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Worm-inspired robot with variable stiffness mechanism including fluidic bellows

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1 Introduction

Recent studies in soft robotics [1] have focused on variable stiffness mechanisms [2]-[6] that can arbitrarily switch the stiffness of a robot. Soft robots have a flexible structure that allows them to undergo large deformations passively and actively, but they deform themselves when they work. If a soft robot can switch stiffness, it can become flexible when it deforms and high stiffness when it works.

A soft gripper [7][8] that can grasp an object while transferring its shape has been realized by utilizing the variable stiffness mechanism. The soft gripper has become a major method of using the variable stiffness mechanism, but further expansion of applications is also expected.

On the other hand, many bio-inspired robots have been studied in various methods (ex. [9]). However, as far as we know, there are few examples of combining the main features of two or more organisms. We think that a structure is constructed by picking out the advantages of the two features would be very effective in adapting to an ever-changing and unknown environment (Figure 1). In switching between these two advantages, we will use the variable stiffness mechanism we have been developing for many years.

In this study, we realized a robot that can move softly like a worm with cilia and can apply pushing force to the external environment such as digging a hole, while protecting itself from external factors such as beetles by using the variable stiffness mechanism. To realize the worm-inspired robot, the variable stiffness mechanism with rubber bellows was used (Figure 2). This robot achieves variable stiffness, curvature, and expansion/contraction functions by applying negative or positive pressure to the inside of the bellows. In this way, a single tube can actively propel like a worm and protect itself from external forces.

In this paper, we present the basic principle of a mechanism that obtains different characteristics by expanding and contracting the enclosed bellows. Based on this principle, we report the realization of a worm-inspired robot with cilia that which becomes high stiffness during contraction and is actively propelled by the extension force of the bellows when positive-pressure is applied.

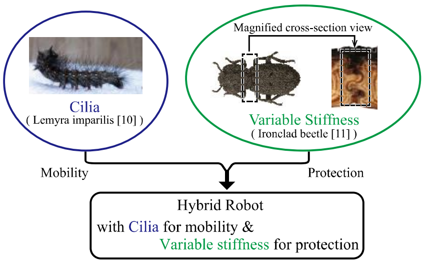
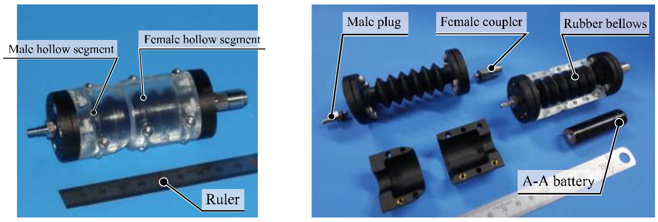


Figure 1: Hybrid robot concept with cilia and variable stiffness.



(a) Prototype including rubber belows. (b) List of parts that make up the prototype.

Figure 2: Prototype of the proposed mechanism.

2 Basic Principle

The proposed mechanism consists of a single rubber bellow enclosed in a link structure composed of hollow segments (Fig. 3). When negative pressure is applied, the bellows contract in the axial direction and the contact force between the segments enables the joint angle to be held.

When the bellow is pressurized, the link structure extends in the axial direction, generating a pushing force toward the external environment. The antagonistic arrangement of the prototype shown in Fig. 2 also makes it possible to provide an active curvature function.

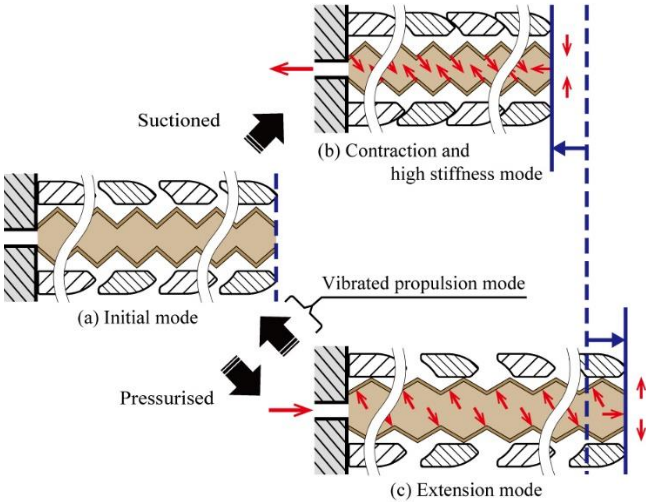


Figure 3: Basic Principle of proposed mechanism.

3 Mechanical Design

Table 1 shows the prototype specifications, Figure 3 shows a cross-section of the prototype and Figure 4 shows how the prototype was assembled. A tapered connector is inserted into the end of the bellows and the bellows is fixed to the connector with adhesive and polyethylene thread. The bellows is clamped between a plate with tapered holes and the connector to prevent air leakage. The bellows is then sandwiched between the divided hollow segments and the segments are fixed to the connector. The coupler is then fixed to the connector to make it possible to connect the prototype arbitrarily.

The segments and connectors of the prototype are made of nylon and manufactured using fused filament fabrication (Mark Two, Markforged, USA). The rubber bellows are made of nitrile for easy bonding (MC-116, Hasegawa bellows, Japan).

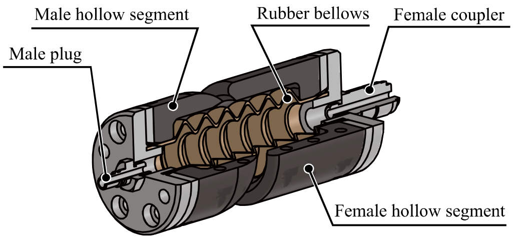


Figure 3: Cross-Section Structure Diagram.

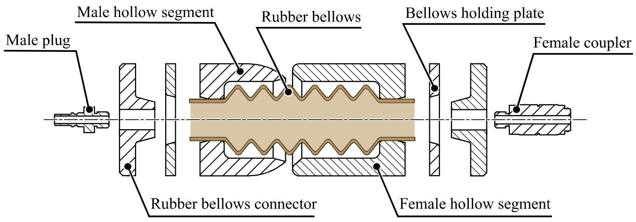


Figure 4: Assembly method of the linear structure.

Table 1: Specifications of the proposed mechanism.

Length of prototype	112 mm
Mass of prototype	72.7 g
Outer segment diameter	35 mm
Inner segment diameter	24 mm
Distance between segments	4 mm
Bellows length	70 mm
Outer bellows diameter	23 mm
Inner bellows diameter	11 mm

4 Experiment and Discussion

4.1 Motion of prototype when negative pressure is applied.

Using a prototype designed according to the basic principle, it has been confirmed that the prototype can become highly stiff at any angle by suction during bending (Figure 5 and supplementary movie).

However, the minimum internal pressure is -35 kPa, and it is currently difficult to maintain the joint angle against its own weight. This is because the rubber bellows crushes in the radial direction when an internal pressure not greater than -35 kPa is applied.

One solution is to seal a ring inside the bellows to prevent it from crushing in the radial direction. The method of sealing the ring is to fabricate the bellows by pouring rubber into a mold. By pouring the rubber while placing the ring in the mold, it is possible to make bellows in which the rubber and ring are combined.

4.2 Motion of prototype when positive pressure is applied.

The prototypes are connected by couplers, and the worm-inspired robot with nylon cilia attached to the surface of the segment is shown in Figure 6(a). The cilia are inclined backward in the direction of propulsion. The cilia prevent the prototype from returning to its initial position when air is released after extension during pressurization.

Repeated extensions during pressurization enable active propulsion (Figure 6(b) and supplementary movie). However, since the current prototype is difficult to propel in any direction, it is a future work to attach wires or other devices for active curvature.

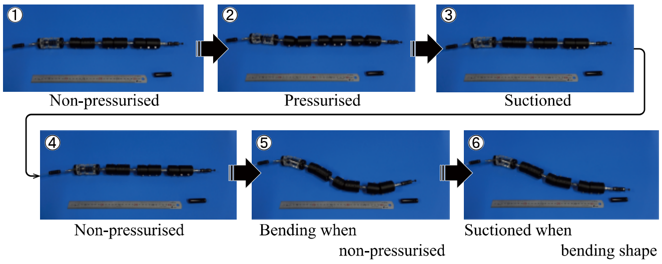
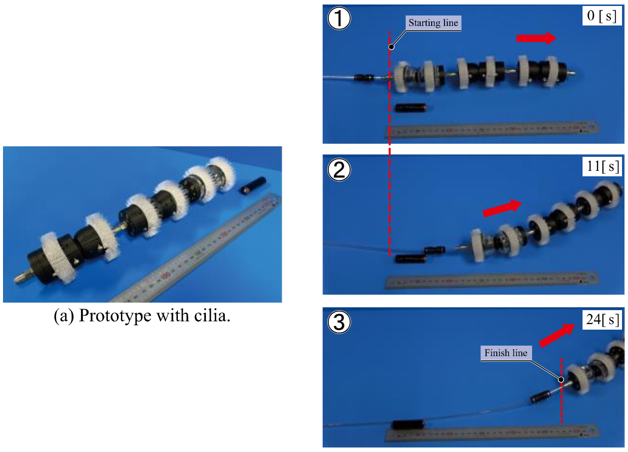


Figure 5: Confirmation of the extension and contraction, bending, variable stiffness (https://youtu.be/BLId27_bsm0).



(a) Prototype with cilia.

(b) Active propulsion.

Figure 6: Active propulsion by axial extension of the prototype with cilia (https://youtu.be/BLId27_bsm0).

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