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Multimaterial Pneumatic Soft Actuators and Robots through a Planar Laser Cutting and Stacking Approach

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Pneumatic soft robotic systems show remarkable potentials in producing versatile locomotion and manipulations, owing to their flexibility in structural design and material selections. However, fabrication of pneumatic soft robotic systems with complex 3D structures and material distribution still remains elusive. Herein, a mode-free fabrication approach, called planar laser cutting and stacking fabrication (PLCSF), is proposed to create pneumatic soft robotic systems with multi-material and complex structure, which involves the following steps: 1) slicing the 3D model of desired pneumatic soft robotic systems into 2D layers; 2) fabricating each layer via laser cutting corresponding 2D membrane; 3) stacking all layers together to finish the fabrication. With the PLCSF approach, various prevalent pneumatic soft actuators are fabricated with complex structures (including fiber-reinforced and pneu-net) and different actuation modes (such as bending, elongation, twisting, abduction, contraction, and grabbing). The scalability of the PLCSF approach to fabricate multiple degrees-of-freedom (DOFs) pneumatic soft actuators with integrated structures, such as twisting-bending pneumatic soft actuators for delivering and bending-elongation-bending pneumatic soft actuators for crawling, is also demonstrated. It is further demonstrated that the PLCSF approach also enables creating a bio-inspired soft hand with nine DOFs, capable of various dexterous motions and manipulations.

1. Introduction

Soft robots,[1] mainly consisted of soft materials (Young modulus < 1 MPa), have shown remarkable compliance and self-adaptation in unstructured environments, which is essential for various applications,[2] such as bioinspired robots,[3,4] rehabilitation,[5,6] and prosthetics.[7,8] Different from traditional robots, soft robots mainly rely on muscle-mimic actuation technologies, such as dielectric elastomer actuators,[9–11] liquid crystal elastomer actuators,[12,13] shape memory polymers,[14] and pneumatic soft actuators.[15–17] Among them, pneumatic soft actuators have shown advantages of large deformation, high force output, and ease of design and control, therefore becoming a hot trend and enjoying increasing interest in the field of soft robots.[15] In general, pneumatic soft actuators mainly consist of networks of chambers that can inflate under compressed air or buckle upon evacuation.[18–20] Based on this working principle, many different pneumatic soft actuators (such as McKibben,[21] pneu-net,[18,22] and fiber-reinforced actuators[23]) have been well developed to generate versatile actuation modes, such as elongation, contraction, bending, and twisting,[24] which have been widely adopted to develop soft robots for various locomotion and manipulations. With the development of structural design and material selection,[25] fabrication[26] also plays a more and more important role in the resulting functions of pneumatic soft actuators and robots.

However, the fabrication of pneumatic soft actuators and soft robots still faces huge challenges in the field of soft robotics. In general, molding is the most prevalent fabrication technique for pneumatic soft actuators and robots, which usually involves multiple steps of casting and assembly, especially when it comes down to multimaterial fabrication and complex structures.[4,27,28] Consequently, it is usually time consuming and difficult to fabricate complex structures. The advances in 3D printing technologies[29,30] (such as Polyjet,[31] Digital Light Processing,[32] Direct Ink Writing,[24,33] and Embedded 3D Print,[34–36] MM 3D Print[37]) enable fabricating multimaterial pneumatic actuators and robots with arbitrary shapes and scales, but their applications are limited to special material and high cost. Recently, some planar fabrication technologies have been adopted for pneumatic soft actuators and robots. For example, by stacking up silicone elastomer layers, a soft robot capable of grasping and locomotion has been achieved.[38] By combining laser cutting and multi-layer-stacking technology, ultrathin pneumatic actuators,[39] microfluidic actuators,[40] and microfluidic robots[41] have also been well developed, showing huge potential to fabricate pneumatic elastomer actuators. In addition, by printing 2D

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polymer precursors on prestretched elastomeric sheets, soft actuators with 3D structures can also be formed via releasing the prestretch of the elastomer sheets.[42] These works provide several mold-free approaches to fabricate 3D structures based on 2D fabrication technologies, but they can mainly generate bending actuations with simple structures. Therefore, the development of effective fabrication approaches for pneumatic soft actuators and robotic systems with complex 3D multimaterials structures and various actuation modes is still quite challenging.

In this work, we propose a planar laser cutting and stacking fabrication (PLCSF) approach that can easily build up multimaterial pneumatic soft actuators and robots (**Figure 1**A). To this end, we first slice the 3D digital model of desired pneumatic soft actuators and robots into a series of 2D layers (Figure 1B) based

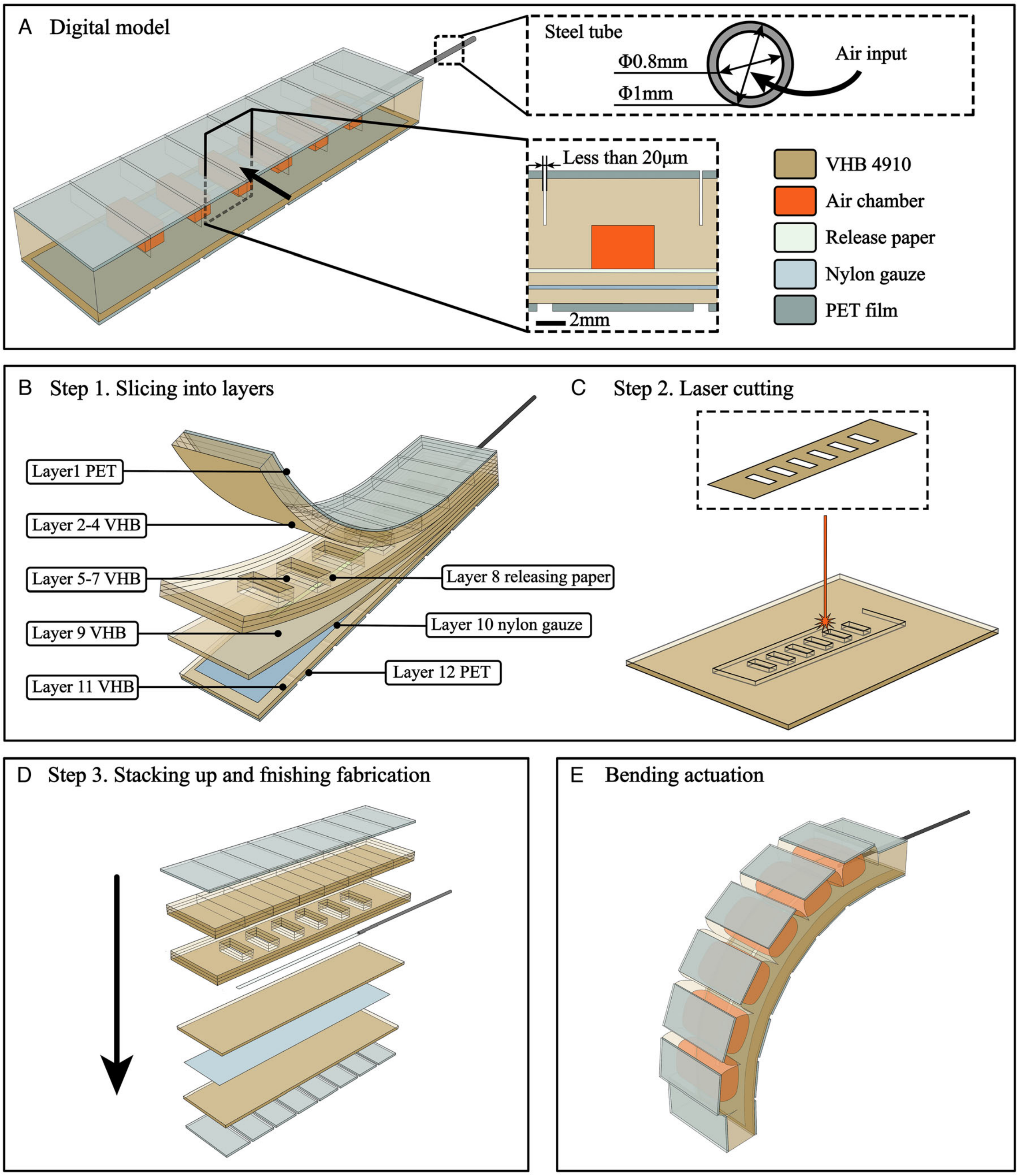

Figure 1. Overview of the PLCSF approach. A) A 3D digital model of a pneu-net actuator that consists of four kinds of materials, including: 1) VHB 4910 is used as the matric material; 2) nylon gauze is working as limiting layers; 3) PET film is utilized for tuning local stiffness; and 4) release paper is adopted to form the air path. B) Slicing the model into 12 layers based on differences of materials and geometric shapes. C) Fabricating each layer by laser cutting. D) Stacking up layers orderly to construct the pneu-net actuator. E) Bending actuation of the pneu-net actuator under compressed air.

on the geometric shapes and material properties. Then, we fabricate each layer by laser cutting (Figure 1C) corresponding laminate materials. Finally, all layers are stacked up orderly to construct desired pneumatic soft actuators and robots (Figure 1D). To verify the effectiveness of the PLCSF approach, we fabricate various pneumatic soft actuators (**Figure 2**, the 3D

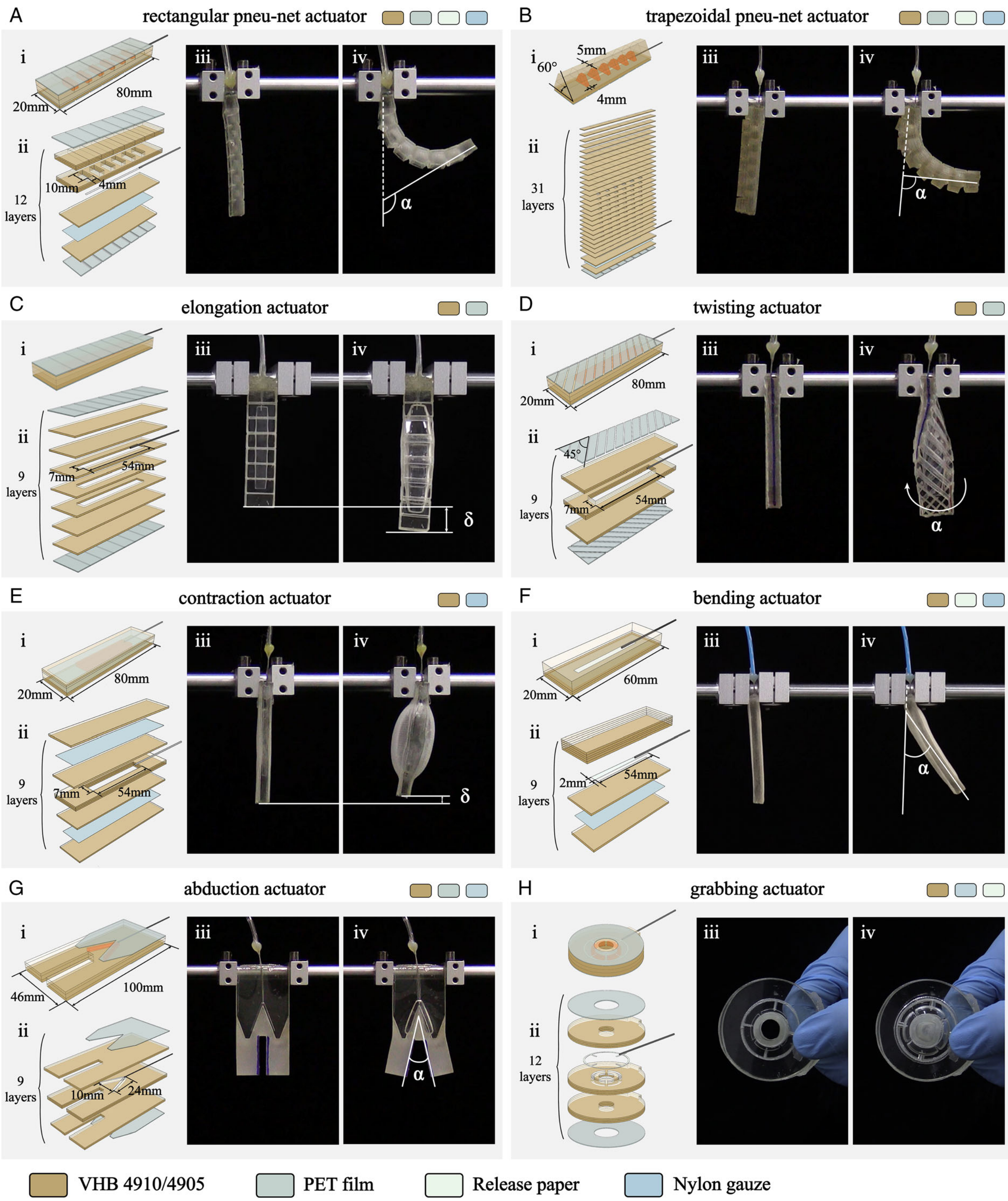

Figure 2. Fabrication of multimaterial pneumatic soft actuators with different structures by the PLCSF approach. A) A pneu-net actuator with a rectangular cross section. B) A pneu-net actuator with a trapezoid cross section. C) An elongation actuator with limiting layers that is vertical to the long axis. D) A twisting actuator with limiting layers that forms an angle with the long axis. E) Contraction actuator with limiting layers that are parallel to the long axis. F) A bending actuator with a chamber at an asymmetric position. G) An abduction actuator with a "V"-shape chamber. H) A grabbing actuator with a circular chamber.

digital models are derived from previous work). The experimental results show that the PLCSF approach can fabricate different pneumatic soft actuators with various 3D structures (fiber-reinforced and pneu-net), multiple materials (VHB 4910, polyethylene terephthalate [PET] film, nylon gauze, and release paper), and diverse actuation modes (bending, elongation, twisting, contraction, abduction, and grabbing), demonstrating the generality of the PLCSF approach. We also demonstrate the scalable capability of the PLCSF approach by developing pneumatic soft actuators with multiple degrees of freedom (DOFs), such as twisting–bending actuations for delivering and bending–elongation–bending actuations for crawling. We further demonstrate that the PLCSF approach can also fabricate a bioinspired soft hand with nine DOFs, including five bending actuations, three abduction actuations, and one opposition actuation, which endows the bioinspired soft hand with capabilities of dexterous motions and manipulations.

2. Result

2.1. Overview of the PLCSF Approach

To illustrate the working principle of the PLCSF approach, we take a pneu-net actuator as an example. Figure 1A shows the 3D digital model of the designed pneu-net actuator that contains six cuboid chambers. The actuator mainly consists of four different materials: 1) VHB 4910 (stretchable material with a thickness of 1 mm; VHB 4910 shows very high bonding ability that can bond different materials together to form an integrated structure) is used as the matric material; 2) nylon gauze (unstretchable material, a thickness of 0.5 mm, 20 mesh) is working as limiting layers; 3) PET film (unstretchable material, a thickness of 0.5 mm) is utilized for tuning local stiffness; and 4) release paper (a thickness of 0.055 mm) is adopted to form the air path. In addition, a steel tube (diameter of 1 mm) is embedded into the pneu-net actuator for air connection. To fabricate the pneu-net actuator, three steps are involved as follows: 1) based on the differences of geometric shapes and material properties, the 3D digital model of the pneu-net actuator is first sliced into 12 layers (Figure 1B), including 2 PET layers (numbered as 1 and 12), 8 VHB layers (numbered as 2 to 7, 9, and 11), 1 release paper layer (numbered as 8), and 1 nylon gauze layer (numbered as 10); 2) then, each layer is separately fabricated by laser cutting with corresponding geometric shape and materials (Figure 1C); and 3) finally, the pneu-net actuator is accomplished by staking all layers together (Figure 1D). Upon compressed air, the inflation of chamber-networks in the pneu-net actuators generates a bending actuation (Figure 1E).

2.2. Pneumatic Soft Actuators with Different 3D Structure

We first investigate the generality of our PLCSF approach on creating different multimaterial pneumatic soft actuators with different structures. To this end, we select eight classical pneumatic soft actuators (such as pneu-net actuators, limiting layer reinforced actuators and actuators with complex chambers) from previous work.

2.2.1. Pneu-Net Actuators

The pneu-net actuator is one of the most prevalent pneumatic soft actuators. Based on the previous description in Section 2.1, we fabricate the pneu-net actuator with a rectangular cross section (Figure 2A) that can generate a bending actuation upon compressed air. Furthermore, we fabricate a pneu-net actuator with a trapezoid cross section (Figure 2B-i). (We should note that to produce a trapezoid cross section, VHB 4905 [a thickness of 0.5 mm] is adopted to decrease the thickness of each layer.) With the PLCSF approach, the trapezoid pneu-net actuator is sliced into 31 layers (Figure 2B-ii), including 26 VHB 4905 layers (numbered as 1–26), 2 VHB 4910 layers (numbered as 28 and 30), 1 release paper layer (numbered as 27), 1 nylon gauze layer (numbered as 29), and 1 PET layers (numbered as 31). After laser cutting and stacking fabrication, the trapezoid pneu-net actuator (Figure 2B-iii) is accomplished, which can also generate a bending actuation (Figure 2B-iv).

2.2.2. Limiting Layer Reinforced Actuators

We next exploit the PLCSF approach to fabricate pneumatic soft actuators with fiber-reinforced structures. (For the convenience of the fabrication, we use laser-cut limiting layers to replace the limiting fiber in this section.) We first fabricate an elongation actuator (Figure 2C-i) that consists of a single cuboid chamber with limiting layers that are vertically distributed to the long axis. Figure 2C-ii shows the sliced layers of the elongation pneumatic soft actuator. After the laser cutting and stacking fabrication process, the accomplished elongation pneumatic soft actuator (Figure 2C-iii) generates an elongation actuation (Figure 2C-iv) because the limiting layers only permit the deformation along the long axis. In addition, with the PLCSF approach, we can easily change the angle of the limiting layer to achieve different actuations. For example, Figure 2D shows a twisting pneumatic soft actuator with a limiting layer that forms an angle α with the long axis. Under compressed air, the inflation of the chamber results in a twisting actuation. Furthermore, when the limiting layer is parallel to the long axis, the pneumatic soft actuator can also achieve a contraction actuation (Figure 2E).

2.2.3. Pneumatic Soft Actuators with Complex Chambers

Apart from changing the limiting layers of the pneumatic soft actuators, the PLCSF approach also paves the way to fabricate complex chambers for different actuations. For example, Figure 2F shows a bending pneumatic soft actuator that consists of a planar rectangular chamber at an asymmetric position. Under compressed air, the asymmetric structure of the pneumatic soft actuators generates a bending actuation. We also fabricate an abduction pneumatic soft actuator with a "V"-shaped chamber (Figure 2G) that can open an angle under compressed air, called abduction actuation. In addition, a pneumatic soft actuator with circular chamber-networks (Figure 2H) can also be achieved by the PLCSF approach, which can generate a grabbing actuation. (See MOV01 and Table S1, Supporting Information, for actuation demonstration and material distribution of the aforementioned eight actuators, respectively.)

2.3. Pneumatic Soft Actuators with Multiple DOFs

We next demonstrate the scalability of the PLCSF approach on building multiple DOFs pneumatic soft actuators with an integrated structure, which shows promising applications in the field of soft robotics.

2.3.1. Twisting–Bending Pneumatic Soft Actuators for Delivering

We first design a pneumatic soft actuator that consists of three DOFs, including two bending actuations (DOF 1 and 2) and one twisting actuation (DOF 3). **Figure 3**A shows the sliced layers of the designed pneumatic soft actuator (see Figure S2A and Table S1, Supporting Information, for more details of the geometric parameters and material distribution, respectively). Based on the PLCSF approach, we accomplish the twisting–bending pneumatic soft actuator, shown in Figure 3B. By individually actuating different DOFs in the order from 1 to 3, the pneumatic soft actuator can generate bending, bending, and twisting actuation, respectively. By synthetical control of different DOFs, this pneumatic soft actuator can be used to deliver a mark pen. The delivering processes (Figure 3C, MOV02, Supporting Information) mainly involve four steps: 1) DOF 1 and 2 are first actuated to generate a bending actuation for holding a mark pen (Figure 3C-ii); 2) then, the DOF 3 is actuated to generate a twisting angle for delivering the mark pen (Figure 3C-iii); 3) the DOF 1 and 2 are unloaded to put the mark pen down (Figure 3C-iv); and 4) the DOF 3 is unloaded to recover the original state (Figure 3C-v). The control sequences of each DOF are shown in Figure 3D.

2.3.2. Bending–Elongation–Bending Pneumatic Soft Actuators for Crawling

Furthermore, we design a pneumatic soft actuator with cascaded three DOFs, including two bending actuations (DOF 1 and 3) and an elongation actuation (DOF 2). To fabricate the pneumatic soft actuator, we first slice it into 12 layers (**Figure 4**A, more details of

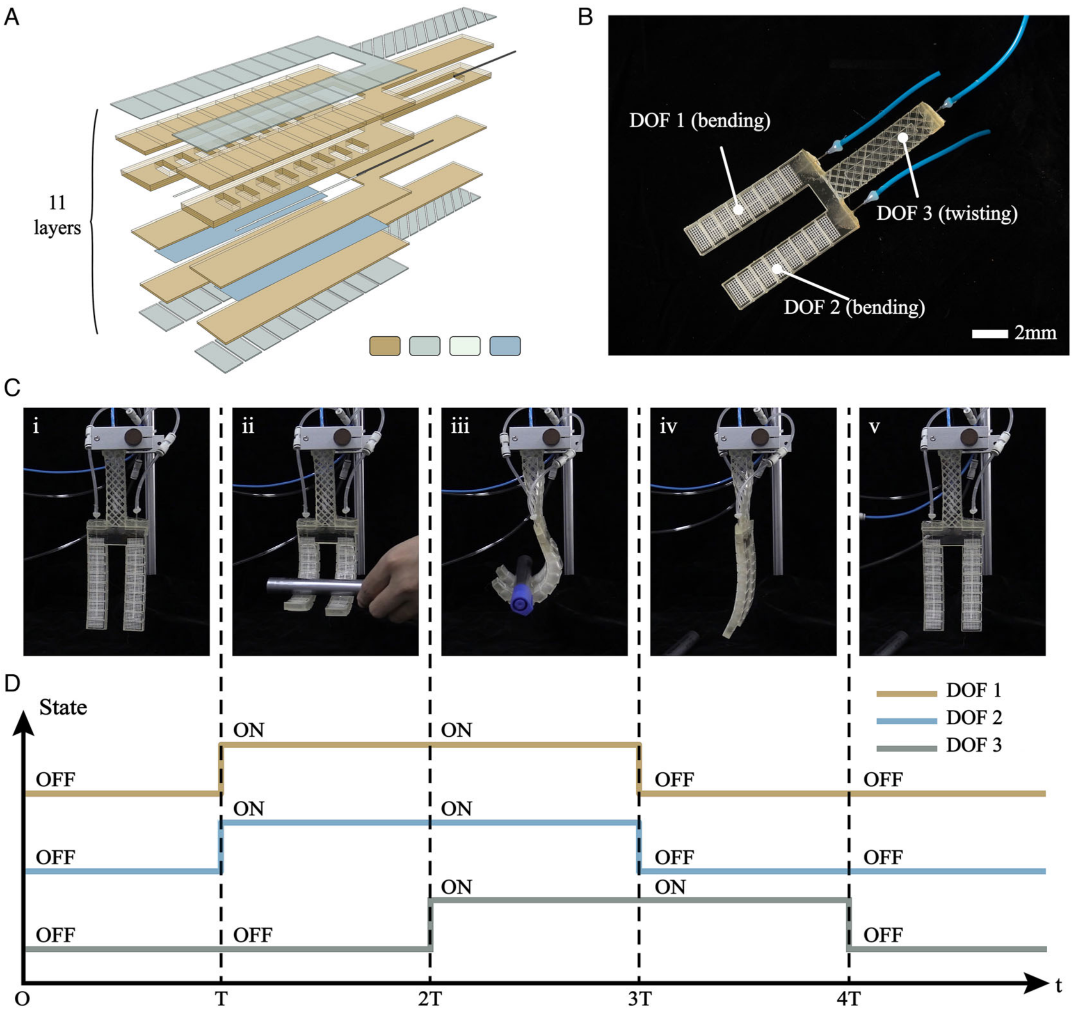

Figure 3. Pneumatic soft actuator with twisting–bending actuations for delivering. A) The sliced layers of the pneumatic soft actuator. B) The accomplished pneumatic soft actuator. C) The delivering processes of the pneumatic soft actuator: i) the original state; ii) holding the mark pen; iii) delivering the mark pen; iv) releasing the mark pen; and v) recovering to the original state. D) The control sequences of the delivering processes.

the geometric parameters and material distribution are shown in Figure S2B and Table S1, Supporting Information, respectively). Then, the pneumatic soft actuator is accomplished by the PLCSF approach (Figure 4B). By separately actuating different DOFs in the order from 1 to 3, the pneumatic soft actuator can generate bending, elongation, and bending, respectively. Based on the pneumatic soft actuator, we install four steel needles at two ends of the actuator to form a soft crawling robot. The working principle of the soft crawling robot can be described as follows: 1) the actuation of DOF 2 can output a periodical elongation–contraction motion; 2) the actuation of DOF 1 and 3 can generate bending deformations, resulting in controllable friction forces (at the initial states, the contact between the needles and ground can generate a friction force whereas the bending deformation will remarkably decrease the friction force by separating the needle from the ground); and 3) by synthetically controlling the motion and friction forces, the soft robots can achieve stable crawling on the ground. The crawling processes (Figure 4C) can be described as following steps: 1) the DOF 1 is actuated to generate a bending actuation, resulting in a decrease in frictional force of the front section; 2) the DOF 2 is actuated and its elongation pushes the front section forward; 3) the DOF 1 is unloaded whereas the DOF 3 is simultaneously actuated to decrease the friction force on the end section; 4) the DOF 2 is unloaded and the contraction pulls the end section forward; and 5) the air pressure in DOF 3 is unloaded to recover initial state. By repeating the aforementioned five steps, the soft robot can achieve stable crawling on a wooden surface platform (Figure 4D, MOV03, Supporting Information).

2.4. Fabricating a Bioinspired Soft Hand

Finally, we demonstrate that the PLCSF approach also enables fabricating soft robots with complex structures. For example, we design a bioinspired soft hand that consists of nine DOFs, including five bending actuations (DOF 1–5), three abduction actuations (DOF 6–8), and one opposition actuation (DOF 9). To fabricate the bioinspired soft hand, we first slice the 3D digital model into 13 layers (**Figure 5**A) and then fabricate it by the

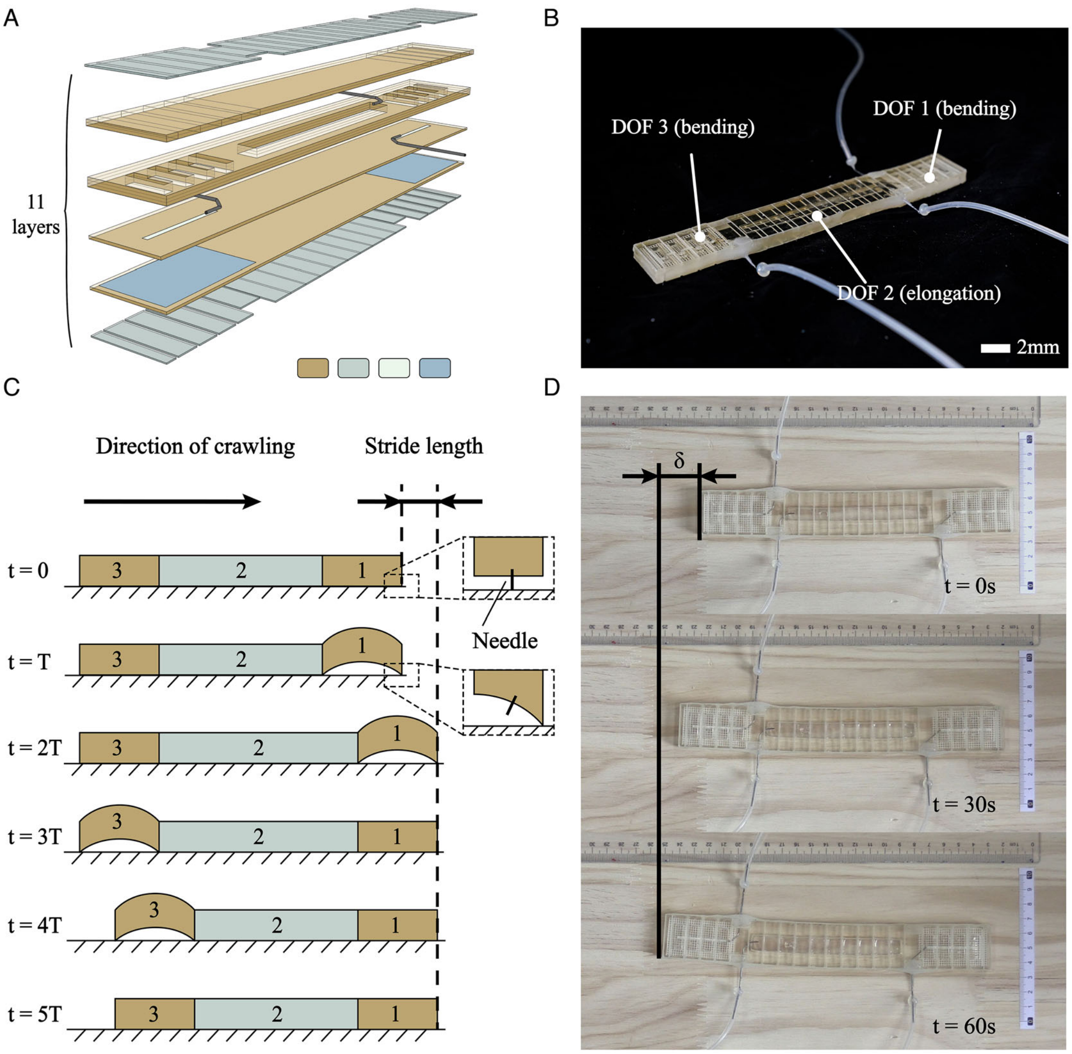

Figure 4. Pneumatic soft actuator with cascaded bending–elongation–bending for crawling. A) The sliced layers of the pneumatic soft actuator. B) The accomplished pneumatic soft actuator. C) The working principle of the crawling processes. D) Still images of crawling on a wooden surface.

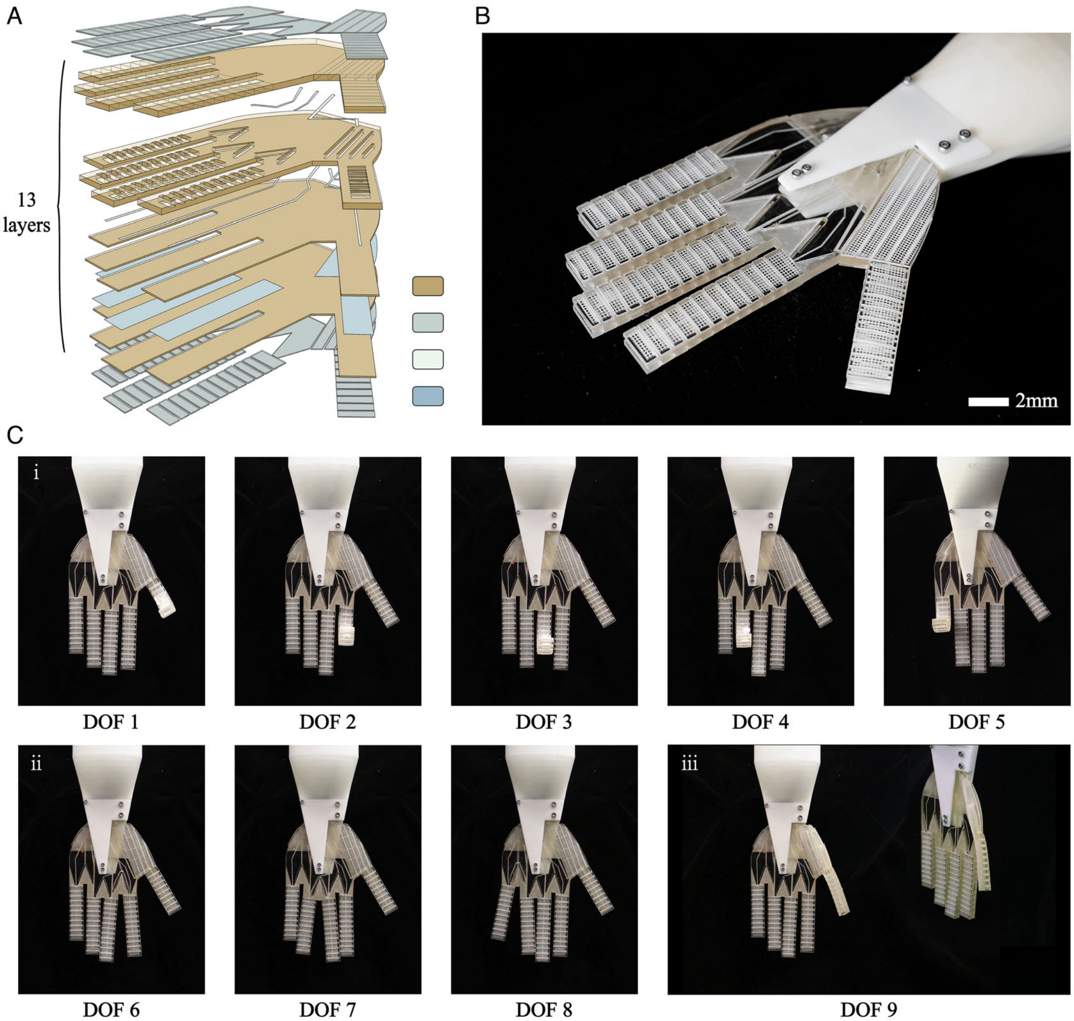

Figure 5. A 9 DOFs bioinspired soft hand. A) The sliced layers of the bioinspired soft hand. B) The bioinspired soft hand accomplished via the PLCSF approach. C) Characterizing the static responses of the bioinspired soft hand: i) the actuation of DOF 1–5 generates bending thumb, forefinger, middle finger, ring finger, and little finger; ii) the actuation of DOF 6–8 generates abduction between index finger and middle finger, middle finger and ring finger, ring finger and little finger, respectively; and iii) the actuation of DOF 9 forms palmar opposition.

PLCSF approach (Figure 5B, See Table S1, Supporting Information, for more details of the material distribution, respectively). It should be noted that for the convenience of fixation, we 3D print an arm-shaped holder for the bioinspired soft hand. To evaluate the performance of the bioinspired soft hand, we first characterize static responses of each DOF (Figure 5C and MOV04, Supporting Information): 1) the actuation of DOF 1–5 achieves bending thumb, index finger, middle finger, ring finger, and little finger, respectively; 2) the actuation of DOF 6–8 generates abduction between index finger and middle finger, middle finger and ring finger, ring finger and little finger, respectively; and 3) the actuation of DOF 9 forms an opposition actuation on the palm. Furthermore, by synthetically actuating the bioinspired soft hand, it can finish various tasks dexterously, such as grasping a small table tennis ball, a balloon, and a bread toy (**Figure 6**A–C), making gestures such as orchid fingers (Figure 6D) and operating a pair of scissors (Figure 6E).

3. Conclusion and Discussion

In this work, we present a PLCSF approach that enables fabricating multimaterial pneumatic soft actuators and robots with complex 3D structures for various actuation modes. To this end, we first slice the 3D digital model of designed pneumatic soft actuators or robots into 2D layers. Then, we fabricate each layer by laser cutting the corresponding membrane materials. Finally, the different layers are stacked up together to form desired pneumatic soft actuators or robots. With our fabrication approach, existed pneumatic soft actuators with different structures and material distribution can be effectively achieved, capable of generating different actuation modes, such as elongation, bending, contraction, twisting, abduction, and grabbing. By taking the advantage of mode-free and 2D-based fabrication, our approach shows the scalable ability to create multi-DOF pneumatic soft robots with integrated structures, such as a twisting–bending pneumatic soft actuator for delivering and a

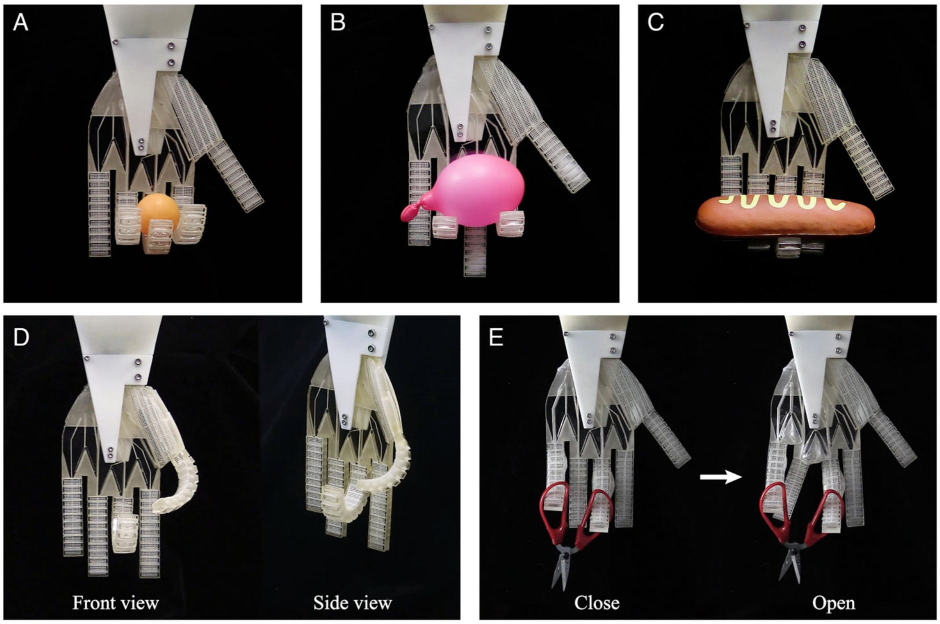

Figure 6. Demonstration of the bioinspired soft hand on dexterous manipulations. A) Grasping a table tennis ball. B) Grasping a balloon. C) Grasping a bread toy. D) Making the gesture of orchid fingers. E) Operating a pair of scissors.

bending–elongation–bending pneumatic soft actuator for crawling, and a bioinspired soft hand with nine DOFs for dexterous motions and manipulations.

Different from previous work,[38–42] the main features of our PLCSF approach lie in the fact that: 1) existed 2D-based fabrication approaches are mainly limited to pneumatic soft actuators with simple structures and usually focus on bending actuation. With our PLCSF approach, we can fabricate various pneumatic soft actuators with different materials (such as VHB 4910, PET), 3D structures (fiber-reinforced and pneu-net), and actuation modes (elongation, bending, contraction, twisting, abduction, and grabbing). 2) Our PLCSF approach shows the advantage of flexible material selections. In our PLCSF approach, different materials with different mechanical properties can be adopted, such as stretchable materials (VHB 4910), unstretchable materials (PET, nylon gauze, and release paper), and steel needles. Therefore, our fabrication approach may pave the way to form stiff–flexible–soft coupled structures for pneumatic soft actuators and robots. Furthermore, we should mention that although the matric material (VHB 4910 from 3M company[43]) has very high bonding ability and no additional adhesive materials are required, other kinds of elastomeric membranes (such as silicone membrane) also can be applied. The main difference is that additional adhesive materials are required to coat both sides of each layer before the stacking process.[38] In addition, the surface of the matric materials can also be activated by some physical or chemical approaches to enhance the bonding ability.[44]

It should also be mentioned that we adopt a manual stacking process to accomplish the pneumatic soft actuators and robots in this work, which may lead to fabrication errors. In addition, the matric material (VHB 4910 from 3M company) is relatively soft, which may result in weaker mechanical performances (such as lower payload capability). In our future work, we will focus on optimizing the material selections and developing automatic stacking processes to improve their performance.

4. Experimental Section

Materials: The pneumatic soft actuators and robots majorly consist of four different materials (Figure S1, Supporting Information): VHB (VHB 4910, 1 mm; VHB 4905, 0.5 mm, 3M company), PET films (TS-PET, 0.5 mm, Dongxuan Plastic Products Co., Ltd.), nylon gauze (20 mesh), and release paper (0.055 mm, Yangze Adhesive Products Co., Ltd.).

Design and Fabrication: The pneumatic soft actuators and robots are designed by using a computer-aided design (CAD) software (Solidworks, Dassault Systemes), and the planar patterns of each layer are designed in CAD software (AutoCAD, AutoDesk). A laser cutting machine (VLS 3.50, Universal Laser Systems) (Figure S1G, Supporting Information) is adopted to fabricate each layer. A laminator (650 mm Cold laminator, Huimeng Office Equipment Co., Ltd.) (Figure S1F, Supporting Information) is adopted during the stacking process to ensure careful stacking and alignment.

Control Method: Each DOF of the actuators and robots was manually controlled by syringes.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

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