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FABRICATION OF AN IN-PIPE MOBILE INSPECTION ROBOT DRIVEN BY PNEUMATIC PRESSURE AND IMITATING MOVING OF A GREEN CATERPILLAR

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ABSTRACT

We have many small diameter pipes that are gas or water pipes for individual or corporate houses and boilers or hot water pipes for industries. They must be periodically inspected in order to protect the accident previously. Diameters of these pipes are different at the place where pipes change from the main to the branch and a step comes here. The inspection robot for these pipes must move different diameter and go over the step. We propose a mobile robot that imitates the moving of a green caterpillar. The robot is constructed by the eight parallel rubber bellows and three suction brakes. The fabricated mobile robot was confirmed to move in different diameter pipes whose diameters are more than 70 mm. Its speed was 20 mm/s.

KEY WORDS

A green caterpillar, In-pipe, Robot, Bellows, Suction brake

INTRODUCTION

We have many small diameter pipes that are gas or water pipes for individual or corporate houses and boilers or hot water pipes for industries. These pipes may be occurred to injure or to corrode by their decrepit. The injury or the corrosion of pipes causes the leak of fluid and links to the accident. So, these pipes must be periodically inspected in order to protect the accident previously. They are settled in the ground or in the narrow spaces and some of them are covered by casings or hard heat insulators. So, it is very difficult to inspect from outside of the pipe. If we can insert a mobile inspection robot into the pipe from the suitable position, we are easy to inspect the pipe. In-pipe mobile robots driven by pneumatic actuator have been proposed by several research groups for same diameter pipes [1], [2]. However, some of these pipes are long and their diameters are different at the place where pipes change from the main to the branch. The diameter of pipes is within 70 mm and 150 mm for example. So, the inspection robot for these pipes must move in different diameter, generating large traction force for the inspection of long distance.

We have fabricated inspection robots applying an earthworm and an inchworm [3], [4]. A braking mechanism which is using cone-shape friction rings for the earthworm type inspection robot is designed for the diameter of 79 mm. Then the inspection robot could not move in pipes whose diameter changes more than 5 mm from 79 mm. The earthworm type inspection robot can not move in pipes that the diameter changes from 70

mm till 150 mm. On the other hand, the inchworm type inspection robot which is using bulging brakes is confirmed to move in pipes whose diameter is 70 mm and 140 mm. However, the traction force of the inchworm type inspection robot changes on the diameter of the pipe. The traction force is 11 N at the 70 mm pipe, but is only 1 N at the 140 mm pipe.
The traction force depends on the friction force of the braking mechanism. So, we propose a suction brake for the braking mechanism. The suction brake can stick on the pipe and hold the pipe by the negative pressure supplied from a vacuum pump. The friction force of the suction brake is so larger than those of another braking mechanism and is predicted easily.
Now, we remark the moving motion of a green caterpillar. The green caterpillar sticks a passage such as the leaf by its prolegs. If we can imitate prolegs by the suction brake, we may obtain large traction force. The green caterpillar moves its prolegs by waving its abdomen. This waving motion is imitated by the action of four parallel rubber bellows actuator driven by pneumatic and vacuum pressure.
The inspection robot that is imitated the green caterpillar can move at the speed of 20 mm/s in the pipe whose diameters are from 70 mm to 150 mm, generating the traction force of as large as 20 N. We may inspect long and different diameter pipes, because we have obtained large traction force. Besides, the green caterpillar type inspection robot has been confirmed to pass the step more than 5 mm.

GREEN CATERPILLAR

We observed moving motion of the green caterpillar. The moving motion is shown in Figure 1. The green caterpillar consists of a head, a thorax and an abdomen. The thorax has six true legs and the abdomen has five pairs of prolegs. Five pairs of prolegs make three groups that are front two pairs, central two pairs and rear one pair of prolegs. The prolegs of the rear one pair are called as claspers. The prolegs are not segmented, but are cylindrical. They are used for walking and clinging as they have microscopic hooks on the base.
The moving of the green caterpillar is as follows.
(a) In the initial condition, the green caterpillar is sticking to the leaf by all of prolegs of the abdomen and is stationary.
(b) The rear abdomen waves and the rear one pair of prolegs (claspers) are taken off.
(c) The central abdomen waves and the central two pairs of prolegs are taken off and the rear one pair of prolegs land on the leaf that is forward direction from the initial condition.
(d) The front abdomen waves and the front two pairs of prolegs are taken off and the central two pairs of prolegs land on the leaf that is forward direction from the initial condition.

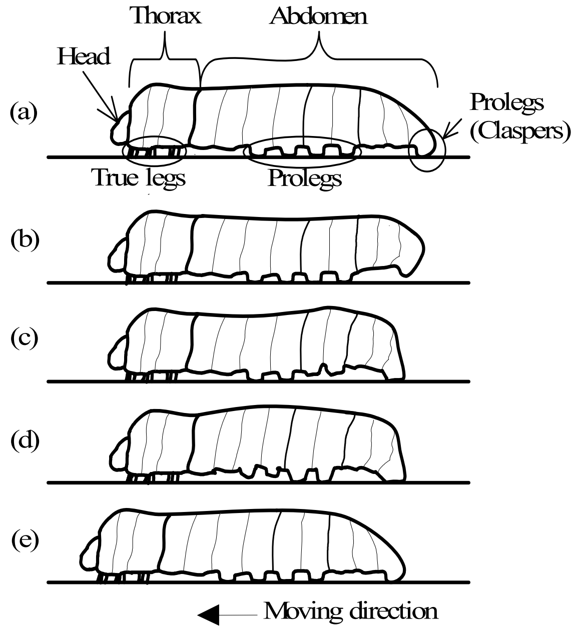

Figure 1 Moving Motion of a green caterpillar

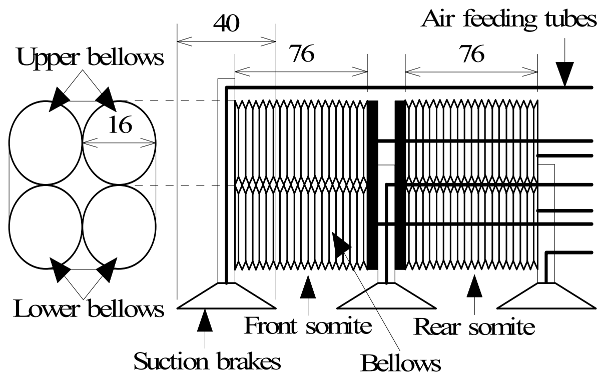

Figure 2 Structure of in-pipe mobile robot

(e) The green caterpillar stops its waving and sticks the all of prolegs to the leaf. Then, the head and the thorax are moved to forward direction. The cycle of moving of the green caterpillar ends.
We understand that the green caterpillar can move to the forward direction by moving of three groups of prolegs in order to the forward direction.

STRUCTURE OF THE ROBOT

A fabricated robot is imitated the abdomen of the green caterpillar. A structure of the robot is shown in Figure 2. The abdomen is imitated by two groups of four parallel rubber bellows actuators which are arranged in the matrix of two rows and two columns. The matrix of two rows and two columns makes a somite of the abdomen.

Two parallel rubber bellows in the same row are supplied same pressure by an air feeding tube. The bellows made of Nitrile Butyl Rubber (NBR) is 16 mm in diameter and 76 mm long. A group of prolegs is imitated by a suction brake. The suction brake is a sucker made of NBR and its diameter is 40 mm. The air feeding tube for positive and negative pressure is connected in the center of the suction brake. Three suction brakes are arranged at the front, the center and the rear of the two groups of four parallel rubber bellows actuators.

CONTROL SYSTEM OF THE ROBOT

A control system of the robot is shown in Figure 3. The system is constructed by a robot, seven electromagnetic valves, two different (positive and negative) pressure sources, a computer and a valve controller. The positive pressure source is an air compressor and the negative pressure source is a vacuum pump. The moving sequence of the robot is programmed in the computer. The electromagnetic valves are controlled by the computer through the valve controller. The electromagnetic valve has three ports. The output ports of the four electromagnetic valves are connected to the bellows for the abdomen through the air feeding tubes. The output ports of the three electromagnetic valves are connected to the suction brakes through the air feeding tubes. The ones of input ports are connected to the vacuum pump and the others are connected to the atmospheric pressure.

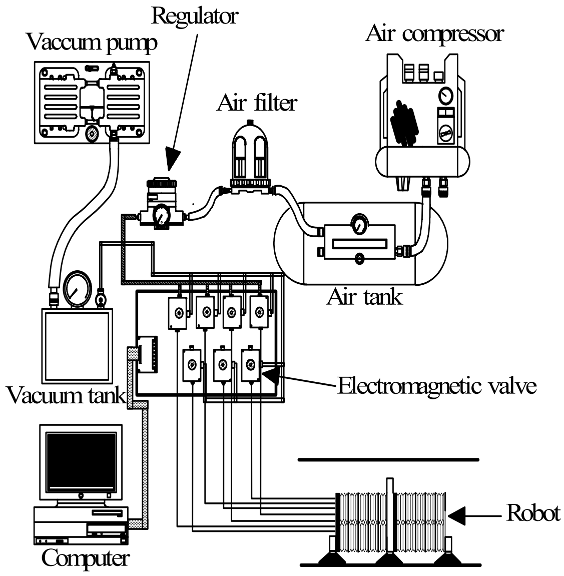

Figure 3 Control system of in-pipe mobile robot

MOVING MOTION OF THE ROBOT

The robot moves in the pipe by stretching and bending motion of two somites and sticking of the suction brakes using positive and negative pressure.

Moving principle of the somite

Moving principle of the somite is shown in Figure 4. The somite consists of bellows. The bellows stretches when positive pressure is supplied and shrinks when negative pressure is supplied. That is, the somite stretches when positive pressure is supplied to the upper and the lower bellows. The somite shrinks when negative pressure is supplied to the upper and the lower bellows. Besides, the somite can bend when different pressure is supplied to the upper and the lower bellows, for example, the somite bends upward, when positive pressure is supplied to the upper and negative pressure is supplied to the lower bellows. The waving motion of the green caterpillar can be imitated by the stretching, shrinking and bending motion of the somite.

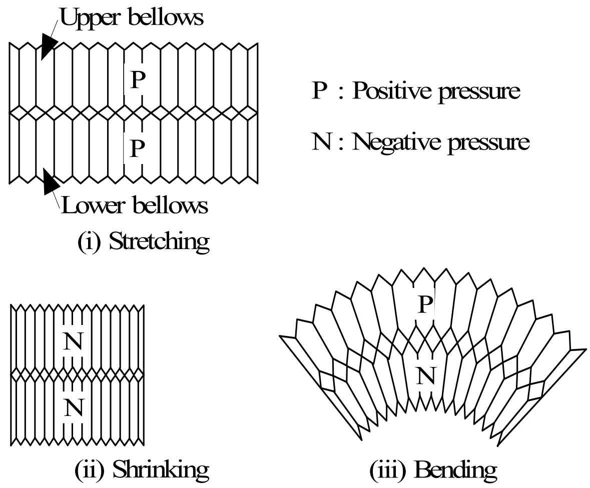

Figure 4 Moving principle of somite

Characteristics of the suction brake

The robot generates friction force by the suction brake. A model of the suction brake is shown in Figure 5. The suction force N by the suction brake is shown by Eq. (1), where p is the pressure at the radius r from the center of

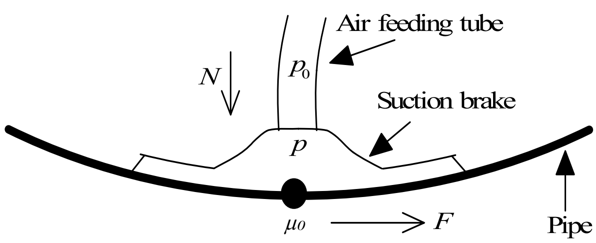

Figure 5 Suction brake model

the suction brake.

$$N = \left| \int p 2\pi r \mathrm{d}r \right| \quad (1)$$

An internal pressure distribution in the suction brake is shown in Figure 6. The internal pressure distribution is measured radially from the center of the suction brake put in the pipes whose diameters are 70 mm and 150 mm. Supplied pressure p_0 is -84 kPa. The internal pressure distribution does not depend on the diameter of the pipe. The internal pressure is -84 kPa at the center of the suction brake and less than -80 kPa at the radius within 8 mm. However, the internal pressure is 0 kPa at the radius over 9 mm. The suction force N is obtained as 21.3 N by using Eq. (1) and the internal pressure distribution shown in Figure 6.
The suction force N is represented by Eq. (2), where A is the area of the suction brake and α is the constant.

$$N = \left| \alpha \, p_0 \, A \right| \quad (2)$$

From comparing of the result of Eq. (1) and Eq. (2), we obtain that the constant α is 0.2. We can predict the suction force N from Eq. (2).
The maximum friction force F is shown by Eq. (3), where μ_0 is the friction factor between the suction brake and the pipe.

$$F = \mu_0 N \quad (3)$$

The friction factor obtained by an experiment is 1.8 in the case of acrylic pipe and the suction brake.
The maximum friction force $\overline{F}$ is measured by an experiment where negative pressure is -84 kPa. A calculated value F and a measured value $\overline{F}$ of the maximum friction force are shown in Figure 7. We may predict the maximum friction force, because the measured value $\overline{F}$ almost coincides with the calculated value F by Eq. (2) and Eq. (3).

Moving principle of the robot and its confirmation

Internal pressure of the robot is measured when the robot is moving in an acrylic pipe whose diameter is 110 mm. Measured results are shown in Figure 8, 9, and 10. Moving motions by the pressure changes are shown in Figure 11. The robot moves to the forward direction by moving its three suction brakes in order to the forward direction. The robot waves its front and rear somite to push the suction brake to the wall of the pipe and to lift up the suction brake from the wall of the pipe. The suction brake can stick the wall of the pipe by supplying the negative pressure and release the wall of the pipe by supplying the atmospheric pressure. In Figure 11, black colored suction brake shows that the suction brake sticks the wall of the pipe and white colored suction brake shows that the suction brake

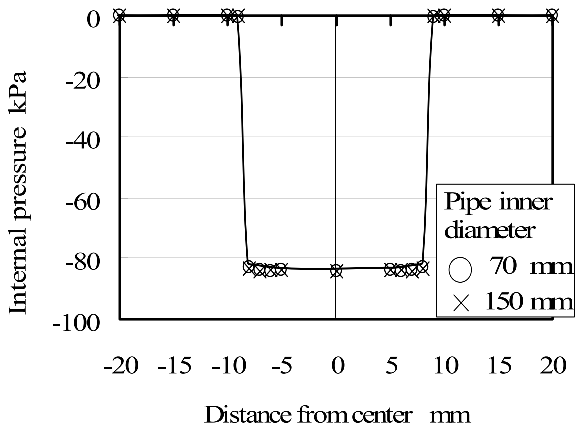

Figure 6 Internal pressure distribution in suction brake

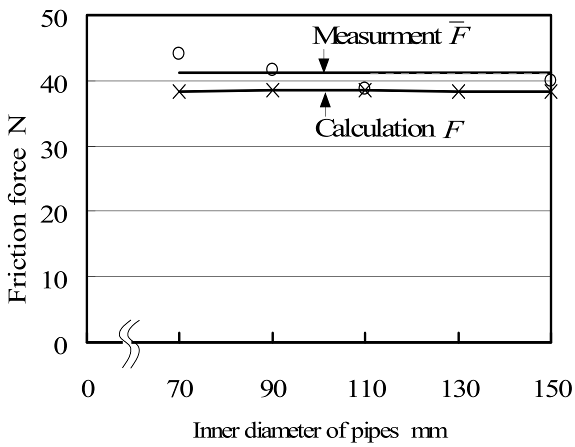

Figure 7 Relationship between diameter of pipes and friction force of suction brake

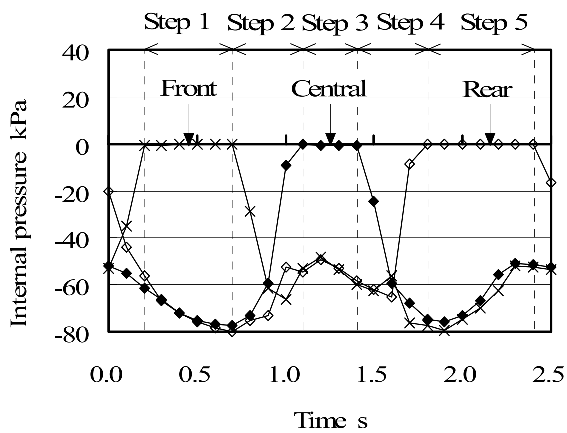

Figure 8 Internal pressure in suction brakes

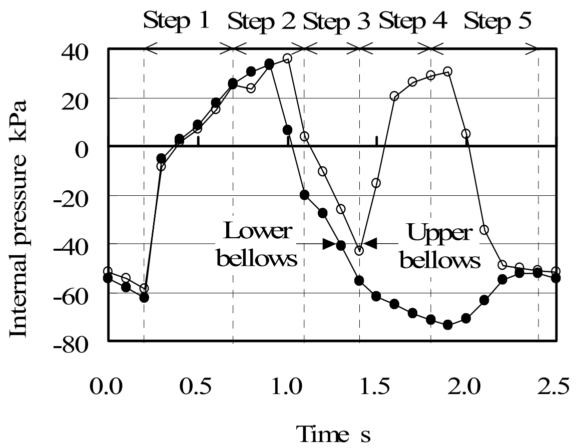

Figure 9 Internal pressure in front somite

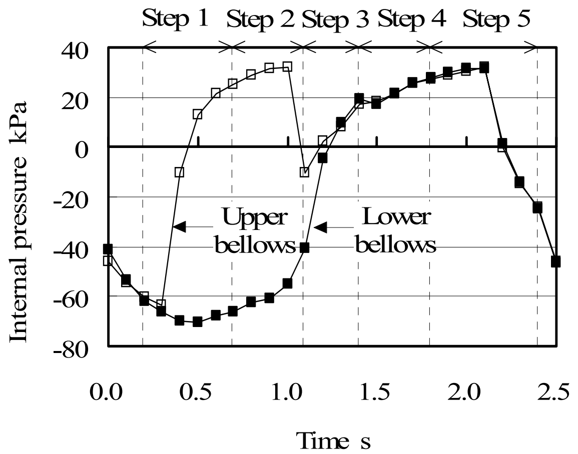

Figure 10 Internal pressure in rear somite

releases the wall of the pipe.

In the initial condition, the robot shrinks its front and rear somite and sticks its three suction brakes on the pipe and is in the stationary.

Step 1: After 0.2 seconds of the moving start, the front suction brake releases the wall of the pipe, because the internal pressure of the suction brake goes up to 0 kPa. After the moment, the suction brake keeps the releasing motion in the time of 0.5 seconds. The front somite stretches to the forward direction, because, the internal pressure of the front somite goes up to 25 kPa from -60 kPa in this time. Then, the front suction brake moves to the forward direction.

Step 2: The front suction brake sticks the wall of the pipe, because the internal pressure of the front suction brake goes down from 0 kPa after 0.8 seconds of the moving start.

Step 3: The central suction brake releases the wall of the pipe, because the internal pressure of the central suction brake goes up to 0 kPa after 1.1 seconds of the moving start. In this time, the front somite shrinks, because the internal pressure of the rear somite goes up over 0 kPa. Then, the central suction brake moves to the forward direction.

Step 4: The central suction brake sticks the wall of the pipe, because the internal pressure of the central suction brake goes down from 0 kPa after 1.5 seconds of the moving start.

Step 5: The rear suction brake releases the wall of the pipe, because the internal pressure of the rear suction brake goes up to 0 kPa after 1.8 seconds of the moving start. The rear somite shrinks because the internal pressure of the rear somite goes down over 0 kPa. Then, the rear suction brake moves to the forward direction.

Step 6: The rear suction brake sticks the wall of the pipe, because the internal pressure of the rear suction brake goes down from 0 kPa after 2.5 seconds of the moving start.

The time required to a series of the moving motion is 2.5 seconds. The robot can move in the pipe by repeating the steps.

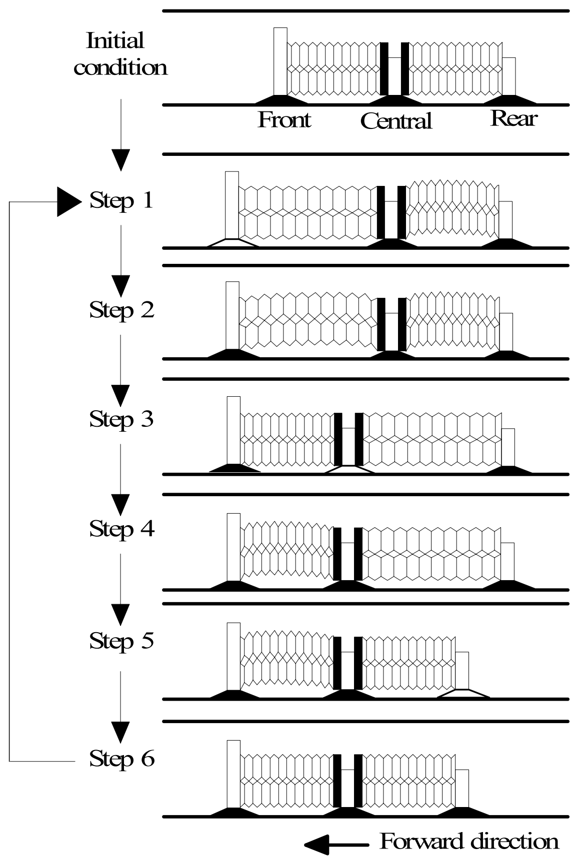

Figure 11 Moving principle of in-pipe mobile robot

MOVING CHARACTERISTICS OF THE ROBOT

The positive pressure of 50 kPa and the negative pressure of -84 kPa are used in the experiment and diameters of pipe made of acrylic are within 70 mm and 150 mm.

Moving speed

Moving speed of the robot is measured in the pipe which is set in horizontal and vertical. The moving speed is shown in Figure 12. Average speed is 20 mm/s in the horizontal case and 23 mm/s in the vertical case. It is confirmed that the moving speed does not depend on the diameters of pipe by the experiment.

Traction force

The experimental traction force is shown in Figure 13. The traction force of 20 N is obtained and does not depend on diameters of the pipe. It is confirmed that the traction force is about half of the maximum friction force.

Confirmation of passing of the step

The robot is confirmed to pass the step of 5 mm that is made by connecting of pipes whose diameters are 110 mm and 120 mm. The robot can pass the step by its waving motion of the somite.

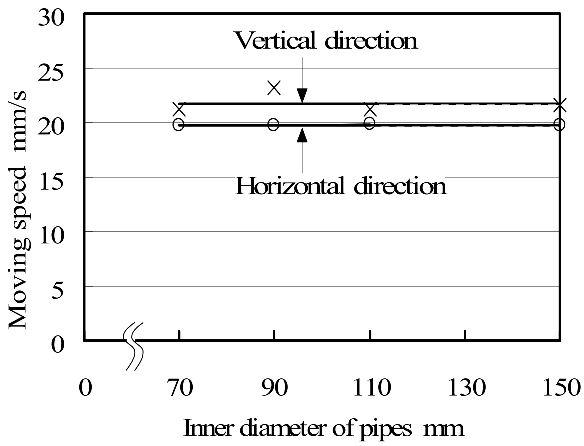

Figure 12 Moving speed of in-pipe mobile robot

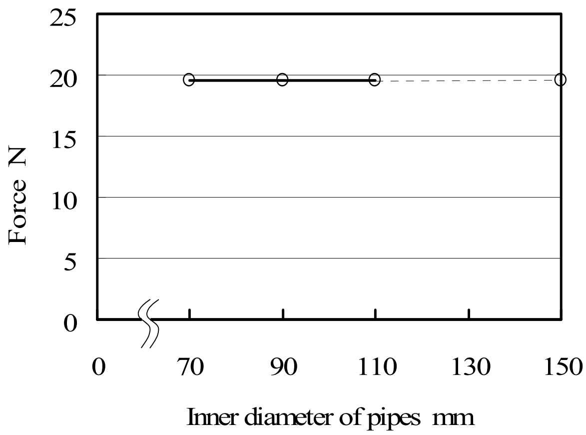

Figure 13 The experimental traction force

CONCLUSIONS

We obtained next conclusions concerning an in-pipe mobile inspection robot which imitates the green caterpillar.

(1) The green caterpillar can move to the forward direction by moving of three groups of prolegs in order to the forward direction. The green caterpillar moves its prolegs by waving its abdomen.

(2) In the fabricated robot, the abdomen of the green caterpillar is imitated by bellows and the prolegs are imitated by the suction brake. The somite structured by four parallel rubber bellows actuators which are arranged in the matrix can imitate the waving motion of the abdomen. The waving motion of the somite could push the suction brake to the wall of the pipe and lift up the suction brake from the wall of the pipe.

(3) The robot that is imitated the motion of the green caterpillar can move pipes whose diameter are more than 70 mm. Average speed is 20 mm/s in the horizontal case and 23 mm/s in the vertical case. The traction force is 20 N and does not depend the diameter of the pipe. This type inspection robot may move long distance, because it has larger traction force. The robot is confirmed to pass the step of 5 mm.

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