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A Multifunctional Underwater Microrobot for Mother-Son Underwater Robot System

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Abstract — **In past few years, various underwater microrobots have been developed with the micromachining technology, development of smart actuators and biomimetic applications. Most of them possess the attributes of flexibility and compact structure. However, their endurances, moving speeds, and load capacities for power supplies and sensors are limited for the small sizes. So, these microrobots are not suitable for the real–world applications. To solve these problems, we proposed a mother–son robot system, which included several microrobots as sons and a newly designed amphibious spherical robot as the mother. The mother robot was actuated by four water–jet propellers and eight servomotors, capable of providing a stable high speed and carrying the microrobots to a desired target location where tasks were to be performed. To implement the mother–son robot system, we proposed a multifunctional underwater microrobot and developed the prototype by using ionic polymer metal composite (IPMC) actuators. The microrobot could perform walking, rotating, grasping, floating, and swimming motions with the compact structure. Then we evaluated its moving speeds in the water tank. At last, we carried out the releasing experiment to demonstrate the feasibility of the mother–son robot system.**

I. INTRODUCTION

UNDERWATER robots have been researched and developed with various configurations, shapes and sizes. They are of great interest for underwater monitoring operations, such as pollution detection and video mapping in restricted underwater environments [1–4]. We classify the underwater robots into two types, medium/large sized robots and microrobots. The scales of medium/large sized robots are from 10 centimeters to a few meters with excellent flexibility and endurances, while the scales of microrobots are from a few millimeters to a few centimeters which are to be used in limited spaces. If a robot is to be used in a complicated underwater environment, such as a narrow pipeline or a region filled with reefs, it should be endowed with the combined attributes of endurance, stable high speed, large load capability, flexibility, compact structure and multi–functionality. However, most of the reported underwater robots are steered by traditional electromagnetic thrusters, which are difficult to miniaturize. Accordingly, motors are rarely found in underwater microrobot applications and special actuator materials are used instead. A variety of smart materials, such as ionic polymer metal composite (IPMC), shape memory alloy pneumatic actuators, and piezoelectric elements, have been investigated for use as artificial muscles in new types of microrobots [5–11]. These microrobots possessed the attributes of flexibility and compact structure, while the endurance, moving speed, and load capability are restricted.

To resolve above problems, a mother–son robot system was proposed, which included several microrobots as sons and a newly designed amphibious spherical robot as the mother. In this system, the mother robot is actuated by four water–jet propellers and eight servomotors, capable of providing a stable high speed and carrying the microrobots to a desired target location where tasks are to be performed [12–13]. When the mother robot reaches the desired location, or encounters a narrow channel that is difficult to navigate, it assumes a stable position and acts as a base station for the microrobots. Then, the microrobots exit the mother robot, proceed to the target position and carry out their tasks.

In our past researches, we have developed a prototype spherical mother robot and evaluated its amphibious motion, which showed a good performance and proved its feasibility in the mother–son robot system. For the microrobots, aside from fish–like and mantaray–like swimming locomotion, we have developed several microrobots that employ biomimetic locomotion to implement walking, floating, and swimming motions [1, 5, 10, 13–17]. However, each of these units implements only some of these underwater motions and it is hard for them to stride over a mall obstacle for the legs are in the lying state. In order to create a compact structure with efficient and precise locomotion, flexibility, and multi–functionality, we have developed a new microrobot with nine IPMC actuators, used as legs, fin or fingers. This unit employs six of its actuators to walk, rotate and float. Two actuators in the front are utilized to implement grasping and one actuator in the rear is used to drive the fin for the swimming motion. Moreover, the microrobot can get across some small obstacles.

This paper is structured as the following. First, we introduce the proposed concept of mother–son underwater robot system. Second, we describe the fabrication and characteristics of the IPMC actuators that are used to drive the microrobot. Third, we show the prototype of the microrobot and carried out experiments to evaluate walking, rotating, grasping, and swimming motions. Fourth, we carry out the release experiment to demonstrate the feasibility of the mother–son robot system. Finally, we present our conclusions.

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II. MOTHER-SON UNDERWATER ROBOT SYSTEM

Underwater microrobots possess some attributes of compact structure, multi–functionality, flexibility, and precise positioning, which can be used in limited underwater environments. However, they lack the attributes of long endurance, stable high speed, and large load capacity. To implement these characteristics, we proposed a mother–son robot system, which included several microrobots as sons and a newly designed amphibious spherical robot as the mother. The mother robot can carry son microrobots to be close to the target position and release these microrobots [10, 13].

Compared with a single large robot, when the final tasks are carried out by microrobots, it is easier to adapt to narrow environments and implement relatively high positioning precision. Also, compared with individual microrobots, the mother–son system offers the following advantages: 1) the motion range of the overall system is expanded; 2) the microrobots can obtain a relatively stable, high power supply from the mother robot; 3) the microrobots can be designed with a more compact structure.

III. DESIGN AND MECHANISMS OF THE MICROROBOT

A. IPMC actuator

Ionic polymer metal composite (IPMC) is an innovative material made of an ionic polymer membrane, chemically plated with gold electrodes on both sides. According to mechanical analysis, bending deformation of an IPMC actuator results from the redistribution of internal water molecules. Under the influence of an applied stimulus, the water molecules in the actuator are redistributed in the following two stages [17]. Its actuation characteristics show significant potential for the propulsion of underwater microrobots. It is lightweight and has a suitable response time, high bending deformation and long life. IPMC is widely used in soft robotic actuators such as artificial muscles, as well as on dynamic sensors [15–22]. The ionic polymer metal composite adopted for this research consists of Au deposited on Nafion^{TM} film with a thickness of 0.2 mm.

B. Proposed structure of the microrobot

Figure 1 shows the proposed structure of the underwater microrobot. It consists of six legs, two fingers, and a caudal fin. Two IPMC fingers are designed to grasp some small objects, while the caudal fin is used to implement swimming. The microrobot can also perform walking, rotating, and floating motions by using six IPMC legs. Two inside legs are called supporters and four outside legs are called drivers. Compared with previous developed lying legs, the newly proposed structure can increase the distance and reduce the friction between the body and ground when it walks on the uneven terrains.

Nine actuators are all 15 mm long, 3 mm wide and 0.2 mm thick. The total size of the microrobot is 65 mm long (including the two fingers and the tail), 52 mm wide and 21 mm high.

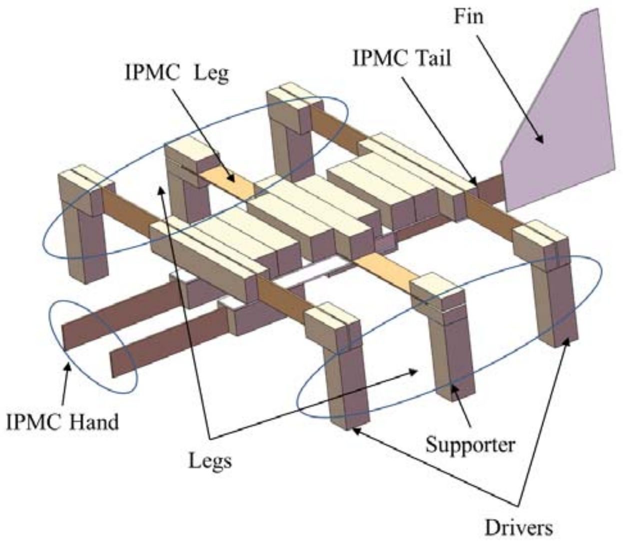


Fig. 1 The proposed structure of the underwater microrobot

C. Mechanism of the walking/rotating motion

The microrobot can perform walking/rotating motions by using two supporters and four drivers that are driven by square waves with the same frequency, and the phase of the two supporters lags 90° behind that of the four drivers. Figure 2 shows one step cycle of walking motion. Changing the bending directions of drivers, the microrobot can walk forward or backward and rotate clockwise or counterclockwise.

D. Mechanism of the grasping motion

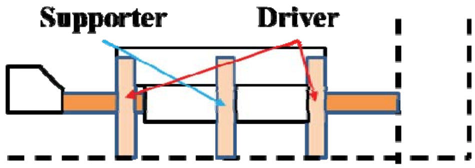
Figure 3 shows enlarged picture of a pair IPMC fingers. The distance between two fingers is 11 mm and they are attached to the front of the microrobot. The generated bending force of two fingers is determined by the driving voltage and the tip displacement. For a given driving voltage, when the deflection increases, the bending force decreases. Hence, the grasping capability is determined by the size of the object and the coefficient of friction when the stimulus is fixed [23].

E. Mechanism of the swimming motion

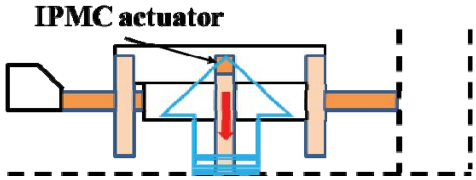
Figure 4 shows enlarged picture of the caudal fin. It consists of one IPMC actuator and one soft fin. Applying square waves, the IPMC actuator bends back-and-forth. Then, the caudal fin implements swing motion and pushes water to generate counterforce. The swimming speed and direction can be controlled by changing the swing frequency and amplitude.

F. Mechanism of the floating motion

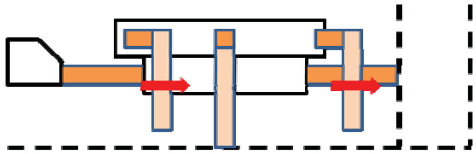
The floating motion can be implemented by decreasing the frequency of the driving voltage. Then, the water around the IPMC surface is electrolyzed to generate gases. Some bubbles are attached on the IPMCs' surface to increase the buoyancy. When the upward force arrives at a certain value, the microrobot starts to float. The buoyancy and floating speed can be controlled by the frequency of the driving voltage.



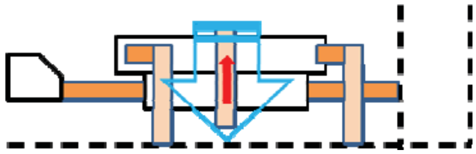
(a) Initial state



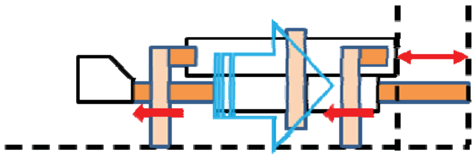
(b) Supporters bent down, drivers are ungrounded



(c) Drivers bent in the direction of movements



(d) Supporters bent up, drivers are grounded



(e)Drivers bent in the opposite direction and paw the ground

Fig. 2 Mechanism of the walking motion

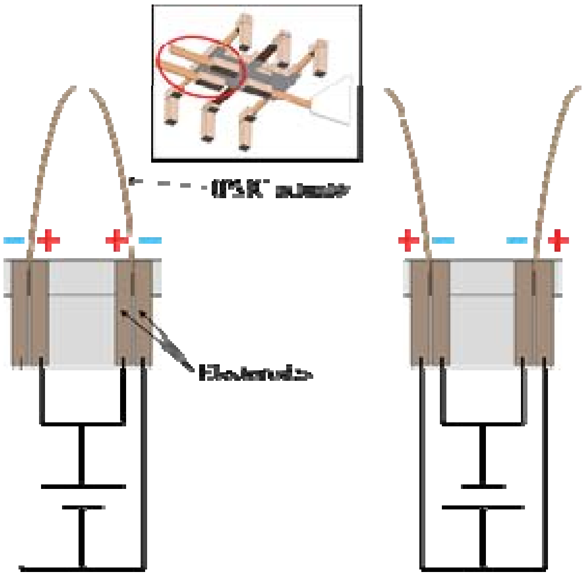
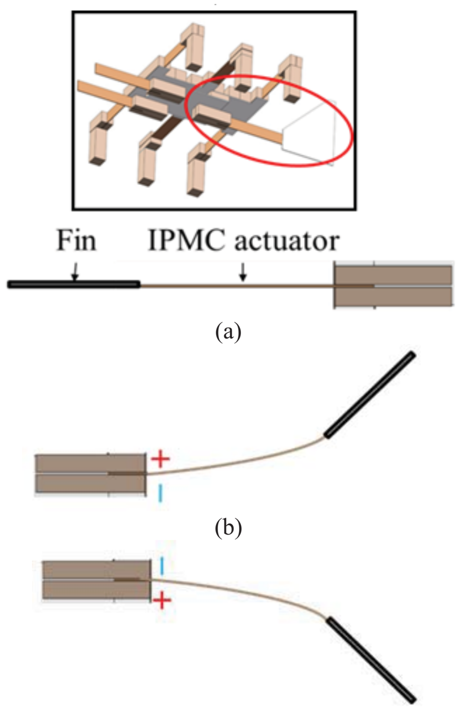


Fig. 3 Mechanism of the grasping motion



(a)

(b)

(c)

Fig. 4 Mechanism of the swimming motion

IV. PROTOTYPE MICROROBOT AND EXPERIMENTS

A. Prototype microrobot

We developed a prototype of the multifunctional underwater microrobot, as shown in Fig. 5. The specifications are shown in Table I. It is 65 mm long, 52 mm wide, and 21 mm high. The weight of the body is 5.32 g. The control signals were transmitted by enamel-covered wires from spherical mother robot.

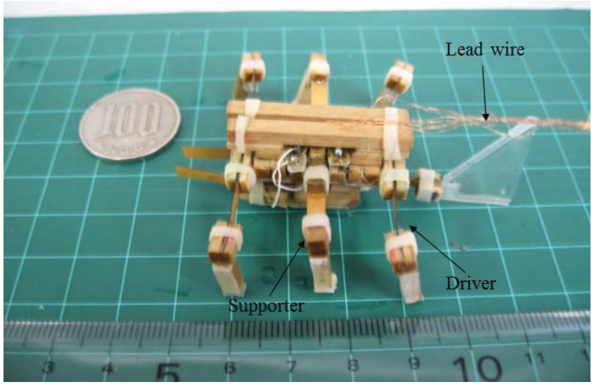


Fig. 5 The prototype multifunctional underwater microrobot.

B. Walking/ rotating experiments

Walking and rotating experiments were carried out in a water tank to evaluate the speeds of the prototype microrobot with a voltage of 8 V. We measured the time when the microrobot moved a distance of 30 mm or a angle of 90°. The experiment was repeated 5 times for one set of driving signal. Then we calculated the average walking and rotating speeds.

The experimental results are shown in Fig. 6 and Fig. 7. The results show that walking and rotating speeds can be controlled by the frequency of the driving voltage. With a voltage of 8 V, a maximum walking speed of 9.1 mm/s was obtained and a maximum rotating speed of 13.2 °/s was attained at 1.25 Hz. When the frequency was higher than 2 Hz, the walking speed approached 0. The displacement of the IPMC actuator would be smaller in a real–world application, due to the body loading, leg slippage and short response time at high frequencies. The walking and rotating speeds of the son robot are proportional to the frequency of the driving voltage, while the deflection of the IPMC is inversely proportional to the frequency. So, there is a peek for the walking or rotating speed for frequency.

TABLE I
SPECIFICATIONS OF PROTOTYPE MICROROBOT

Length	65 (mm)
Width	52（mm）
Height	21 (mm)
Weight	5.32 (g)
IPMC legs	15×3×0.2 (mm^3) ×6
IPMC hand	15×3×0.2 (mm^3) ×2
IPMC fin	15×3×0.2 (mm^3) ×1

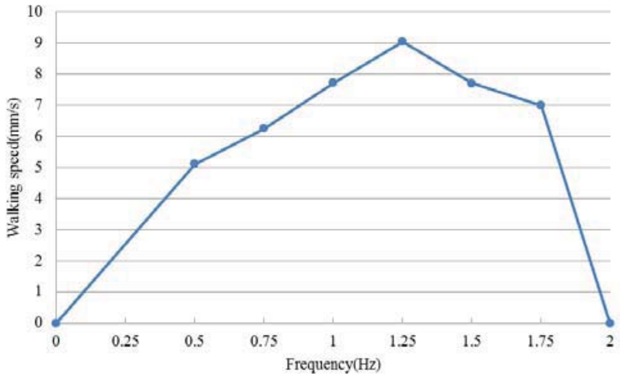


Fig. 6 Experimental walking speeds

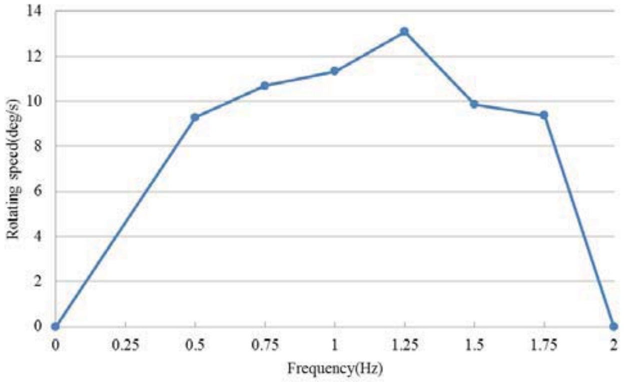
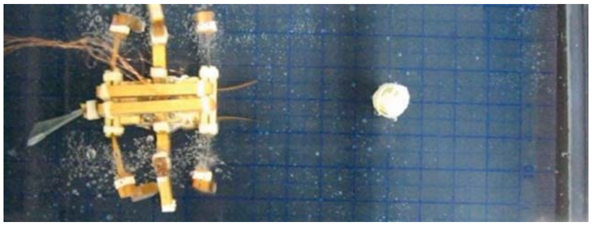


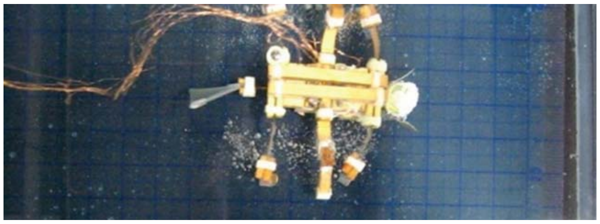
Fig. 7 Experimental rotating speeds

C. Grasping experiment

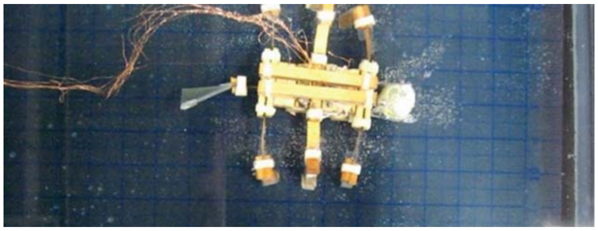
We carried out the grasping experiment to prove the feasibility of the microrobot that could grasp some small objects and carry them to desired position, as shown in Fig 8. The distance between two IPMC fingers is designed with 10 mm. While opening its two fingers, the maximal tip displacement of one IPMC finger is 5 mm. So, the width range of object should be less than 20 mm. In this experiment, we chose a cylindrical object. The diameter of the cylindrical object is 10 mm and its height is 18 mm.



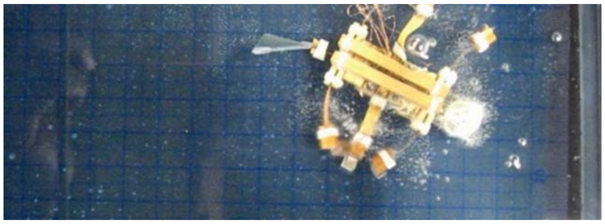
(a) Initial state



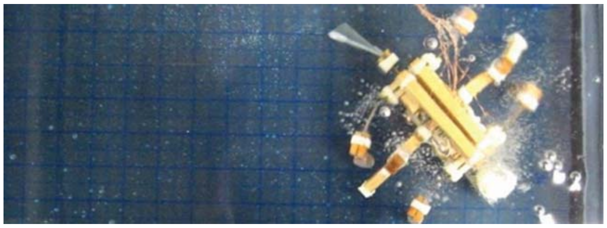
(b) Walking forward and opening two fingers



(c) Grasping motion



(d) Rotational motion



(e) Final state

Fig. 8 Grasping experiment

D. Swimming experiment

We carried out swimming experiments for the prototype microrobot on a flat underwater surface. The frequency of the applied voltage ranged from 0.25 Hz to 2 Hz with a voltage of 8 V. In these tests, we measured the time when the microrobot moved a distance of 100 mm and calculated the average swimming speed for each applied signal. The experimental results are shown in Fig. 9. The results show that swimming speed can be controlled by the applied frequency. With a voltage of 8 V, a maximum swimming speed of 8.9 mm/s was obtained at 1.25 Hz. When the frequency was higher than 2 Hz, the swimming speed also approached 0.

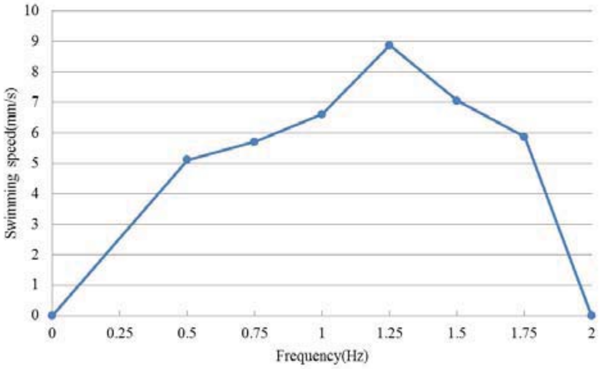
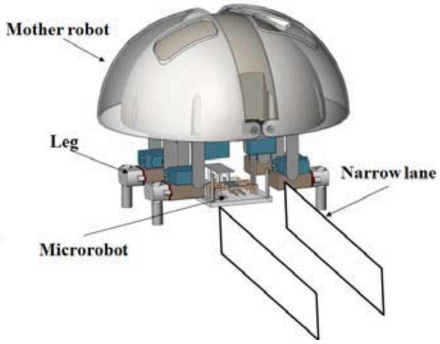


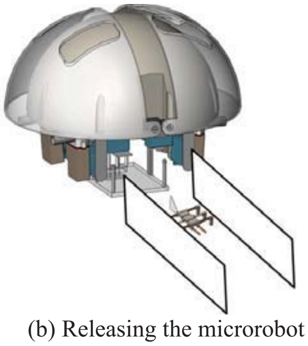
Fig. 9 Experimental swimming speeds

V. MICROROBOT RELEASING EXPERIMENT

The proposed mother-son robot system is designed for the tasks in a limited underwater space, such a narrow channel. It assumes when the mother robot reaches the desired location, or encounters a narrow channel that is difficult to navigate, the microrobots exit the mother robot, proceed to the target position and carry out their tasks. We have developed a amphibious mother robot in previous researches [25-28]. Figure 10 shows the potential condition for the mother–son robot system.

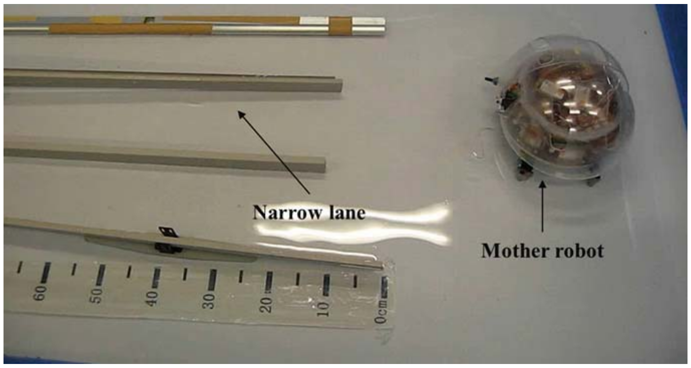


(a) Encountering a narrow channel



(b) Releasing the microrobot
Fig. 10 Assumed condition

To prove the feasibility of the of the mother-son underwater robot system, firstly we carried out release experiment for the microrobot from the mother robot. We assumed that the previous developed mother robot encountered a narrow channel that was not able to get across. Then the mother robot sat down and released a microrobot, as shown in Fig. 11.



(a) Initial position

(b) Encountering a narrow channel

(c) Releasing the microrobot
Fig. 11 Microrobot releasing experiment

VI. CONCLUSIONS

In this paper, we proposed a multifunctional underwater microrobot by using nine ionic polymer metal composite (IPMC) actuators for the mother–son robot system. Firstly, we introduced the concept of mother–son underwater robot system to implement tasks in restricted operating areas. Then, we described the fabrication and characteristic of IPMC actuator, and proposed the conceptual structure and mechanism of the multifunctional underwater microrobot. Also, we developed the prototype microrobot and carried out experiments to evaluate walking, rotating, grasping, and swimming motions. The experimental results indicate that these motion speeds can be controlled by the frequency of applied voltage. Lastly, we carried out the microrobot releasing experiment from the mother robot. We used the previous developed amphibious spherical mother robot to carry the microrobot. When the mother robot walked forward and encountered a narrow channel that could not get across. Then it released the microrobot to swim into the narrow channel.

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