made of a pneumatical actuator that elongates or contracts along the axial direction when inflated or deflated. Due to the contact with the substrate of the feet, there is an additional constraint to prevent the elongation (when inflated) or contraction (when inflated) of the body actuator in the bottom interface. Thus, a symmetric bending deformation will occur during the inflation or deflation process. However, the symmetric bending and elongating coupled deformation results in equal movements in both ends. Therefore, it cannot move forward on the substrate. To address this issue, anisotropic friction feet are introduced.

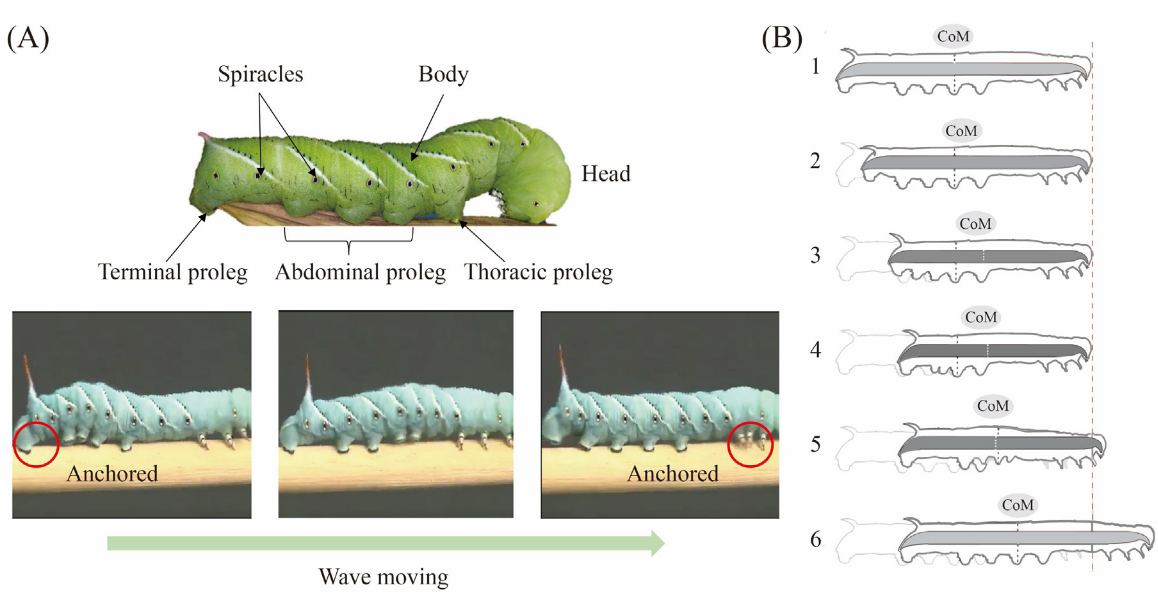

Fig. 1. The biological structure and crawling mechanism of caterpillars. (A) Pictures about main structure and locomotion of a caterpillar. (B). The light outline is the initial position of each crawling step and the black dashed line represents the final position of this step (the picture is adapted from [27]). Each crawling gait consists of 6 steps with the center of mass (CoM) moving forward continuously.

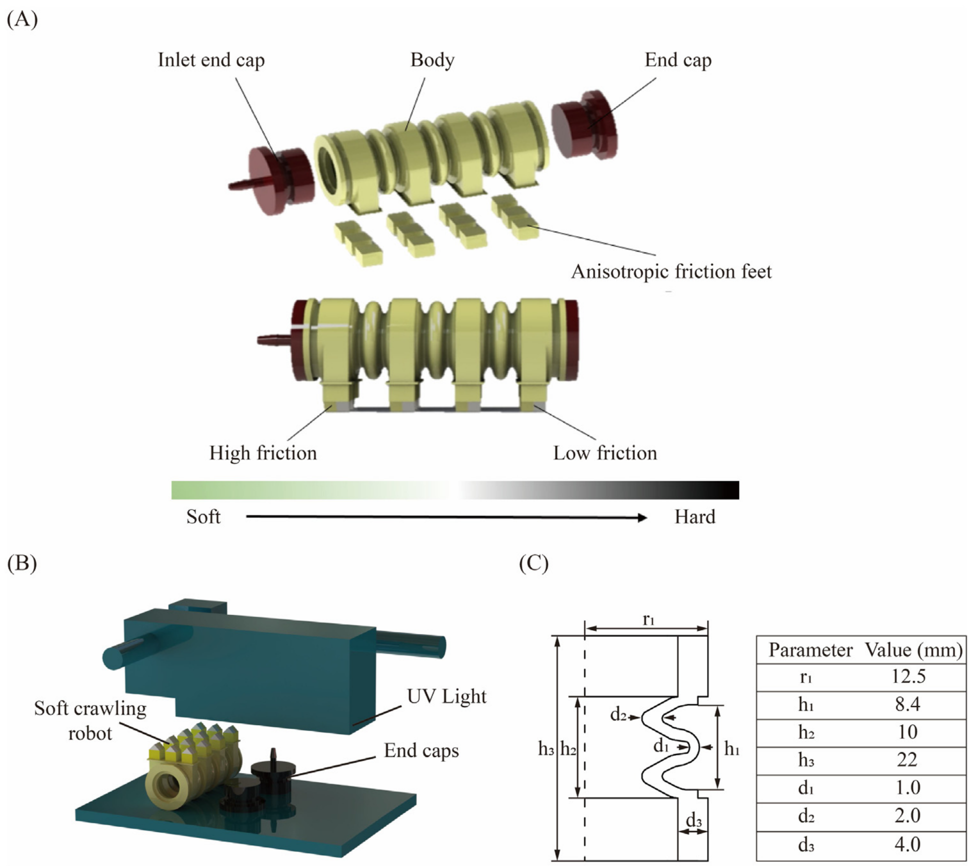

Fig. 3. Prototype of the soft crawling robot fabricated by hybrid multi-material 3D printing. (A) Computer-aided design (CAD) model of the soft crawling robot, consisting of the body, anisotropic friction feet and two end caps. (B) Schematic illustration of fabricating three parts of the soft crawling robot on a commercial Polyjet multi-material 3D printer. (C) Half vertical cross-section of a single bellow-type chamber in deflated state. The vertical dashed line represents the center line of the bellow-type actuator. Parameter values are on the right of (C).

To analyze the locomotion of the soft crawling robot, we present a kinematic model with two parameters for the robot locomotion. The first one is the displacement on the moving direction (x) and the other is the bending angle with vertical axis (α). We define the friction of feet as f_i (i = 1, 2, 3, 4). Thus, the joint space and configuration space can be described as $q_i = [x_i, \alpha_i]^T$ and $C(x, \alpha) = \left[q_1^T, q_2^T, q_3^T, q_4^T\right]^T$ respectively. Three bellow-type segments are denoted as ①, ②, ③. According to the symmetry of the structure, we can obtain that$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 0$. As shown in the Fig. 2, in the initial static phase, each segment doesn't bend and elongate and bending angle of each feet is equal to zero ($\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$). When the robot is inflated, at the beginning of this phase, all feet remain motionless because the driven force is smaller than the maximum static friction. However, each segment has occurred coupled bending and elongating deformation. Although there is no displacement on the moving direction, feet begin to bend symmetrically (α_1, $\alpha_2 < 0$, α_3, $\alpha_4 > 0$). As the supplied pressure increases, there is a transition of the contact material for the feet. The back feet are using high friction part to contact with the substrate and the front feet are using low friction part to contact with the substrate. When the driven force reaches the value of the maximum static friction, the front feet start sliding forward and the back feet are still anchored on the substrate. In the deflation process, the crawling robot will bend in the reverse direction. Before the bending angle of front feet reaches zero, the back feet remain anchored on the substrate and the front feet can still slide on the substrate. Meanwhile, the robot will slide back for a short distance. As the $\alpha_4 < 0$, the bellow-type body will continue to shorten while the contact state of the front feet and the back feet will change. The front feet will anchor the substrate and the back feet will slide forward until all bending angles come to the initial state ($\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$). As a result, an inflation and deflation cycle produces the moving forward gait of the soft crawling robot. Through this periodically gait, the robot can keep moving forward.

2.3. Structure design and fabrication of the soft crawling robot

According to the above proposed locomotion model, we design and fabricate the pneumatically-driven soft crawling robot with multiple materials (Fig. 3(A)). The robot comprises a hollow, cylinder bellow-type actuator as the deformable body, 12 multi-material feet, and two caps assembled at both ends serving as air inlet and seal connectors, respectively. We generate the geometry of the robot using computer-aided design (CAD) software and directly print it using a commercial Polyjet 3D printer (Fig. 3(B)).

Commercial materials that are available for the Polyjet 3D printer (J750, Stratasys Ltd., USA) include a stretchable, translucent photopolymer (Agilus 30 Clr); a series of rigid opaque material which owns the same physical properties but only different with color (e.g. VeroBlackPlus, VeroPureWhite, VeroMagenta, etc); and a soluble, low-yield polymer (SUP706B) as the support material (Stratasys Ltd., USA). Published data sheets show that the material hardness used in the fabrication of the robot ranges the from 30A to 86D. We also perform tensile experiments of the Agilus material on a materials testing machine (Model Z0020, ZwickRoell, Germany). As shown in Fig. 4(A), the stretchable resin is capable to sustain 140 % strain which is equal to the reported data [29]. Besides, from the result shown in the Fig. 4(B), we can see that there is a sig-

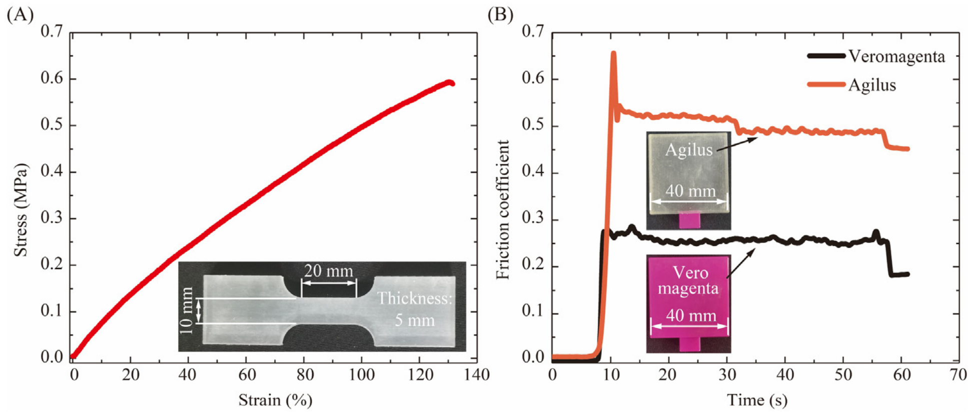

Fig. 4. Characterization on the mechanical properties of the printing materials used in the soft crawling robot. (A) Stress of specimens located on the bottom right is plotted as a function of strain. (B) Friction coefficient of two kinds of materials (Agilus and Vero magenta, Stratasys Ltd., USA) are measured on a cloth substrate. Note that, for the Vero series material such as Veromagenta, Veropurewhite, and Veroblack, they have almost same friction properties but only different with color. So we only test the specimen of Veromagenta to represent the Vero series.

nificant difference in friction property between these two kinds of materials (Agilus and Veromagenta). The Agilus material owns a higher friction coefficient than the Vero series materials. Notably, the experimental results demonstrate that the kinetic friction of the Veromagenta specimen fluctuates and is occasionally higher than the static friction, possibly due to the uneven substrate and the sensor noise from the environment.

From the result about tensile experiments, we can see that the Agilus material is inappropriate to sustain a large deformation. Thus, we select to design the bellow-type actuator as its deformable body. Based on the numerical shape optimization results of the 3D printed bellow-type actuator with Agilus material [28], we increase the thickness of the valley and decrease the thickness of the peak to obtain a better strain minimization performance. This non-uniform thickness design can contribute to a uniform stress distribution and significantly improve the fatigue life. We proportionally scale the thickness parameters of the bellow-type actuator according to the optimized parameters reported in [28]. The dimension parameters and their values are shown in Fig. 3(C). Due to the difference in friction property of used materials, we can design anisotropic frictional robot feet. Each foot consists of two parallel laminated photopolymer layers (VeroPureWhite layer and Agilus 30 Clr layer, thickness, 3 mm). These two kinds of materials have different frictional properties when sliding on the same substrate.

2.4. Fabrication of the soft crawling robot

It is noted that all parts of the robot can be integratedly printed including the bellow-type body, anisotropic feet (including hybrid soft and rigid components), and end caps (including inlet end cap and end cap). In this sense, it will introduce a challenge to remove the support materials from the bellow-type body through the narrow air inlet. Therefore, we make a compromise in the current work by printing these parts independently and assembling them together with the interference fitting (Fig. 3(B)). This kind of fabrication method can effectively obviate the need for complex molding techniques and assembly. It is important to thoroughly remove the support materials in the inner chamber, which generally limits the deformation of the bellow-type actuator. To remove the support materials, we first manually clean most of the support material located in the inner and external surface of the printed model. Then, we employ a high-pressure water cleaner to further remove the remainder support materials. Besides, we print all parts with glossy surface in the GrabCAD Print software (version 1.28.16.50383) to further reduce the removal complexity of support materials. The

Table 1
Printing parameters used to fabricate the robot.

Parameter	Value	Unit
Infill percentage	100	%
Primary layer thickness	0.014	mm
Printing temperature	75	°C
Curing method	UV	–
Support material	SUP706B	–

printing parameters (i.e. infill percentage, primary layer thickness, printing temperature) to fabricate the soft crawling robot are set based on the datasheet of the used J750 printer, which are listed in Table 1.

3. Characterization of the soft crawling robot

3.1. Experimental setup

To evaluate the friction performance of different shape of feet, we build an experimental platform to quantify the difference of the directional friction (Fig. 5). The soft crawling robot placed on a cloth flat substrate is pulled by a steeping motor driven stage (SGSP26-200, OptoSigma Inc., Japan) equipped with a 2 lb load cell (LSB205 JR S-Beam Load Cell 2.0, FUTEK Advanced Sensor Technology, Inc., USA) for 55 mm at a constant rate of 1 mm/s. To eliminate the inner force of the connection medium, we use polyethylene thread instead of the rigid rod to connect the robot to the load cell. We adopt the dSPACE-DS1103 control board equipped with 16-bit analog-to-digital converters and 16-bit digital-to-analog converters to control the movement and collect the sensor data. We adjust the height of the force sensor to ensure that the polyethylene thread is horizontal to the substrate. The force data (F) recorded during the uniform motion is used to approximate the sliding friction. An effective coefficient of friction is then calculated from the measured force as

$$\mu = \frac{F}{F_N} \tag{1}$$

where $F_N \approx 0.28\,\mathrm{N}$ is the weight of the soft crawling robot. By changing the direction of the robot, we can measure the friction of the robot feet in both forward ($F_{forward}$) and backward ($F_{backward}$) direction. Thus, different friction coefficients can be calculated as:

$$\mu_{forward} = \frac{F_{forward}}{F_N}, \ \mu_{backward} = \frac{F_{backward}}{F_N} \tag{2}$$

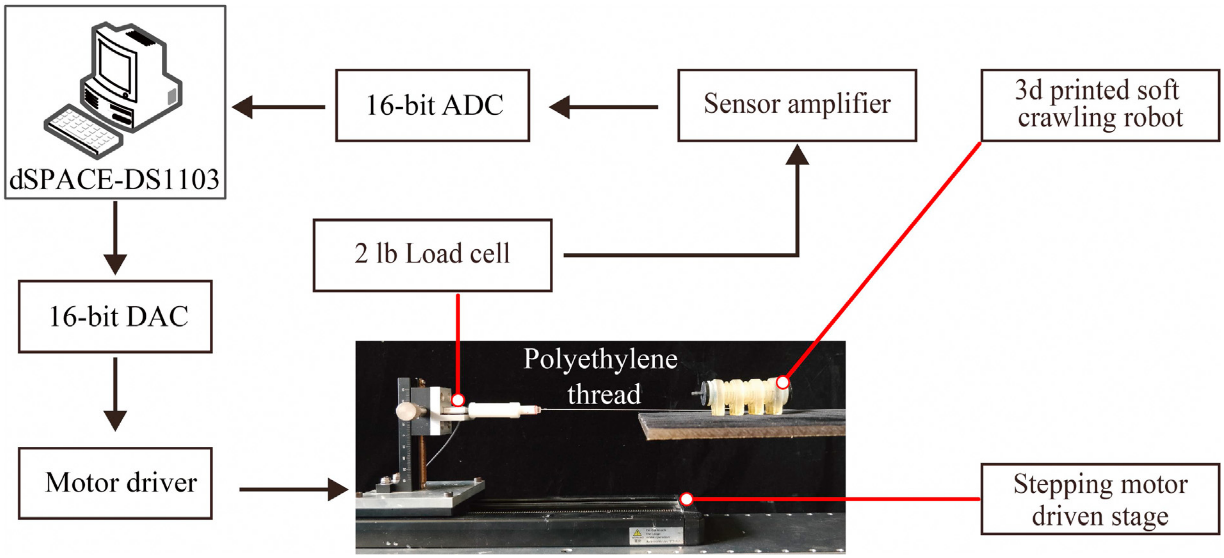

Fig. 5. Experimental setup for the characterization of the anisotropic-friction feet of the soft crawling robot.

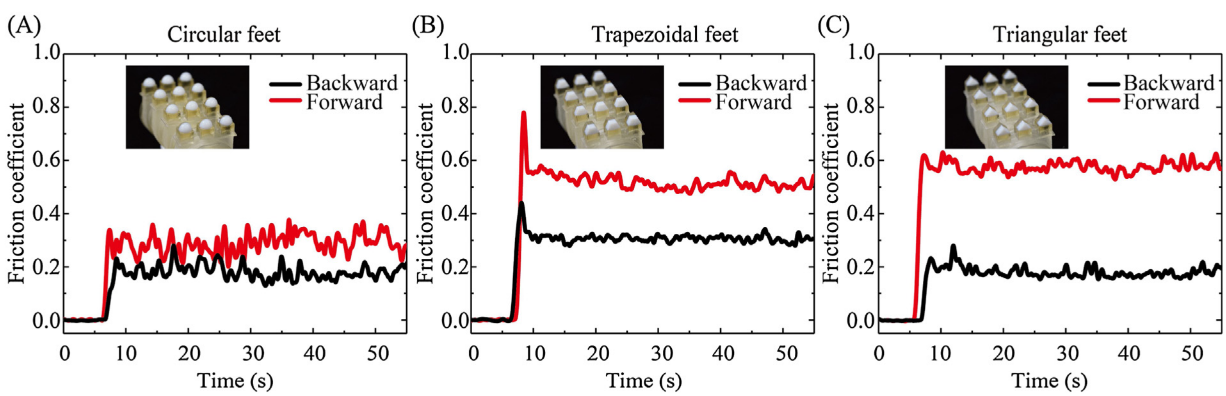

Fig. 6. Effect of the cross-section shapes of robot feet on the anisotropic friction performance. All friction coefficients of three kinds of feet ((A) circular feet, (B) trapezoidal feet, (C) triangular feet) are measured on a cloth substrate in both forward and backward direction.

According to the calculated friction coefficient for both forward and backward direction, we can quantify the efficiency of robot with different cross-section shapes. A larger difference between $\mu_{backward}$ and $\mu_{forward}$ will contribute to a better crawling performance. The results shown in Fig. 6 indicate that the triangular feet have the most superior performance compared to trapezoidal and circular feet.

3.2. Crawling performances of soft crawling robots with different shapes of feet

The anisotropic friction properties of the soft crawling robot consisting of the cross-section shape and material properties of robot feet are the key to the locomotion of the crawling robot. We further conduct a set of experiments to test the crawling performance on a cloth flat substrate. All three crawling robots with different feet are set to autonomously crawl a same length (35 cm) with a periodic gait and we record the time to compare their locomotion velocities. We use a camera to record the experiments and analyze the displacement as well as velocity of the robot using open source software (Kinovea) [30] by selecting the end cap as a marker.

Results in Fig. 6 demonstrate that all three kinds of feet can generate anisotropic friction when autonomously crawling on the substrate. We can see from the results that the robot with triangular cross-section feet shows a superior performance (Fig. 7), which also verify the conclusion that the triangular cross-section shapes of the feet can achieve the largest difference of friction coefficient in forward and backward direction.

4. Autonomous control and applications of the soft crawling robot

4.1. Design of the closed-loop control system for the soft crawling robot

In this section, we develop a customized two-level control system with a low-level feedback controller and high-level planner for the soft crawling robot (Fig. 8(A)). The low-level feedback controller is implemented into a customized control board, consisting of a micro-controller unit (MCU, Arduino Inc., Italy), a pressure sensor (XGZP6847, Cfsensor Co., Ltd, China), a micro pneumatic pump (370-B, Weilici Inc., China) and a two-three-way miniature pneumatic solenoid valve (X-valve, Parker Hannifin Corporation, USA).

In order to provide the power, the micro pneumatic pump and valve should work at the rated voltage of 12 V, we employ a DC power to power the micro pneumatic pump and valve at 12 V and a relay at 5 V. Based on the pressure information, an on-off control algorithm (Fig. 8(B)) implemented in MCU regulates the state of relay to control the state of the valve for inflation or deflation of the pneumatic body of the robot. When the measured pressure is

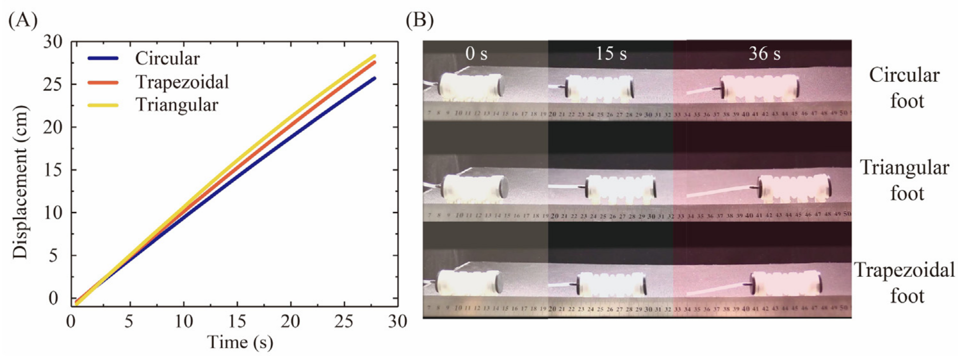

Fig. 7. Crawling results of soft crawling robot with different kinds of feet crawling on a cloth substrate. (A) Displacement is plotted as a function versus time. (B) Still image of the crawling process.

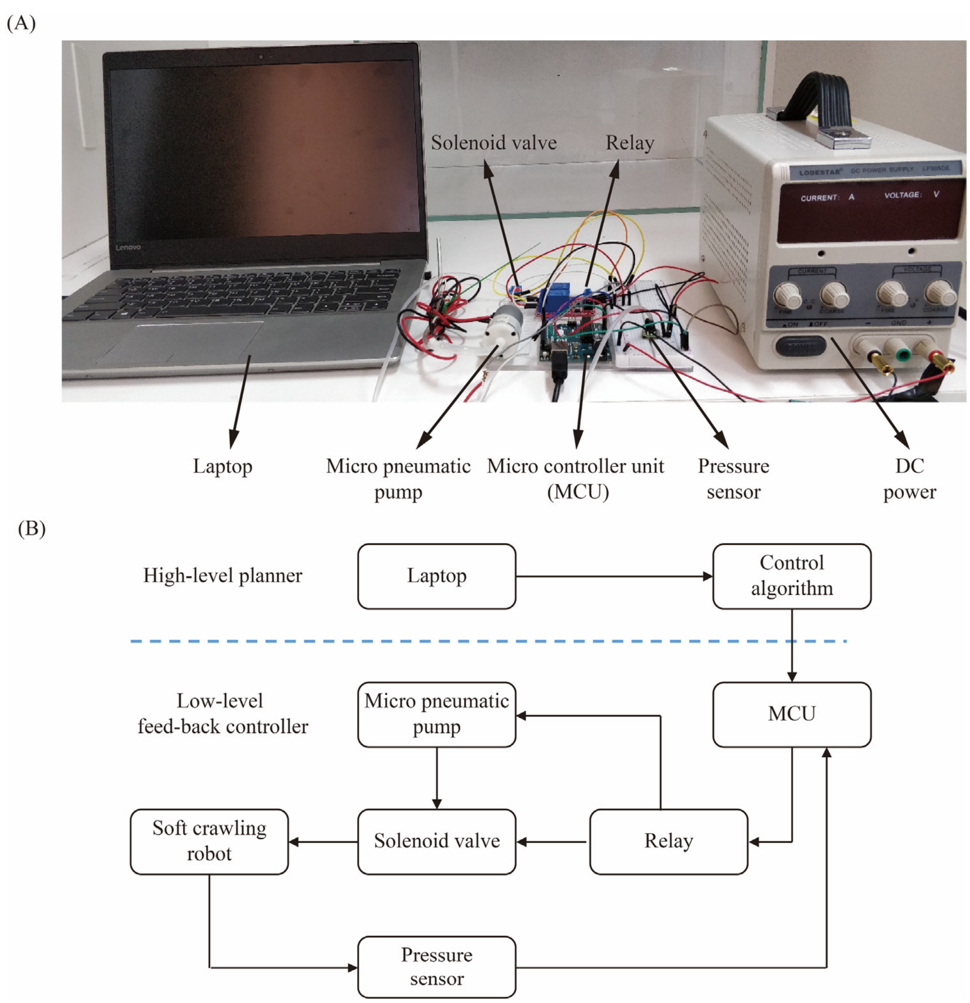

Fig. 8. The closed-loop control system of the soft crawling robot. (A) Image of the pneumatic control system. (B) The diagram of the closed-loop control system.

lower than the pre-defined minimum threshold P_{min} (i.e., 1 kPa), the algorithm controls the state of relay to inflate the body actuator. It should be note that we choose P_{min} as 1 kPa rather than 0 kPa to eliminate the zero drift effect of the pressure sensor for the feedback control. On the other hand, the algorithm controls the state of relay to deflate the pneumatic body of the robot when the measured pressure is higher than the pre-defined maximum pressure P_{max} (i.e., 50 kPa).

4.2. *Crawling application in a curve plastic tube*

Next, we demonstrate a potential application of our soft crawling robot in a curve plastic tube (Fig. 9). The experimental results demonstrate that our soft crawling robot can successfully go through the curve tube (with the length of 25 cm) within 190 s.

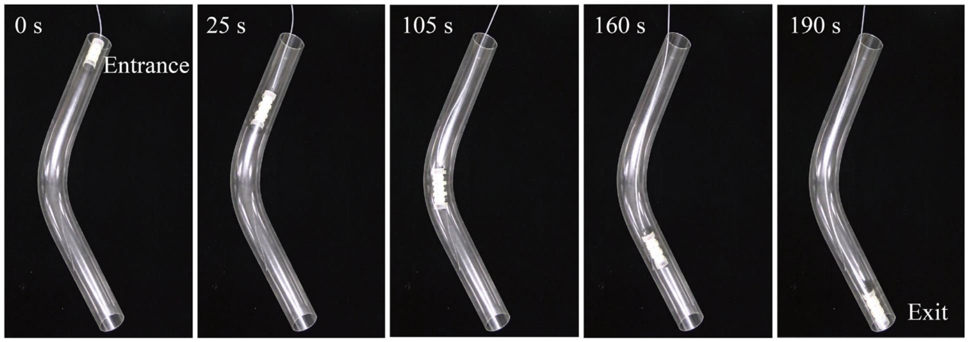

Fig. 9. Demonstration of the soft crawling robot when crawling in a curve plastic tube (top view).

5. Conclusion

In this research, a hybrid multi-material 3D printed pneumatical soft crawling robot inspired by caterpillars is designed and fabricated. The robot compromises a pneumatically bellow-type body, 12 anisotropic friction feet and two ends cap. We develop the passive synergy locomotion model between the deformation of the bellow-type body and anisotropic friction feet for the unidirectional crawling. By using the hybrid multi-material 3D printing, the robot be directly printed without complex assemble process. Then, an experimental testing platform is established to measure the friction coefficient on a cloth flat substrate in both forward and backward direction. By changing the cross-section shapes of the robot feet, we demonstrate that there are the significant differences on the crawling performance and the triangular shape feet can obtain a superior movement efficiency with a velocity of 1.05 cm/s (0.16 body length per second). We then build a pneumatic closed-loop feedback control system to autonomously drive the soft crawling robot. Finally, we conduct an experiment to demonstrate the ability of the soft crawling robot through a curve plastic tube.

CRediT authorship contribution statement

Xinjun Sheng: Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Haipeng Xu:** Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Ningbin Zhang:** Methodology, Investigation. **Ningyuan Ding:** Methodology, Investigation. **Xiangyang Zhu:** Supervision, Conceptualization, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **Guoying Gu:** Supervision, Conceptualization, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

None.

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