Pipe Climbing Robot TAOYAKA VII

Simplified Control of Grasping Force Using a Current Sensor

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***Abstract*— This paper presents a bioinspired pipe-climbing robot that can grasp various columnar objects with unknown shapes by utilizing a passive mechanism. Through this proposed passive mechanism, the arm replicates octopus-like behavior, allowing it to conform to unknown objects without sensing their shape. In this paper, we improved our previous robot and installed current sensors to measure the motor current and estimate the grasping force. Using the current information, the robot controls the grasping force and climbs various columnar objects with different shapes. To demonstrate the effectiveness of the proposed robot, an improved version was developed, and experiments were conducted. As a result, we confirmed that the proposed system works well and that the robot could grasp various unknown-shaped objects using a preset grasping motor current.**

Keywords-climbing robot; flexible mechanism; passive mechanism; bio-inspired robot; octopus-like robot.

I. INTRODUCTION

Autonomous systems operating in unknown, complex environments—such as autonomous vehicles, domestic robots, agricultural robots, construction robots, and rescue robots—have attracted great attention, and various research efforts are being conducted in this area. In general, controlling these robots in complex environments is very challenging because, in unknown environments, robots need various sensors to gather extensive information about their surroundings, and significant computational resources are required to process this information. Additionally, controlling the robots' many degrees of freedom also demands considerable computational power.

On the other hand, even lower organisms in nature can exhibit intelligent behavior in natural environments. In particular, some of these organisms do not possess enough processing ability to control the many degrees of freedom of their bodies in complex natural surroundings. Nevertheless, their behavior remains adaptive.

The mechanism by which they achieve adaptive behavior is not yet fully understood. However, it is thought that the interaction between the body and environment plays an important role, and that flexible or passive mechanisms are crucial for making use of this interaction. Based on this concept, various soft robots have been developed [1]-[14].

In our previous work, we developed various bio-inspired robots with flexible or passive mechanisms, among which the pipe-climbing robot TAOYAKA [1]-[3] is one example. TAOYAKA's arms have multiple passive joints, and by simply pulling a string with a motor, octopus-like movements are achieved, allowing the arm to hold pipes of unknown shapes. In the earlier version of this robot [1], motion control was successfully realized through the interaction between the robot and the pipe. However, controlling the grasping force remained a challenge.

In summary, the biggest challenge in our projects is how to control the many degrees of freedom of a robot in a complex environment. The solution lies in utilizing the interaction between the body and the environment by mimicking the strategies of real creatures.

In particular, this research focuses on grasping force. We improved the previous robot by adding a function to control the grasping force using a simplified method that employs motor current sensors.

The remainder of this paper is organized as follows. Section II introduces the strategy of the octopus. Section III reviews related work and previous research. Section IV proposes an improved robot design. In Section V, we present an experiment to demonstrate the effectiveness of the proposed approach. Finally, Section VI concludes the paper.

II. RERATED WORK AND PREVIOUS WORK

We introduce the behavior of octopuses that inspired us to develop our robot, and we explain earlier and related robots.

A. *Strategy of octopus*

The octopus can grasp various objects of unknown shapes without seeing them. To achieve this intelligent behavior, the octopus uses a strategy in which it gradually contacts its flexible arm with the unknown object from the root to the tip, as shown in Figure 1. Through this strategy, the shape of the arm is determined by the interaction with the object, allowing it to cover the object without sensing its shape.

Our robot, TAOYAKA, is designed to replicate this strategy and can climb pipes or pillars of unknown shapes.

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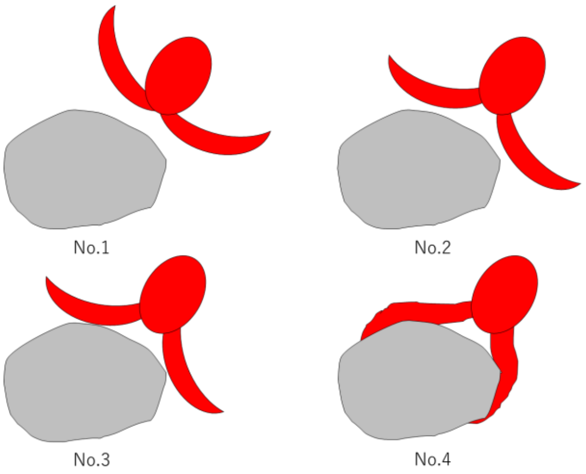


Figure 1. Grasping strategy of octopus

B. *Soft robots*

Recently, various soft or flexible robots have been developed because they can adapt to complex environments through interaction [4]-[8]. Many conventional soft robots are driven by air, and a pushing force is used to move the body [4]-[8]. However, high pressure reduces softness, and adaptability decreases when generating large forces.

In our previous study [9], we took this disadvantage into account and proposed a novel mechanism driven by the pulling force of a string. In another study [10], we confirmed the advantages of the pulling mechanism through experiments. Using this mechanism, we developed an octopus-like manipulator, as shown in Figure 2 [9][10]. This manipulator can easily pick up objects of unknown shapes by replicating the octopus's strategy. In [10], we proposed utilizing the dynamics of a soft body to reproduce octopus-like behavior and demonstrated its effectiveness through experiments. Subsequently, we applied this grasping mechanism to a pipe-climbing robot, TAOYAKA (Figure 3) [1]-[3]. This robot can grasp pipes or pillars of unknown shapes and climb them. TAOYAKA has two versions based on size: in [1][2], we developed larger versions made with an aluminum frame for structural support and passive rubber joints for flexible movement. In [3], we developed a smaller version using silicone rubber, which can climb real tree branches thanks to its flexibility (Figure 4).

These robots were able to achieve adaptive behaviors despite their simple mechanisms. This provides a significant advantage over conventional complex control mechanisms. However, the grasping force was not adjustable and remained constant. As a result, it was necessary to set an appropriate grasping force in advance, and autonomous control of the grasping hand was anticipated.

In this paper, we introduce a simple controller for regulating the grasping force, utilizing a current sensor to enhance the adaptability of TAOYAKA VI.

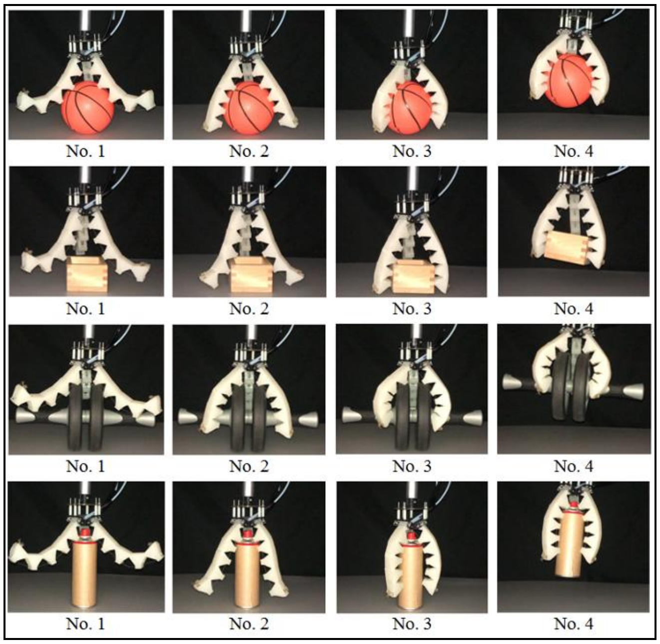


Figure 2. Octopus-like manipulator

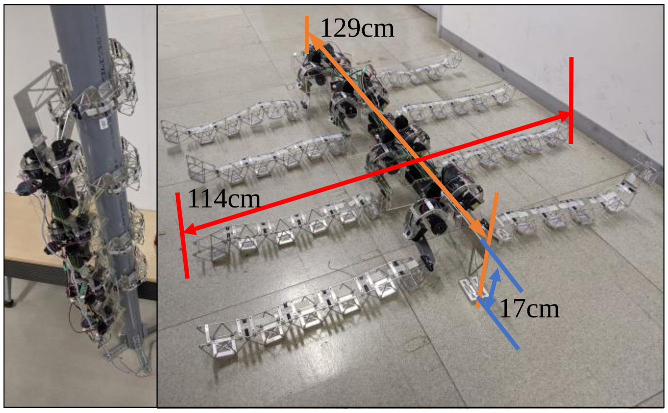
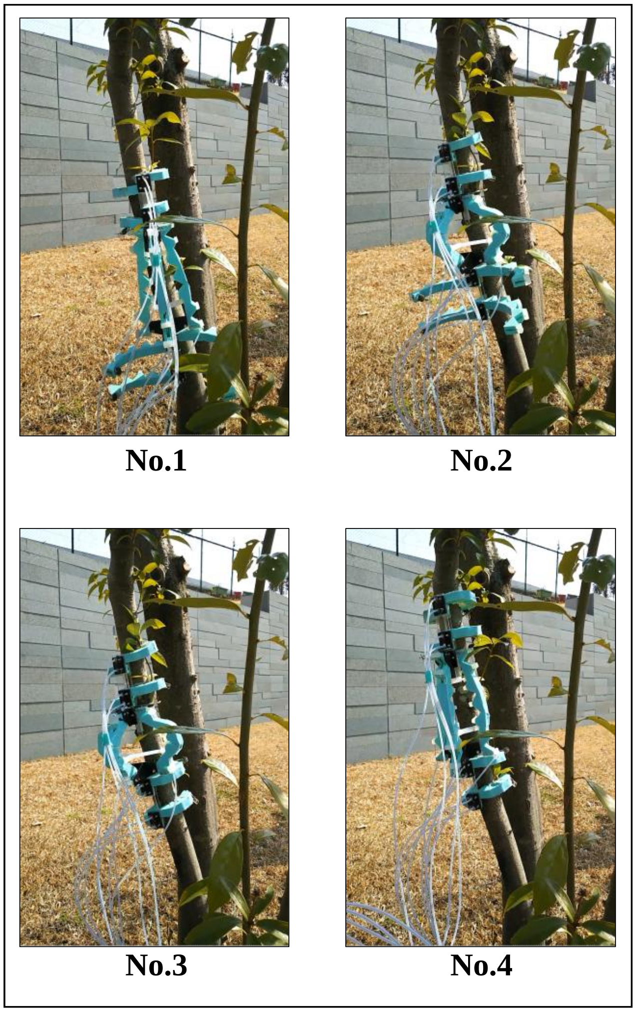


Figure 3. TAOYAKA V



No.1 **No.2**

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Figure 4. TAOYAKA-SII

III. TAOYAKA VII

We develop TAOYAKA VII by improving previous robot. Figure 5 shows the robot that we are developing, and Table 1 shows its specification.

TABLE I. SPECIFICATION OF THE TAOYAKA VII

Weight	3.0 kg
Length	105 cm
Height	149 cm
Servomotor	KRS-2572HV ICS
Worm Gear	TAMIYA Woem Gear Box HE
Microcomputer	Arduino Mega 2560
Power supply	DC power supply 12V25A

To reduce the weight, the size of the robot is slightly smaller than the previous one. The passive mechanism and moving motion are the same as the previous one, but in this version, we install grasping force control. Details are as follows.

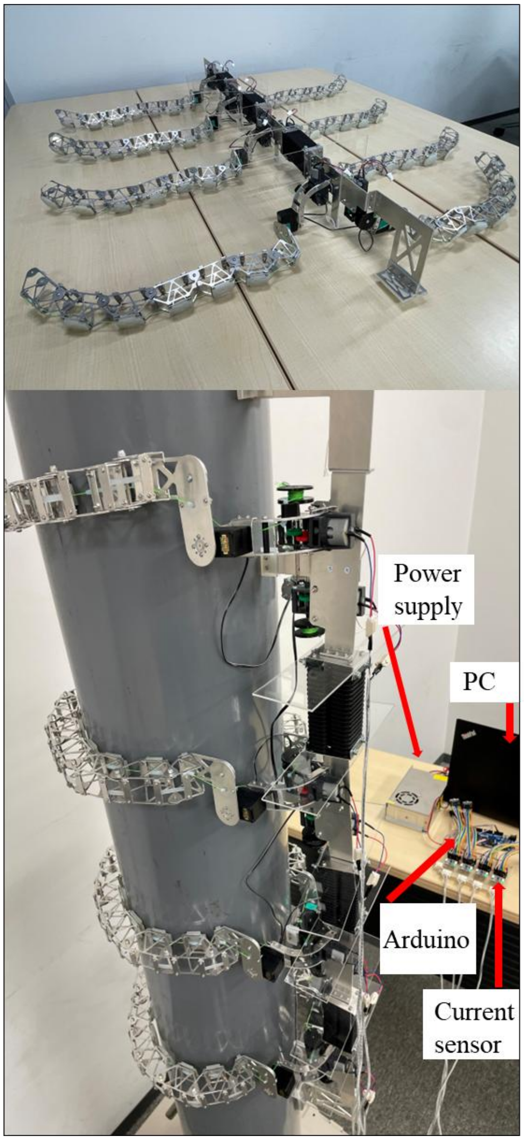

Figure 5. TAOYAKA VII

A. *Mechanisn of the arm*

Figure 6 shows the proposed arm mechanism. The arm is composed of seven passive joints and is driven by one motor with worm gear. A string is installed through the arm, and by pulling the string, the arm is closed. Rubber bands are attached between links, and the rubber strength gradually increases from the root to the tip. Owing to the difference of rubber tension, the arm moves from the root to the tip by just pulling the string, and the octopus-like movement is replicated. Figure 7 shows the octopus-like movement.

At TAOYAKA VII, we install current sensors on the motor that pulls the string. By monitoring these sensors, we can detect excessive torque and cut off the current. Since the motor has a worm gear, even if the electrical power is turned off, the arm remains locked, and the robot can keep holding.

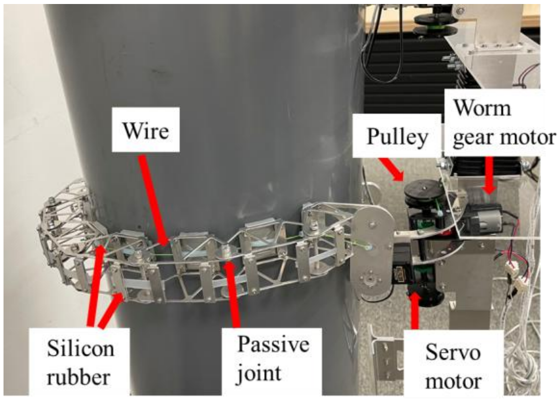

Figure 6. Arm mechanism

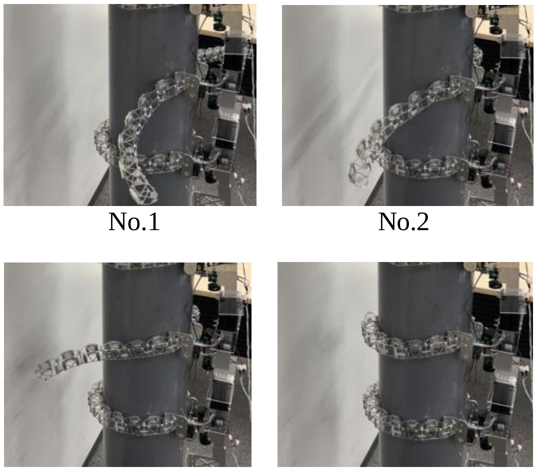
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Figure 7. Octopus-like movement

B. *Control method and motion pattern for Climbing*

The robot consists of four segments, and each segment has two arms, as shown in Figure 5. Each arm is connected to the trunk via a servomotor. When the servomotor rotates, the trunk rises, as illustrated in Figure 8. Figure 9 shows the flowchart for controlling the robot, and Figure 10 shows the climbing pattern.

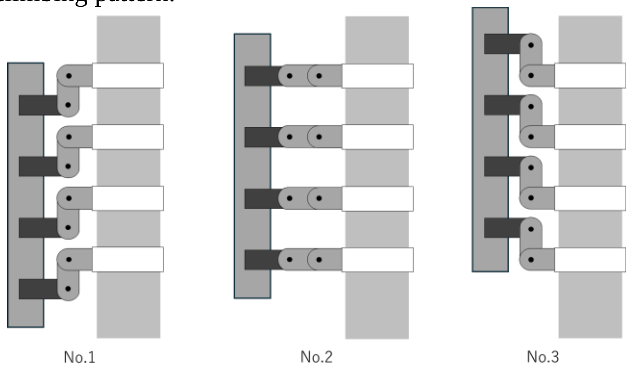


Figure 8. Rising motion

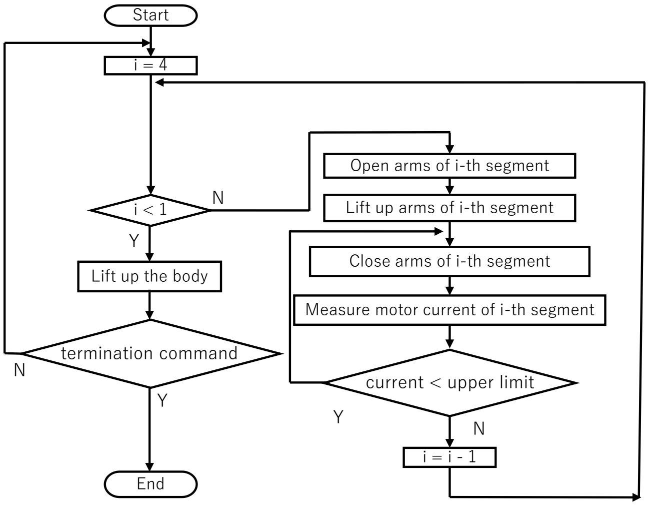


Figure 9. Flowchart for controlling the robot

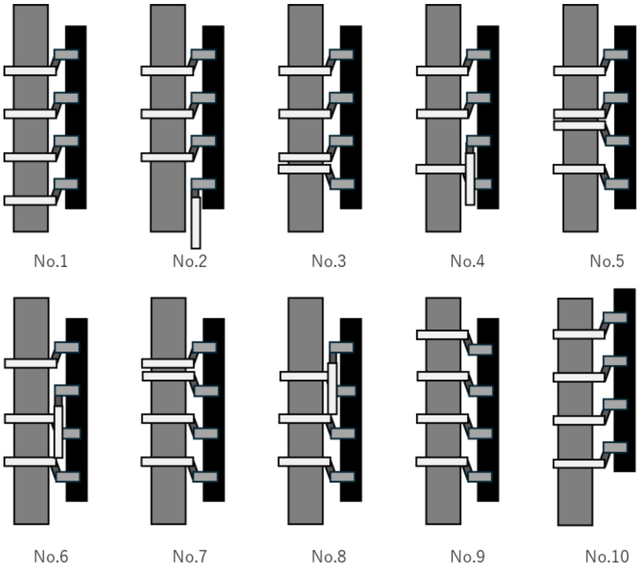


Figure 10. Climbing Pattern

By repeating the pattern of Figure 10, the robot ascends the pipe.

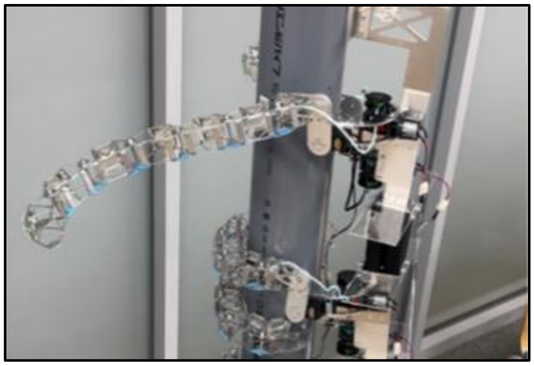
IV. EXPERIMENT

We conducted experiments to validate the proposed control scheme for grasping force. To control the grasping force, we used the motor current. We applied the same control algorithm to three pipes with different diameters. Figure 11 presents a typical behavior for one arm, and Figure 12 shows the motor current.

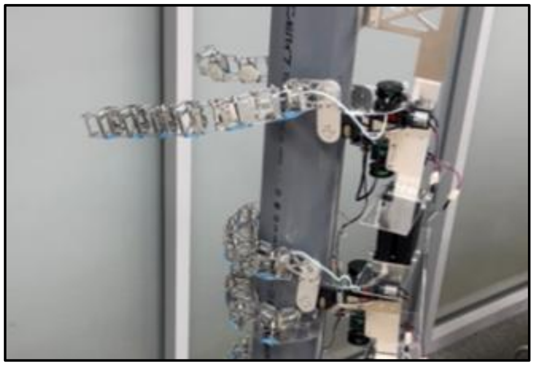
As shown in Figure 12, in the no-control case, the current was saturated at a high level, indicating that the grasping force was too high to grasp soft objects. In contrast, in the case of the proposed control, the current was cut off around the desired value.

In each experiment, the maximum current exceeded 1500 mA even though the desired value was set to 1500 mA. This is because the sampling time in this experiment was set to 0.2 seconds, meaning that the current value was measured every 0.2 seconds. The motor power was cut off only when the current first exceeded 1500 mA. Therefore, if more precise control is required, this can be addressed by shortening the sampling time.

Since the proposed mechanism employs a worm gear, as shown in Figure 6, the arm can maintain its grasp even when the motor current is cut off. Thus, the maximum grasping force can be easily controlled by the simple control scheme shown in Figure 9.



No. 1



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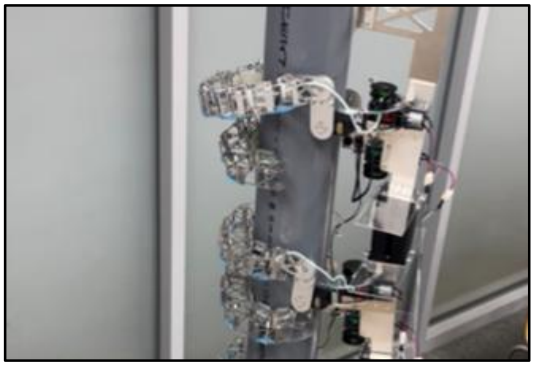

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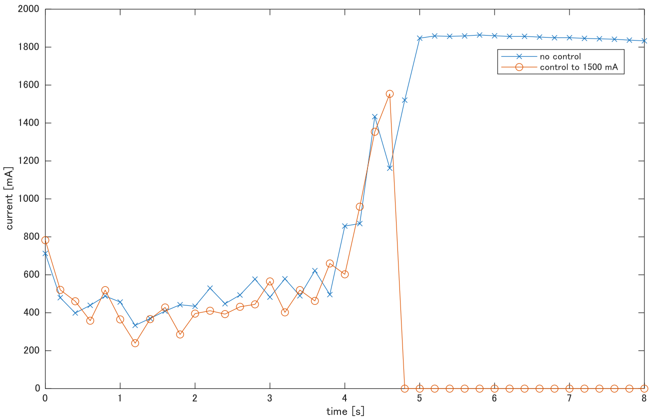
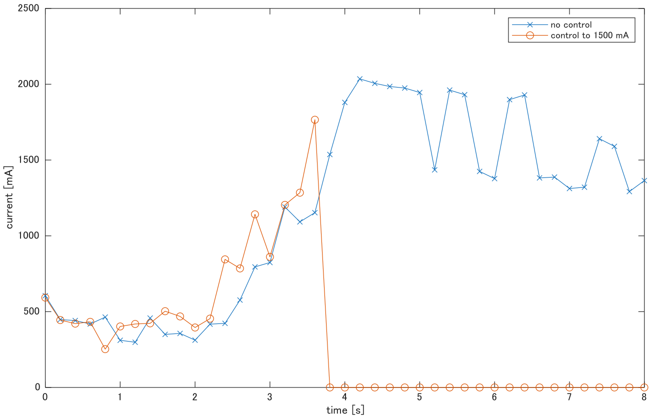
Figure 11. Realized movement

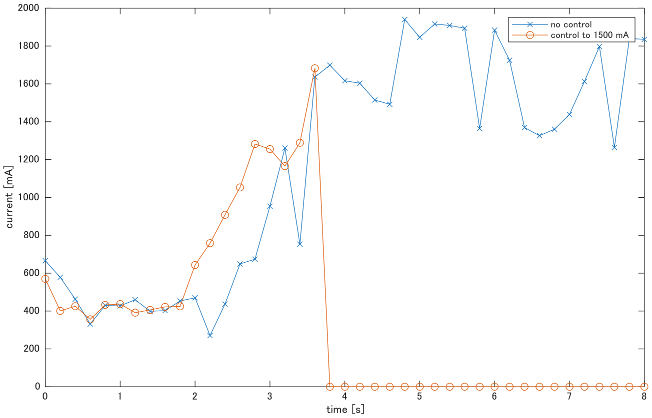
Our next step is to apply the control scheme to all the arms and conduct climbing experiments on various soft columnar objects.



a) Small paipe (diameter = 144 mm)



b) Medium paipe (diameter = 216 mm)



c) Large pipe (diameter = 257 mm)

Figure 12. Experimental result of the current control

V. CONCLUSION

In this paper, we focus on the adaptive mechanisms of animals and apply a passive and flexible mechanism to a pipe-climbing robot. We improved the previous robot by adding a function to control the grasping force using a simplified method that employs motor current sensors.

With the proposed mechanism, the arm replicates octopus-like behavior and can grip the pipe using a preset grasping motor current. Our future work is to apply this robot to columnar objects with unknown dents and bumps to demonstrate the effectiveness of the proposed mechanism.

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