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Hydraulic-driven soft robot for entering into small gap fed by indirect information of contacting state

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***Abstract*— The soft robot which has an elastic body has increased interest because of its prospects with regard to entering into small gaps such as in rubble by deforming the body according to a contacting object like an amoeba. One of the issues regarding the soft robot is the locomotion ability and another is effective usage of an appropriate sensor because the present actuator or sensor has a rigid body that prevents the deformation of the robot. This paper describes water-driven robot that generates friction locally to kick or pull the body, and it explains indirect sensing for the soft robot. A water pressure sensor is adopted to indirectly measure the contact information, and is attached near the flexible body. Because the sensor does not prevent deformation by setting an appropriate position, the body can deform according to a shape of a contact obstacle, and the sensor indicates a difference in the shape of the obstacles by moving under the obstacle. The paper also describes a feedback controller by using the pressure information that avoids break of the body inflated by water.**

***Index Terms*— Amoeba-like soft robot, Entering into small gap, Water-driven mechanism, Control of local friction**

I. Introduction

A soft robot [1], [2], [3], [4], [5], [6], [7], [8], [6], which deforms the shape of its elastic body according to a contact object, has elicited increased interest. A part of the robots are equipped with a chamber, which is inflated or deflated by the supply or release of fluid, respectively. Almost all of such approaches use gas or air as the fluid [6], [3]. The air is useful fluid because it does not pollute the robot considering the case of a hydraulic actuator, and an elasticity of the chamber changes according to the pressure. Some authors have proposed a controller to change locomotion by tuning air pressure of a McKibben pneumatic actuator [9].

One of the issues for the soft robot driven by air is an ability of the locomotion. Although the body fulfilled by air is very soft and it is expected to deform its shape according to a contacting object when the robot enters into the gap, the body cannot anchor on the ground but slip because the air is very light and the friction between the body and ground is not generated. Even in the case of the locomotion on a flat plane, the friction is too small to prevent slippage, and then the robot cannot kick or push its body that require enough friction on the contact point. Bernth et al. constructed the mechanism that generates the friction by bending its body [10]. However, this mechanism is constructed by rigid motor and wire, and they prevents the advantage of the soft body. Another issue is establishment of a sensing mechanism. Current sensors possess rigid parts, preventing the deformation of the elastic body when the sensor is attached on the body. Concerned with the sensing mechanism, some researchers do not incorporate the sensor and the robot moves without a feedback controller [2], [3], while others adopt the rigid sensor placed outside the elastic body[11]. Some authors have adopted air pressure sensor to measure the inner pressure of the McKibben actuator, which supports the joints of a robot finger, and the amount and direction of an external force on the tips of the finger is estimated from the pressure [11]. Although this force cannot be measured directly, the rigid sensor does not prevent the deformation of the elastic actuator by the external force because the sensor is not placed on the actuator but on the air tube.

Authors have developed a robot that has two chambers and is driven by water, which is heavier than air [5]. The robot employs *local friction* which is a distribution of the points that occur friction between the robot and ground to anchor the body against the reaction force when the robot contacts the obstacle. By selecting from the chambers to supply or release water, the friction between the chamber and the ground is controlled. By utilizing such a local friction, the paper explains that the robot makes contact with the obstacle by deforming its body shape and plugs into the gap by anchoring the chamber. It also explains a sensing and feedback controller for the movable hydraulic-driven soft robot. In order to measure contact information such as the contact point of the body with the obstacle and the height of the gap, we adopted a water pressure sensor. Because pressure increases when the chamber contacts the obstacle and the trajectory of the pressure depends on a shape of the obstacle contacted and height of the gap, the soft robot is expected to recognize such information in directly from the sensor information. We then measured the pressure trajectory with different gap heights, contact positions, and obstacle shapes. By utilizing such sensor information, we propose a simple feedback controller that detects contact information

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and activates water supply and release.

II. Configuration of the hydraulic-driven soft robot

A. Hydraulic-driven soft robot

One of the advantages of a soft robot is that its body deforms according to the obstacle. Some robots are driven by air as a fluid. Although the body shape can be changed by supplying and exhausting air, the weight of the body is not changed because air weights approximately zero comparing with a body frame. In case of entering into a small gap, it is expected that the robot moves by deforming its body according to contact obstacle as shown in Figure 1. However, the reaction force by body deformation occurs slippage between the body and the ground because the weight of the robot is light and friction between the body and the ground to resist the reaction force is not occurred. Therefore, the robot cannot enter into the obstacle by the slippage.

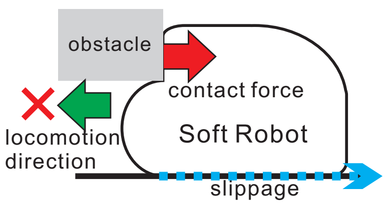
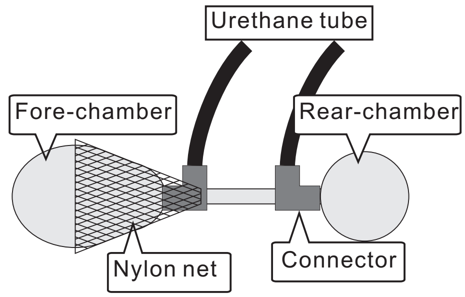
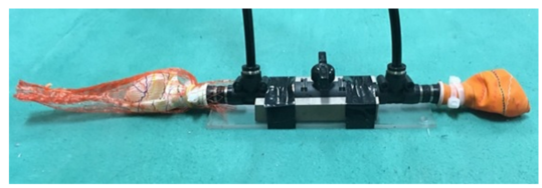


Fig. 1. Contact of the obstacle and reaction force that prevents moving forward by occurring slippage

Figure 2(a) shows our developed soft robot that is driven by water. Figure 2(b) shows physical robot. The robot equips two water balloons as chambers that store water. The chamber fulfilled by water as well as air can deform its shape according to a contacting obstacle, but water is heavier than air. Therefore, by selecting a chamber for supplying or releasing water, local friction between the chamber and the ground can be controlled. That is, when the water is supplied into the chamber, friction is increased and vice versa. By controlling local friction, it is expected that the robot resist the reaction force when the part of the body contacts the obstacle, and the robot plugs into and enters into a narrow gap with contacting the obstacle. In this paper, the chamber at fore and rear position is called as “Fore chamber” and “Rear chamber”, respectively. Weight of the chamber changes from approximately 0 g when water is released, and it is 500 g when water is supplied. Each chamber is connected by the connector (PISCO PV6), and the connectors are fixed on a PLA board. The board is called as “Trunk”. Width, depth, height, and weight of the trunk is 140, 40, 35mm and 120g. A nylon net is attached around the fore chamber in order to achieve effective forward locomotion. As shown in the figure, the fore-chamber equips nylon net. The friction between the net and the chamber is low, and the one between the net and the ground is not low. By utilizing such characteristics of the nylon net, the fore-chamber slides within the nylon net without friction when the water is supplied into the fore-chamber (see Figure 4(a)), and the force to move backward due to the inflation of the fore-chamber is omitted. A detail of the nylon net is explained in [5].



(a) schematic design



(b) pysical robot

Fig. 2. Hydraulic driven robot equipping two elastic chambers[5]

B. System configuration for driving the robot

Figure 3 shows a system to supply or release water to fore or rear chamber. The system has two water pumps (12V 60W) three water valves (SMC VDW22JZ1D). The pumps and valves are connected by an urethane tube (PISCO UB-0640). An inner diameter of the tube is 4mm. Maximum pressure of the pump is 0.85 MPa and flow volume is 5 L/min. One pump (pump M in the Figure 3) pumps water out of the tank. The other (pump N) releases to the tank. Valve A and B select a chamber for supplying or releasing water. Valve C prevents back flow of water when water is pumped out of the tank, and it is open when water is released from the chamber selected by valve A or B.

C. Procedure to move forward

In order to plug into and enter into the gap, the robot needs to move forward. Although some researches have reported the robot that moves in a pipe [12] and colon [10] under the assumption that the robot is initially set on such a narrow space, few research discuss the physical robot mechanism that enters into the narrow gap from from an unobstructed

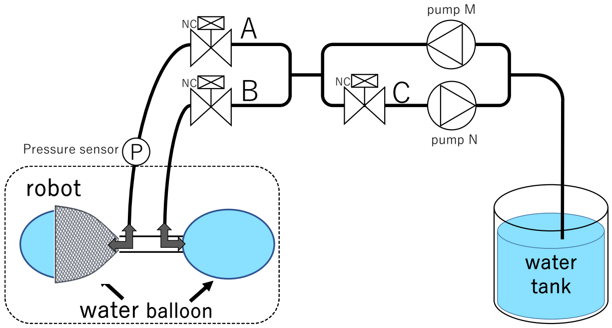


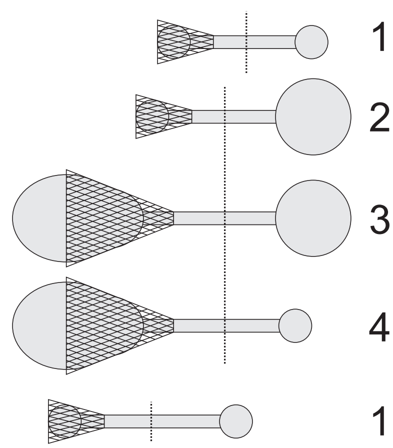
Fig. 3. Water supply / release system

space. Figure 4(a) shows a procedure to move forward. The detail of the procedure is explained in the previous work [5]. From state 1 to 2, water is supplied into the rear chamber to move forward by the inflation of the chamber. Because friction between the fore chamber and the ground is approximately zero, the fore chamber does not prevent moving forward by the inflation. From state 2 to 3, water is supplied into the fore chamber. In this phase, as explained above, the fore-chamber slides within the nylon net and the force to move backward are almost decreased. Additionally, because friction between the heavy rear chamber by the water and the ground is higher, the rear chamber anchors on the ground and the trunk does not move backward. From state 3 to 4, water is released from the rear chamber. At that time, the force to move backward is occurred by the deflation of the rear chamber. However, because friction between the heavy fore chamber with nylon net is higher, the fore chamber anchors on the ground. From state 4 to next 1, water is released from the fore chamber. Because friction between the rear chamber and the ground is approximately zero, the force by the deflation of the fore chamber brings the body forward. Figure 4(b) shows time sequence of the valve A, B and C and pump M and N shown in Figure 3. Pump M is operated to pump up the water by closing valve C. Pump N is operated to release water while valve C is open. Valve A and B select the chamber to supply or release water. An amount of water is operated by setting supply periods T_f and T_r. A relationship between T_f, T_r and locomotion performance on a flat plane without the obstacle is described in our previous work [5].

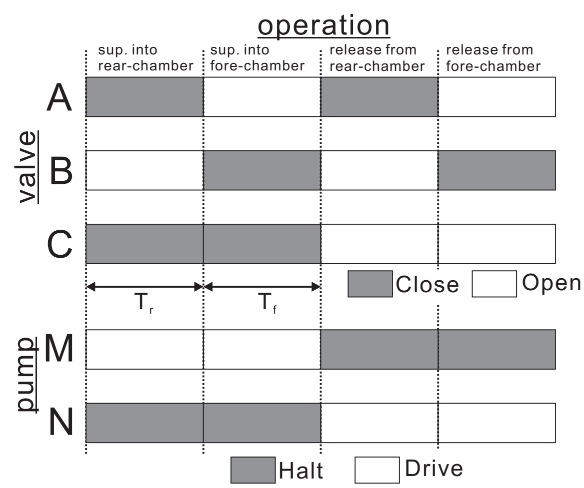
III. Sensory Information on Contact Obstacle

A. Water pressure for estimating a contact state

It is important to discuss a usable sensor for a soft robot. In order to measure a state of the soft body such as deformation of the elastic body according to contacting obstacle, one of the effective ways is to attach a sensor on the elastic body. However, it is very difficult to product a elastic sensor that does not prevent extension and contraction of the elastic body. Therefore, in our research, we put a present rigid sensor on the position where the sensor does not prevent the deformation of the body. A part of the authors have proposed a method to estimate an amount and direction of an external force on a robot finger supported by antagonistic pneumatic actuators. In order to estimate the amount and direction of the force, an air pressure sensor was utilized considering that the they influence a deformation of the elastic actuator and the pressure is changed by the deformation. Because a rigid pressure sensor was attached aside from the elastic actuators, it did not prevent deformation of the elastic actuator. They demonstrated that the magnitude and direction of the force is accurately estimated, and they concluded that such approach is effective for the soft robot [11].



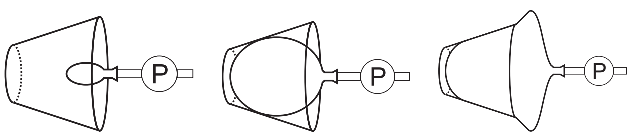
(a) Procedure



(b) Valve and pump operation

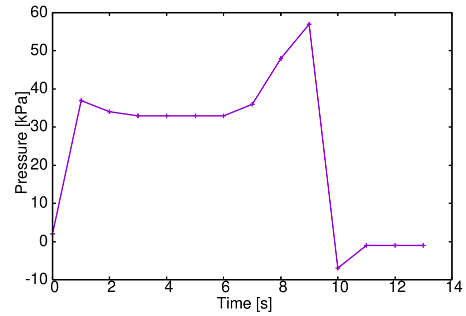
Fig. 4. Procedure to move forward

Because the dynamics of the liquid according to the pressure is very complex, we had test trial to observe the pressure profile when the chamber contacted the object by using physical chamber. The chamber was set in the cup as shown in Figure 5. The chamber inflated by supplying water, and it contacted the cup. The water was continuously supplied after contacting the cup. Figure 6(a) shows the pressure profiles. In this trial, water supply was quit to avoid break of chamber at 9s. As comparison, the chamber was inflated without contacting cup. The profile is shown in Figure 6(b). As shown in the Figuire 6(a), the pressure keeps constant except initial moment of supplying water (0-1s), and it increases after contacting cup (6-9s) while the pressure still keeps same when the chamber does not contacts the cup as shown in Figure 6(b). From these comparison, it is confirmed that the pressure rises when the chamber contacts the obstacle.

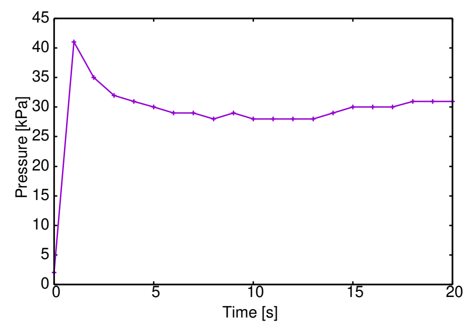


(a) chamber without water (b) chamber contacting on the dimple (c) chamber running off the dimple

Fig. 5. Step-by-step inflation of a chamber within a dimple



(a) Inflation with obstacle contact



(b) Open space inflation

Fig. 6. Profile of the water pressure when water is supplied into the fore-chamber with and without contacting obstacle

Utilizing such mechanism, we observe the pressure of the chamber to detect the contact of the object. As shown in Figure 3, the pressure sensor is attached near the fore chamber so that the sensor does not prevent an inflation, deflation, and deformation of the chamber. In order to confirm an effect of the pressure sensor, the pressure profiles with different heights of the gap, different shapes of the obstacle, and various positions of the contact point of the chamber were measured. In these experiments, the nylon net explained in the previous section was removed.

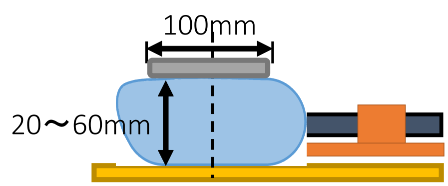


Fig. 7. Fore chamber contacting on 100mm width flat obstacle with different height of the gap

B. Water pressure profiles on different height of the gap

The pressure profiles when the fore chamber contacts the different heights of the gap were measured. The gap was set from 20mm to 60mm by 10mm. A shape of the obstacle was flat obstacle. As shown in the Figure 7, the fore chamber contacted the center of the flat obstacle. The width of the obstacle was 100mm. For comparison, a pressure profile when the chamber inflated without obstacle was also recorded.

Figure 8 shows the profiles of the water pressure of the fore chamber when the chamber contacted the flat obstacle with different heights. Except a case that the height of the gap was 20mm, water was supplied into fore chamber at 3 s, and it was sealed at 13 s, that is, water was supplied for 10 sec and then sealed in the fore chamber. When the height of the gap was 20mm, water supply was quit at 5 s because the pressure was largely increased just after water was supplied, and water was leaked from the chamber due to the higher pressure. The pressures increased higher than the case that the chamber inflated without obstacle, and it an amount of the pressure was higher when the height of the gap was smaller, and it kept higher except the case of 20 mm after quitting the water supply. From this results, the height of the gap can be distinguished by observing the water pressure profile.

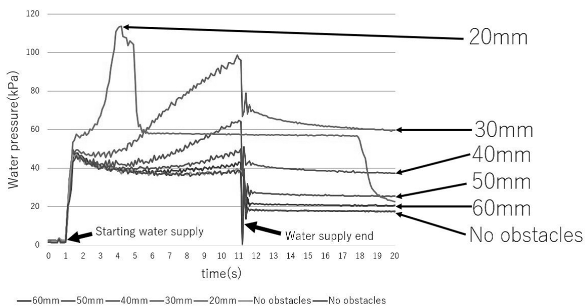


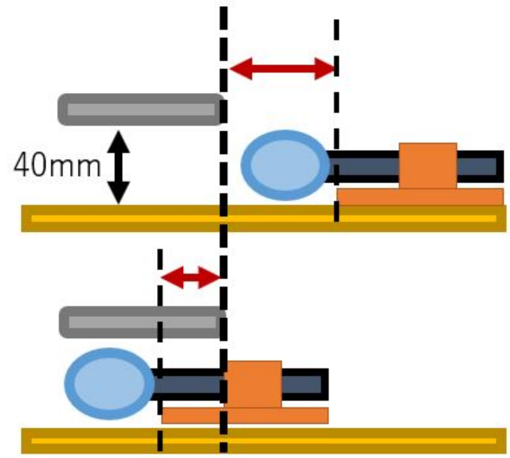
Fig. 8. Pressure profiles on different height of the gap

C. *Pressure profiles on different contact point of the chamber and obstacles*

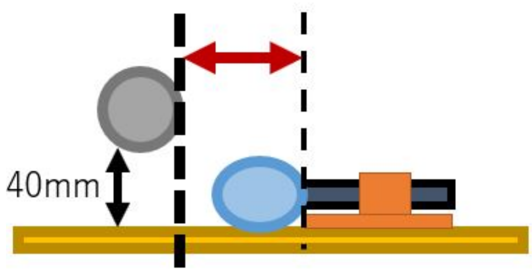
Profiles of the water pressure of the fore chamber were measured when the different position of the fore chamber contacted the different shapes of obstacle. Firstly, the chamber contacted the flat obstacle explained above. The height of the gap was fixed as 40mm. A distance between the edge of the trunk and edge of the obstacle was set from -60mm to $+130$mm before supplying water in order to change the contacting position of the chamber. When the edge of the trunk was not under the obstacle as shown in upper picture of the Figure 9(a), the distance was negative, and vice versa. In the experiment, we observed that a tip of the chamber contacted the flat obstacle when the distance was -30mm, and the largest area of the chamber contacted the obstacle when the distance was $+20$mm as shown in bottom of the figure.

Secondly, the chamber contacted the cylindrical obstacle as shown in Figure 9(b). Diameter of the obstacle was 28 mm. Minimum height of the gap was fixed as 40mm, and distance between the edge of the trunk and the edge of the obstacle before supplying water was changed from -60 mm to $+60$ mm. In the experiment, we observed that a tip of the chamber contacted the obstacle when the distance between the edge of the trunk and obstacle was -30 mm, the middle of the chamber contacted the obstacle when the distance was 0 mm.

Figure 10(a) shows the pressure profiles when the different position of the chamber contacted the flat obstacle. Same with the previous experiment, water was supplied into the fore chamber at 3 s and it was sealed at 13 s. As shown in the figure, the pressure increased higher when water was supplied and it kept higher after sealing water in case that the larger area of the chamber contacted the obstacle. Figure 10(b) shows the pressure profiles when the different position of the chamber contacted the cylindrical obstacle. As shown in the figure, the pressure increased largely just after water was supplied, and the pressure kept higher after stopping water supply when the middle of the chamber contacted the



(a) Flat obstacle (upper: negative distance, bottom: positive distance)



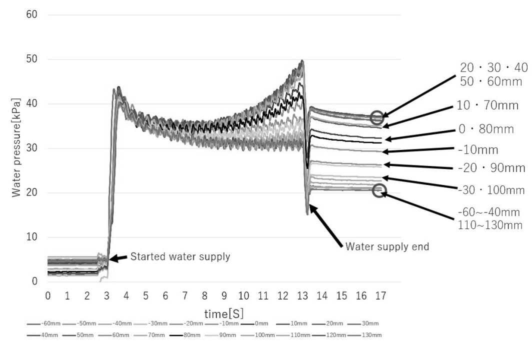
(b) Cylindrical obstacle

Fig. 9. Experimental setup contacting different position of the chamber and obstacles

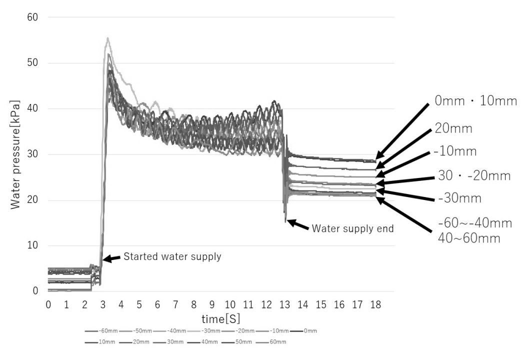
obstacle. When the tips or root of the chamber contacted the obstacle, the pressure did not increase so higher.

D. *Estimation of the obstacle shape by entering into the gap*

From previous experiments in which the fore chamber contacted the different shape of the obstacle, the pressure and contact point of the chamber varies according to the shape of the obstacle. In both case, the pressure increased when the chamber moves forward, and then it decreased after the chamber moves over the middle of the obstacle. Figure 11 shows relationships between the contacting position and the pressure after quitting the water supply when the chamber contacted the flat and cylindrical obstacle. In case of the flat plane that is wider than the cylinder, higher pressure was observed at many steps than the case of the cylindrical obstacle. Therefore, assuming that the robot moves forward with same velocity at every step while entering into the



(a) Flat obstacle



(b) Cylindrical obstacle

Fig. 10. Pressure profiles by different contact points and obstacles

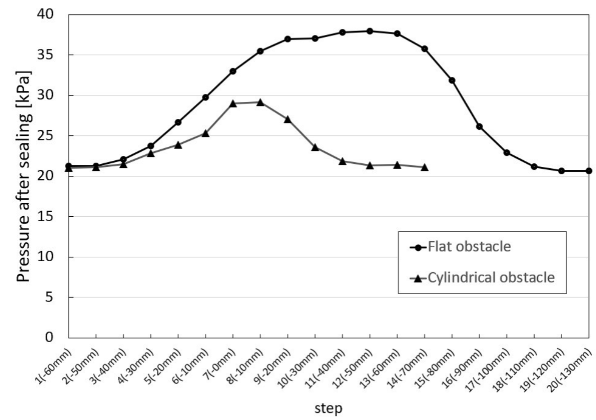


Fig. 11. Relationship between the contacting position and the pressure

obstacle, these figure explain that the pressure increases and keep higher value for many step when the chamber contacts the flat obstacle, and that the pressure increases and decreases in short steps when the chamber contacts the cylindrical obstacle. Therefore, the developed soft robot can "scan" a shape of the obstacle while entering into the obstacle. The conventional rigid robots have required special actuator and sensor for locomotion, deformation, and measurement of the state. On the other hand, water of the developed soft robot combines with a medium of the actuation, deformation and sensing. This approach utilizes an advantage of the soft robot that the body can deform according to the shape of the obstacle, and the developed robot realizes such capability by adopting water.

IV. Feedback controller for entering into the gap from unobstructed space

A. Feedback controller

From previous experiments, the water pressure of the fore chamber can be the information of contacting obstacle. In this section, we demonstrate that the robot enters into the gap by avoiding burst of the chamber due to higher water pressure at contacting the obstacle. The feedback controller that detects a contact the obstacle is proposed. As shown in the Figure 8, the pressure converged into a certain value P when the fore chamber inflated by the water supply without contacting an obstacle (approximately 7 - 12 sec in the figure). We then set up a rule that the water supply into the fore chamber between the state 2 to 3 in Figure 4(a) is quit and the operation switches to the next state (from state 3 to 4) when the pressure of the fore chamber at the phase of supplying water into the chamber is over 20 % higher than the pressure P. If the pressure does not reach to 20 % higher than P while supplying water into the fore chamber, the water supply continues for 10 sec, and switches to the next state. By quitting the water supply at the higher water pressure, the burst of the chamber is avoided and the chamber provides sufficient friction not only between the ground but also the obstacle. In the test trial, we measured the pressure when the chamber inflated without contacting an obstacle. Figure 12 shows the pressure profile. As shown in the figure, the pressure was converged into 35.5 kPa though the pressure increases just after water supplied. Therefore, the water supply is quit when the pressure increases and reaches to 43 kPa. Considering the impulsive pressure increase just after water supply, the feedback controller was activated 2.5 sec after the valve is open and the pump to supply water is driven.

B. Experiment for entering into a small gap by using the feedback controller

For evaluation of the procedure to move forward and the feedback controller explained above, we let the robot enter into a flat obstacle. The height of the gap between the ground and obstacle was 40 mm. The basic procedure of the locomotion is explained in the previous section. Figure 13 shows five cycles of the entering into the obstacle when the period

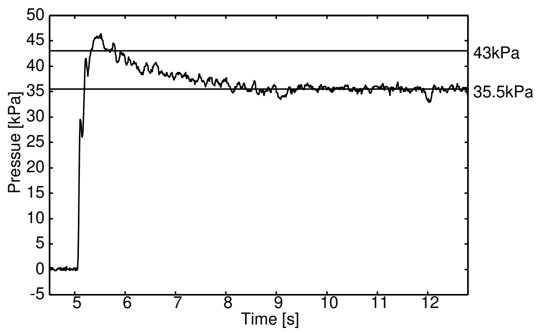


Fig. 12. Pressure profile when water is supplied into fore chamber without contacting obstacle

of the water supply for rear chamber $T_r = 20$ s. Note that the period of the water supply for fore chamber T_f depends on the state of the contacting obstacle as explained above. In the first cycle as shown in the first row of the figure, the fore chamber did not contact the obstacle. After second cycle as shown in the second to fifth rows of the figure, the fore chamber contacted the obstacle and the shape of the chamber was deformed at state 3, the 3rd column. A reaction force was occurred to move backward while the chamber contacted the obstacle. However, the rear chamber anchored by filling water and generating friction between the rear chamber and the ground. Therefore, the robot did not slip, and it plugged into the gap. Finally, the robot succeeded to enter into the gap. Figure 14(a) shows the pressure profile after the valve A was open and the pump M was activated. Because the chamber did not contact the obstacle, the pressure except period of 2.5 sec (after 24 sec) did not reach to 43 kPa. Therefore, water was supplied for 10 sec. Figure 14(b) shows the pressure profile at supplying water into the fore chamber at third cycle. Because the chamber contact the obstacle, the pressure reached to 43 kPa, and water supply was halted to switch the next operation. We also set the height of gap between the ground and obstacle from 10mm to 50mm. When the height is over 30mm, the robot succeeded to enter into the gap by using the feedback controller. However, because the height of the tips of fore chamber that increases according to the inflation of the chamber is more than 30mm, the robot sometimes succeeded to enter the gap (success rate: 40 %) when the height of the gap was 20mm, and consistently failed to enter the gap when the height was less than 10mm. By using the feedback controller, the robot detected the contact of the obstacle, and switched the operation automatically without entering the chamber due to the higher water pressure. From this result, we conclude that water is suitable medium for entering into the gap by generating local friction, and worked effectively by using the water pressure sensor to detect the contact state regarding the obstacle.

V. Conclusion

In this paper, we explained the soft robot driven and supported by water. It also explained the method to estimate the contact information such as the height of the gap, the contact position of the body, and the shape of the obstacle by utilizing the water pressure. Because water is heavier than air, local friction between the selected chamber and the ground can be controlled by supplying water into the chamber. By generating large friction, the chamber anchors on the ground against external force such as reaction force of the contacting obstacle and pushing force by the inflation of the other chamber. We also explained the sensing of water pressure to detect that the chamber contacts the obstacle.

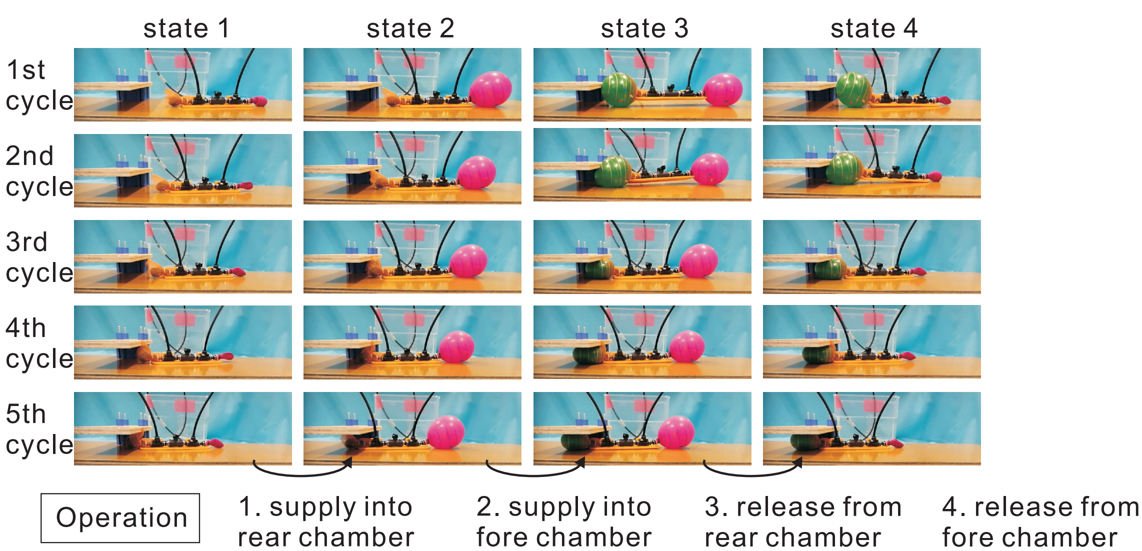
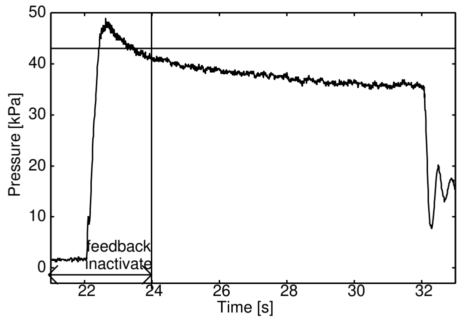
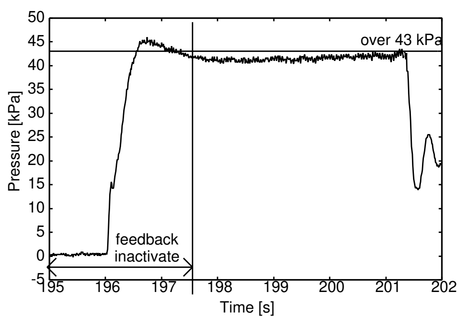


Fig. 13. Plugging and entering into the gap when $T_r = 20$ s using the feedback controller to activate the valve and pump operation



(a) 1st cycle



(b) 3rd cycle

Fig. 14. Pressure profile when water is supplied into fore chamber

Experimental results showed that the pressure was varied by the height of the gap and the contact point of the chamber. The relationship between the contact point and the pressure was varied by the shape of the obstacle. These results suggest a novel sensing method that the robot moves and records the information of the deformation by contacting obstacle and scans the environment by aligning the recorded information. The paper demonstrated that the robot plugged and broke through the gap by using the feedback controller in which the valve and pump operation were activated according to the pressure. From these results, it is concluded that water of the soft robot can be medium of actuator for locomotion, elastic deformation of the body, operation of the local weight, and the sensor to detect the contact information.

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