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A 2D Pneumatic Soft Robot with Suckers for Locomotion

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***Abstract*— Soft robots have a great application potential in agriculture, military and disaster search and rescue and a flexible locomotivity is required for soft robots. This paper presents the design and fabrication procedure of a soft pneumatic robot that can move in different directions with various gaits and is called 2D-SSR. The robot is composed of two soft actuators, which perform pure 2D bending, and three rigid connectors with three suckers. Based on specific sequences of seven air channels and the derived geometric kinematics, various gaits including moving forward and turning were simulated. The critical conditions of periodic locomotion were analyzed and the relationship between air pressure and bending angle was acquired in some tests. In order to verify the feasibility of the development of the new soft robot and gait simulations, the experiments of moving forward and turning were executed on both the single-module robot and double-module robot.**

I. INTRODUCTION

Owing to the much better environmental adaptability, more compliant flexibility, and higher motor capability and security than rigid robot, soft robots have been a hot point in the field of robotics, especially moving soft robots. With the advantage of random deformation, moving soft robots can imitate the motion forms of various creatures in the nature [1], [2]. They make itself in different motion states through active deformation so that they can adapt themselves to the environment that human beings cannot reach for the purpose of expanding the working scope.

Based on simple mechanical principles [3] and auxiliary soft actuators for generating different frictions, a range of moving soft robots have been developed. A pneumatic soft robotic snake was explored from the aspects of design improvement [4], dynamic characteristics, theoretical motion model [5] and sensing detection and realized excellent autonomous undulatory serpentine locomotion [6] with some wheels as the friction generator. Besides, another pneumatic soft snake robot with hook and loop was developed for the geometric gait implementation [7]. Different from the aforementioned robots, OriSnake could not only achieve turning and straight walking, but also move in three dimensions through the actuation by motor and internal cables [8]. For the purposes of improving the slithering locomotion and generating different frictions in horizontal and vertical directions, a novel mechanism [9] which had a rectangular beam with an isotropic coefficient of friction between its contact surface and the flat ground was designed. Unfortunately, the aforementioned robots and mechanisms can just accomplish the snake-like gait which is easily limited in complex environments. Thus, other moving soft robots are presented to accomplish various interesting gaits, including the worm gait [10], inchworm gaits [11], rolling gait [12] and hopping gait [13]. Importantly, moving soft robots should have the ability to change their gait as the working environment changes.

Flexible mobility in various environments is required for moving soft robots. In the study, to satisfy the requirement, we developed a 2D pneumatic soft sucker robot (2D-SSR for short) for achieving various locomotion gaits, including transverse locomotion gait, snake locomotion gait and turning gait in various environments. The part structure, system configuration, fabrication process and the analysis and simulation of periodic motion based on kinematics are presented in the following sections in details. In addition, the prototype was tested to get the relationship between air pressure in the chambers and bending angle in three directions. Finally, various gaits for forward walking and turning were experimentally tested to verify the feasibility and effectiveness of the developed robot.

II. DEVELOPMENT OF 2D-SSR

A. Prototype Design

By a tendon-driven actuating method, a one-chambered pneumatic soft actuator can bend in one direction and a two-chambered pneumatic soft actuator can bend in two directions. A pneumatic soft actuator for pure in-plane bending motion was developed [14]. Fiber net and 2D free chain were used as the anisotropic soft and rigid restrains, respectively. In order to generate the different frictional forces between the actuators, three suckers were connected to both ends of the two actuators. In this way, a soft sucker robot (2D-SSR) was designed to realize some flexible and diverse movement gaits.

The robot is composed of four chambers, three vacuum suckers and three connectors. The four chambers and three vacuum suckers can be divided into two sets(Fig. 1a). C_1, C_4

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and C_7 actuated by negative pressure are in one set, whereas C_2, C_3, C_5 and C_6 actuated by positive pressure are in the other set. The connector, composed of two buckles, two press plates and two caps with some convex plates, played a role in fixing the suckers and connecting and supporting the two actuators. In order to fixing the suckers, the upper press plate, downward press plate as well as two caps with an irregularly-shaped hole were used to limit the degree of freedom in the vertical direction and horizontal direction severally. The convex plates, generated inside the two caps, were used to compress the soft actuator tightly and the buckles were used for tightly bundling with two caps so that the soft actuators could connect firmly with the suckers. The prototype of 2D-SSR is shown in Fig. 1b. The specific parameters of the structure are determined as small as possible, mainly based on experience of available fabrication, as shown in Table I.

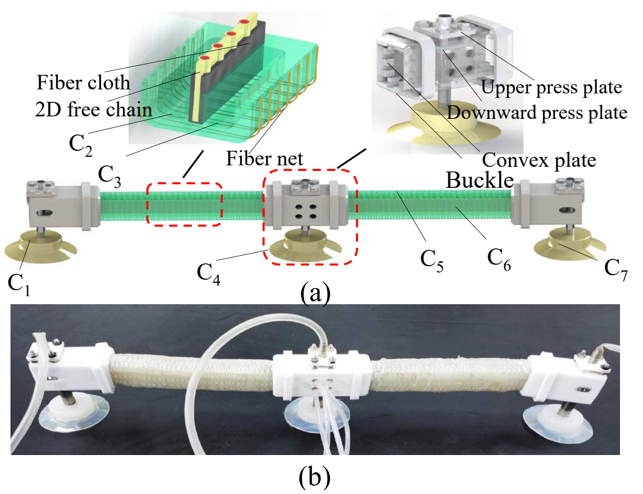


Fig. 1. Structure model of 2D-SSR. (a) 3D design model of 2D-SSR. (b) Experimental prototype of 2D-SSR.

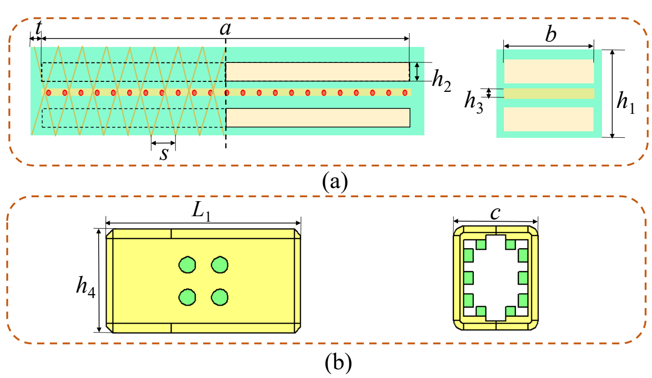


Fig. 2. Specific parameters of 2D-SSR. (a) Structure of the soft actuator (side view and sectional view). (b) Structure of the rigid link (side view and sectional view).

B. Assembly procedure

The fabrication process has been described in detail [14]. After two soft actuators were finished, the assembling process of 2D-SSR started. The whole assembling procedure was divided into four steps in Fig. 3. In the first step, an aluminum pipe, connected to the suckers with thread, was assembled with two caps and the downward press plate by screws. It is worth noting that the aluminum pipe should not be screwed down fully so that the aluminum pipe had the degree of freedom in the axial direction. In the second step, the upper press plate was fixed on the aluminum pipe with nut tightly. In the third step, two soft actuators were added to both sides of the connector and bundled tightly with two buckles. In the last step, other two connectors and suckers were assembled to the other ends of the actuators. After four steps were finished, the 2D-SSR was fabricated for work.

TABLE I
SPECIFIC PARAMETERS OF 2D-SSR

Parameters	Value(mm)
Length of the chambers a	125
Length of the rigid links L_1	50
Width of the chambers b	16
Width of the rigid links c	25
Wall thickness t	3
Space of the reinforce fiber net s	4
Height of the actuator h_1	22
Height of the chambers h_2	6
Height of the 2D free chain h_3	4
Height of the rigid links h_4	27

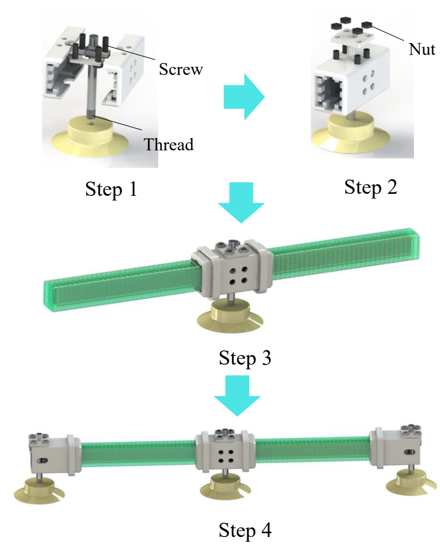


Fig. 3. Assembling process of 2D-SSR

III. KINEMATICS AND GAIT ANALYSIS

A. Kinematics

The design of soft robots does not involve concept of real link length or joint angles. Therefore, a simplified geometric kinematic model is suitable for describing the position and orientation during locomotion. Naturally, taking the length of rigid connectors between soft parts into account, a kinematic model of the 2D-SSR is obtained. However, it is worth noting that the connectors (rigid link) and actuators (soft segment) are described by a straight line and a uniform arc for simplifying the simulation process. The simplified model

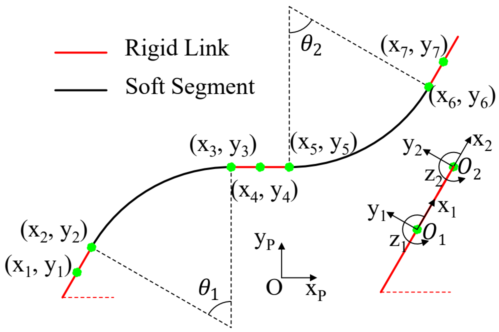


Fig. 4. The geometric model of the 2D-SSR and the coordinate system position

is shown in Fig. 4. A general 2D-SSR comprises three rigid links with a length L_1 and two soft parts with a length L_2. The θ_1 and θ_2 are the bending angles of two soft parts. Besides, eight coordinate systems are established, including three coordinate systems at the center of rigid links (O_1, O_4, O_7), four coordinate systems at the end of soft parts (O_2, O_3, O_5, O_6) and one fixed world coordinate (O_p). Consequently, based on the deformation law of the robot and the motion gaits, the 2D-SSRs body position relationship is obtained and the geometric center and rotation angle of the robot are analyzed.

According to the homogeneous coordinate transformation matrix, every coordinate can be transformed into the base coordinate system (O_p), which is fixed and coincident with the base coordinate O_1 system. The homogeneous coordinate transformation matrix of adjacent coordinate system on a rigid link can be derived as follows (i = 2, 4, 5 and 7).

$$ {}^{i-1}_{i}\mathrm{T} = \begin{bmatrix} 1 & 0 & 0 & \frac{L_1}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

The transformation matrix of adjacent coordinate system on a soft part can be described as follows as well (j = 3 and 6).

$$ {}^{j-1}_{j}\mathrm{T} = \begin{bmatrix} \cos\theta_{j/3} & -\sin\theta_{j/3} & 0 & \frac{L_2}{\theta_{j/3}}\cos\theta_{j/3} \\ \sin\theta_{j/3} & \cos\theta_{j/3} & 0 & \frac{2L_2}{\theta_{j/3}}\sin^2\frac{\theta_{j/3}}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

Thus, the positions of the end and center of rigid links can be calculated as (k = 1, 2, 3, 4, 5, 6 and 7).

$$ {}^{1}_{k}\mathrm{P} = {}^{1}_{2}\mathrm{T}\,{}^{2}_{3}\mathrm{T}\ldots{}^{k-1}_{k}\mathrm{T}P_k \tag{3} $$

where ${}^{1}_{k}\mathrm{P}$ (x, y, z) is the position coordinate in the coordinate system O_1 and P_k is the position coordinate in the k^{th} coordinate system.

B. Periodic motion and Simulation

The locomotion of 2D-SSR is multifarious and has a high degree of mobility. A periodic motion has two states: inflation and deflation, which are controlled by combining four chambers with three vacuum suckers according to different sequences, the 2D-SSR can achieve straight movement and turning with various gaits like transverse locomotion gait, snake-like locomotion gaits and turning gait. Based on the kinematics, the simulation of the three gaits shown in Fig. 5 was performed in Matlab.

The transverse locomotion gait involves six steps, as shown in Fig. 5a. Friction is required for the robot locomotion. The three suckers are the generator of the difference friction during the whole motion and the displacement is generated for by the two soft actuators for locomotion. At the starting point, the central sucker were pumped to generate the bigger friction (Step 1 in Fig. 5a). The two chambers (C_3, C_6) from the same side of two actuators are inflated to bend (Step 2 in Fig. 5a). When the other two suckers go forward, they are also pumped and the central sucker is deflated simultaneously (Step 3 in Fig. 5a). Then, the two chambers mentioned (C_3, C_6) above are deflated and the other two side chambers (C_2, C_5) are inflated to push the central sucker forward (Step 4 in Fig. 5a). It is worth noting that the screws from the two suckers at the edge should not be tightened completely. Otherwise, the central sucker cannot move. Similarly, the central sucker is inflated and the other two suckers are deflated. The two chambers (C_2, C_5) are deflated and the other two chambers (C_3, C_6) are inflated (Step 5 and Step 6 in Fig. 5a). Through repeating these steps with inflating and deflating periodically, the robot moves forward.

The posture of the snake locomotion gait is like sine wave. The suckers on the head, called the first sucker (C_7), are pumped for fixing and one set of two chambers (C_3, C_5) are inflated to bend so that the other two suckers (C_1, C_4) are pulled forward (Step 1 and Step 2 in Fig. 5b). Next, the suckers at the end, called the second sucker (C_1), are pumped and the first sucker is deflated (Step 3 in Fig. 5b). The above mentioned set of chambers are deflated and the second set of two chambers are inflated. The elastic restoring force is generated by the first set of chambers and the bending force is generated by the second set of chambers. In this way, a large step length is formed (Steps 4 to 6 in Fig. 5b). Similarly, the two suckers at the end are actuated in turn and the inflating chambers are deflated to achieve the whole gait (Steps 7 to 8 in Fig. 5b).

The turning step is simpler than the straight step. The central sucker is pumped and fixed on the floor (Step 1 in Fig. 5c) and one of the chambers in each soft actuator is inflated to bend (Step 2 in Fig. 4c). Importantly, the two inflating chambers are respectively in the two sides of the actuator. Next, one of the suckers at the edge is pumped and the central sucker is deflated for changing the fixing point (Step 3 in Fig. 5c). At last, the two inflating chambers are deflated to make the whole body to turn (Step 4 in Fig. 5c). The screws of three suckers are tightened completely and the other chambers, which are not actuated, should be inflated to overcome the resistance generated during the turning process of the whole body turning in step Step 4.

The coordination of seven air channels (C_1 to C_7) is critical for accomplishing the three gaits with 2D-SSR.

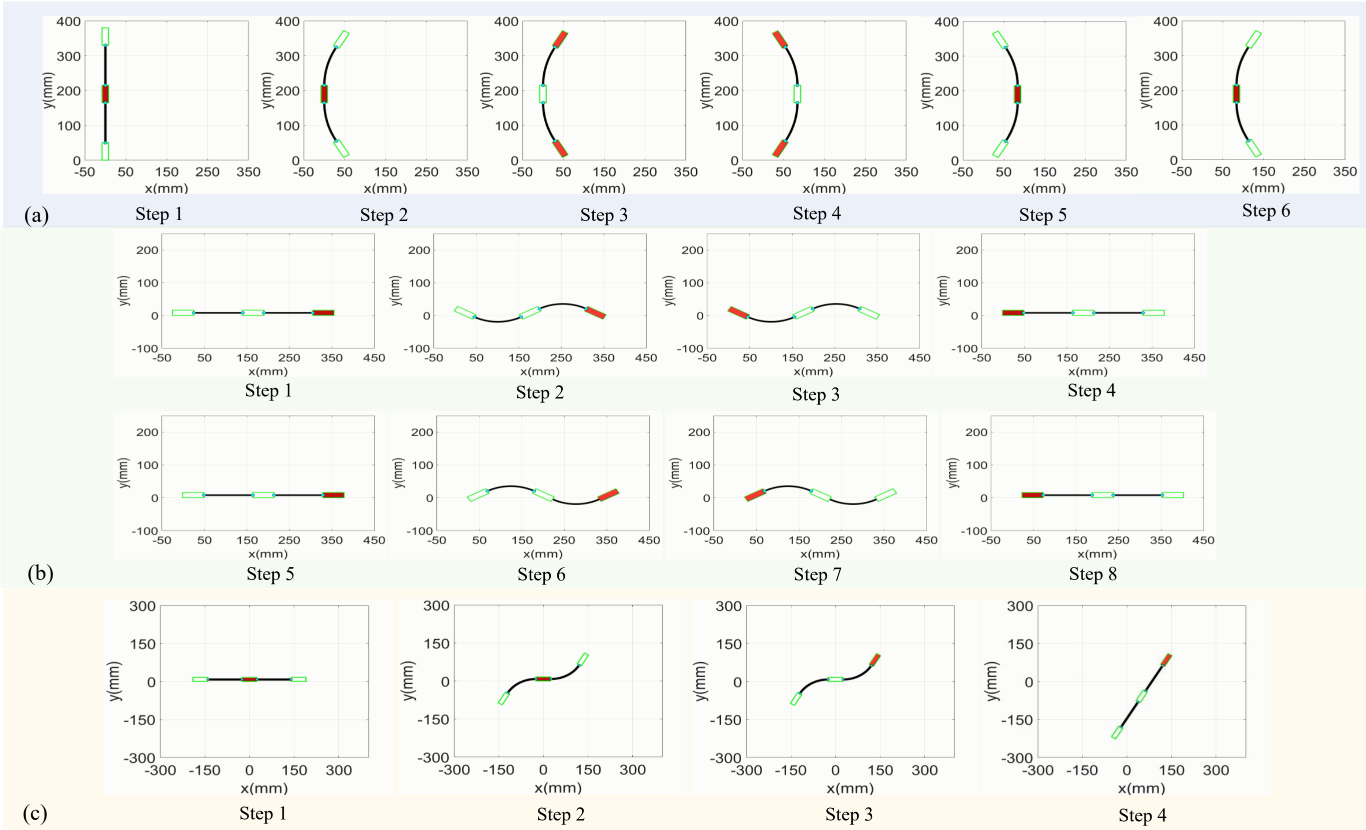
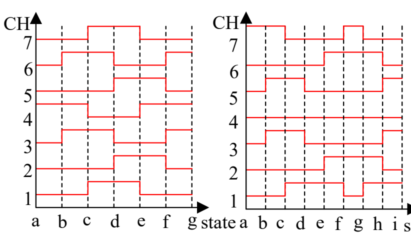
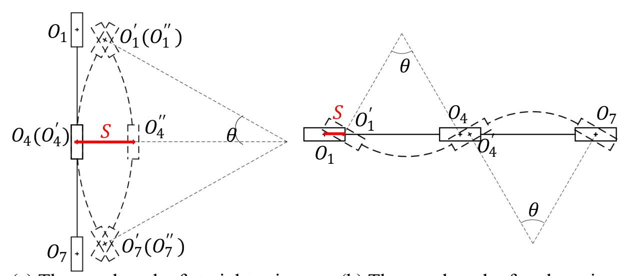


Fig. 5. Locomotion gait of 2D-SSR: (a) transverse locomotion gait, (b) snake locomotion gait, (c) turning gait.



(a) Transverse moving gait (b) Snake gait (c) Turning gait

Fig. 6. The state sequence of seven air channels.



(a) The step length of straight gait (b) The step length of snake gait

Fig. 7. Step length analysis diagram of 2D-SSR.

The ON-OFF signals or pass-and-break, the state logic or sequence of the seven air channels are shown in Fig. 6. The horizontal and vertical coordinates are the states of motion and the air channels shown in Fig. 1. The high and low states indicate ON and OFF, respectively. In addition, the state switch interval is unequal and changeable so that we are able to improve the moving speed of the 2D-SSR by reducing state time.

C. Locomotion Analysis

Step length is an important performance indicator for evaluating the locomotion of the 2D-SSR. Based on the kinematics and locomotion gaits mentioned above, the theoretical step length of the transverse locomotion gait and snake locomotion gait can be calculated easily. As indicated in Fig. 7, the solid line and dashed line indicate the original state and the state after motion respectively. The red line indicates the displacement between the two states, and are described with s_1 and s_2. The step length of transverse locomotion gait and snake locomotion gait can be derived as follows:

$$s_1 = 2(2\frac{L_2}{\theta}(1-\cos\theta) + L_1\cos\theta) \quad (4)$$

$$s_2 = 4(L_2 - L_1\cos(\frac{\theta}{2}) - \frac{2L_2}{\theta}\sin\frac{\theta}{2}) \quad (5)$$

where θ is the bending angle of each soft parts. Obviously, the average speed of these two gait also can be derived as follows:

$$v_1 = \frac{s_1}{\sum_{i=1}^{n}\frac{1}{f_i}} \qquad (n=6) \quad (6)$$

$$v_2 = \frac{s_2}{\sum_{i=1}^{n}\frac{1}{f_i}} \qquad (n=8) \quad (7)$$

where n and f_i respectively indicate the number of steps in one periodic gait and the frequency of each step. According to equation 6-7, we can easily control the motion speed by adjust the frequencies of the air sequence.

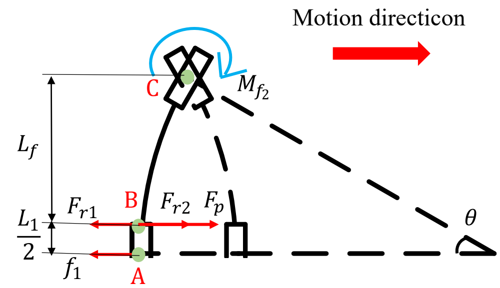


Fig. 8. Force analysis diagram of half 2D-SSR.

As mentioned above, the tightness of the screws on the three suckers is important for the robot to achieve various gaits. In other words, it is necessary to maintain a rotational degree of freedom between suckers and aluminum pipe so that the elastic restoring force and bending force can push the robot forward. Thus, the critical condition of force in the robot should be analyzed.

Here, taking the transverse locomotion gait as an example, the locomotion analysis was performed.This gait involves two rotations of aluminum pipe, which the rotation from Step 3 to Step 4 and the other rotation from Step 5 to from Step 6 Due to the symmetry, it is only necessary to analyze the force on half of the robot. Fig. 8 shows the force analysis diagram of half 2D-SSR from Step 3 to Step 4. The robot moves from the state indicated in solid line to the state indicated in dashed line. Points A, B, C are respectively the center of the central sucker (C_4), the end of the central sucker (C_4) and the center of the sucker (C_1). In this case, four forces and one moment, including the friction of central sucker f_1, the elastic resistance F_{r1} caused by elastomer, the elastic restoring force F_{r2} caused by deflating two chambers, bending force F_p caused by other inflated two chambers and one resisting moment M_{f2} caused by the torsion of screw, are applied on the robot. The analysis shows that the rotation of the screw on the sucker is the key to robot locomotion. The rotation conditions to be satisfied are provided as follows:

$$(F_p + F_{r2} - F_{r1})L_f - M_{f2} - f_1(L_f + \frac{L_1}{2}) > 0 \qquad (8)$$

where L_f is the moment arm from Point B to Point C and can be calculated as:

$$L_f = \frac{L_2}{\theta}\sin\theta\cos\theta + \frac{L_1}{2}\sin\theta \qquad (9)$$

IV. EXPERIMENTS AND RESULTS

A. Pressure Test for Bending Angle

The relationship between pressure and bending angle largely affects the turning gait of 2D-SSR. A pneumatic control system [15] which could adjust air pressure in real time with nine air channels were adopted in this test. Besides,

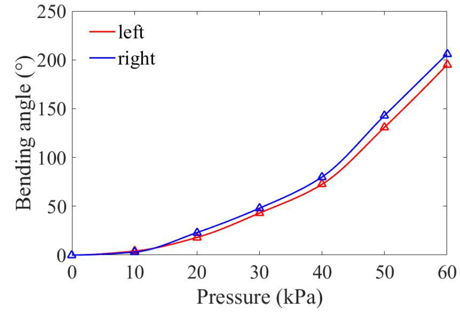
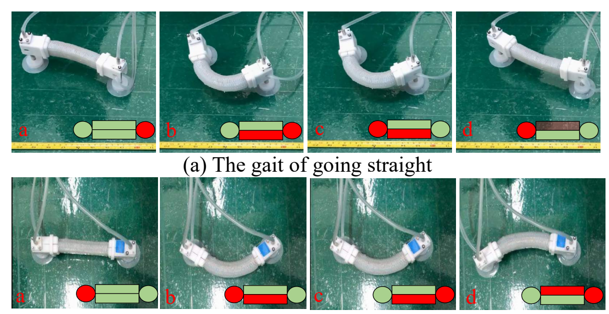


Fig. 9. Relationship between air pressure and bending angle.

an IMU was fixed at the end of the actuator to measure the angle corresponding to the pressure in each chamber. The testing results are shown in Fig. 9. The bending angle was positively proportional to the air pressure for both chambers. The result was consistent with our intuitive experiences. In addition, as the pressure increased, the bending angle increased. In other words, the relationship between pressure and bending angle showed significant nonlinearity.

B. Single-Module Test



(a) The gait of going straight

(b) The gait of turning

Fig. 10. Single module locomotion of going straight and turning. At the bottom right corners of the subgraphs, the ON air channel in each step are shown in red, and OFF air channels shown in green.

The single-module robot is composed of one soft actuator, two connectors and two suckers. As shown in Fig. 10, even though the degree of freedom of the single-module robot is less than that of 2D-SSR it can dexterously achieve forward walking and turning. Both walking straight (Fig. 10a) and turning (Fig. 10b) depend on the sucker fixation and actuator bending cooperation. The gaits of them are similar except Step d is different. The pressure of chamber during forward gait is smaller than that during turning gait, as indicated in pale red in Fig. 10a. The larger pressure allows the sucker to generate reversed bending, whereas the smaller pressure just overcomes the friction and makes the actuator to restore its original state. With the proper sequence, the speed of straight walking reached 4.5 mm/s.

C. Double-Module Test

In addition, the double-module robot (2D-SSR) could move, had more interesting locomotion gaits and reached a faster speed. According to the simulation gait sequences shown in Fig. 6, the 2D-SSR prototype could vividly display the simulation gaits shown in Fig. 5. The experimental performances shown in Fig. 11, Fig. 12 and Fig. 13, corresponded to the transverse locomotion gait, snake locomotion gait and turning gait, respectively. In the simulation of the three gaits, the 2D-SSR prototype was fixed on the floor to generate the larger friction by actuating suckers, so that the displacement could be generated by actuating soft actuators. Because of the longer resisting arm, reverse inflation is needed to make the soft actuators to restore its original shape (Fig. 12e, Fig. 12h), which is described by pale red in the subgraph. With various locomotion gaits, the 2D-SSR could flexibly move in different environments. After some complete locomotion periods, the speeds of transverse locomotion gait and snake locomotion gait respectively reached 18.4 mm/s and 8.1 mm/h, which were faster than that of the single-module robot.

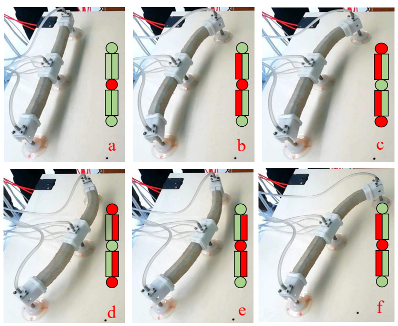


Fig. 11. The transverse moving gait of 2D-SSR. At the bottom right corners of the subgraphs, the ON air channel in each step are shown in red, and OFF air channels shown in green.

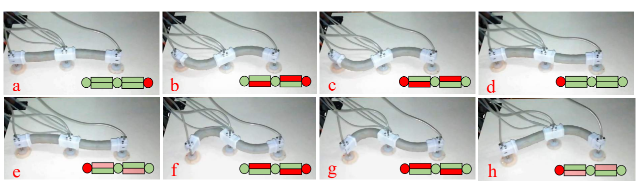


Fig. 12. The snake moving gait of 2D-SSR. At the bottom right corners of the subgraphs, the ON air channel in each step are shown in red, and OFF air channels shown in green.

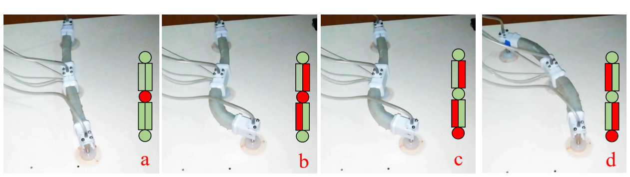


Fig. 13. The turning gait of 2D-SSR. At the bottom right corners of the subgraphs, the ON air channel in each step are shown in red, and OFF air channels shown in green.

V. CONCLUSIONS

In this study, a novel, flexible and reconfigurable soft sucker robot, moving in plane, has been developed. This robot has five sections, including two sections made of soft actuators bending in pure in-plane and other three sections made of rigid connectors with three suckers. The design of the configuration, part structure, fabrication process, and geometric kinematics have been presented in details in this study. Based on the kinematics and specific sequences, the periodic locomotion of three gaits was analyzed and simulated. The critical conditions for the motion were explained. The tests with the prototype indicated that bending angle of the soft actuator was positively nonlinearly correlated to air pressure. The experiments of walking forward and turning have verified the good performance of the single- and double-module robots. The forward locomotion speed of transverse locomotion gait (about 18.4 mm/s) was faster than that of snake locomotion gait' (about 8.1 mm/s) and single module moving (about 4.5 mm/s) and may be accelerated by optimizing sequence planning. In the future, we aim to investigate more interesting gait with the robot by changing the logic of sequence and adding more modules.We also will optimize the configuration of the robot to make the robot achieving moving on 3D plane.

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