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Development of a Peristaltic Crawling Inspection Robot for 1-inch Gas Pipes with Continuous Elbows

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***Abstract*—This paper describes the development of an inspection robot for use in 1-inch gas pipes.**

These pipes are commonly used in residences and between gas meters and a main pipe that is buried under the road, and they require regular inspection. However, appropriately advanced inspection technologies have not yet been developed. An endoscope, which is the current inspection method, can only be utilized in a limited inspection scenarios. As for robot inspection, current in-pipe robots cannot pass through a 90-degree elbow, which has a radius of curvature equal to its inside diameter (R_c = 1.0 ID). However these elbows are frequently encountered in real-life environments.

In this study, to solve these problems, we developed a peristaltic crawling robot with pneumatic artificial muscles for use in 1-inch gas pipes. This robot can pass through a 90-degree elbow (R_c = 1.0 ID) in the horizontal and vertical planes. In addition, this robot can be equipped with an endoscope and take videos inside a pipe. However, has been unable to pass through continuous elbows, which are occasionally encountered. For use in real-life environments, a robot is needed that can pass through continuous elbows.

In this paper, we report the development of a robot that can pass through continuous elbows.

I. INTRODUCTION

The objective of this study is the development of an in-pipe inspection robot that can inspect a complex network of 1-inch gas pipes.

These pipes are commonly used in residences and between gas meters and a main pipe that is buried under the road, as shown in Figure 1. The need for 1-inch gas pipe inspection is high because they are in common use all around us. Such an inspection involves checking the health of pipes, preventing illegal construction, locating pipes, and identifying areas of water leakage. Currently, 1-inch gas pipes are inspected by using an endoscope. However, owing to the limitations of the endoscope, a number of pipes remain uninspected. When probing complicated and long piping, the endoscope eventually deflects and fails to penetrate further.

To solve this problem, various in-pipe inspection robots have been developed. However, these robots have drawbacks. For example, a snake-like robot [1] requires a large space for moving, while the problem with wheel-type robots [2]-[4] is that it is difficult to reduce their size because of their complex structure. Therefore, these types of robots are not suitable for moving in narrow pipes such as 1-inch gas pipes. In addition, a ciliary vibration mechanisms robot [5] cannot move backward or climb vertical. Several robots for use in 1-inch pipe have been reported [6], [7]. However, there is no report of robots that can pass through a 90-degree elbow, the radius of curvature of which is equal to its inside diameter (Rc = 1.0 ID), except for the robot that was developed by the authors [8]. These elbows are frequently encountered in real-life environments. In addition, there are continuous elbows between gas meters and the main pipe, which lies under the road as shown in Figure 1. It is difficult for a robot to pass through continuous elbows because the distance between the two elbows is short. Thus, currently there are no robots that can pass through continuous elbows. However, to use in-pipe robots for inspections in real-life environments, the robots need the ability to pass through continuous elbows.

To this end, the authors have studied robots that emulate the peristaltic crawling of an earthworm [9]-[13]. An earthworm's peristaltic crawling requires little room for motion, and the ground contact area is large. Therefore, this motion enables the robot move stably in a narrow pipe. Earlier, the authors developed a robot for use in a 1-inch pipe [8]. This robot can pass through a 90-degree horizontal elbow and climb vertical in it. In addition, it can be equipped with an endoscope and take videos inside the pipe. However, this robot has problems in that it requires a significant amount of time to pass through an elbow, and cannot pass through complex piping arrays of 1-inch gas pipes, such as continuous elbows.

Thus, in this study the authors seek to develop a peristaltic crawling robot that can inspect a complex array of 1-inch gas pipes containing continuous elbows.

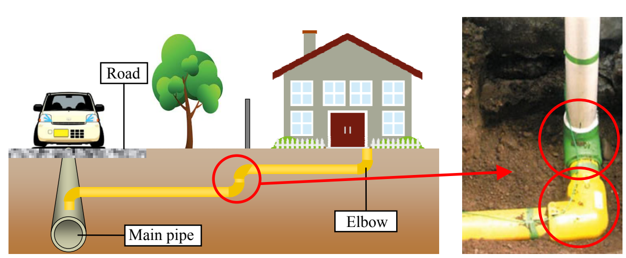

Figure 1. Common configurations of 1-inch gas pipes.

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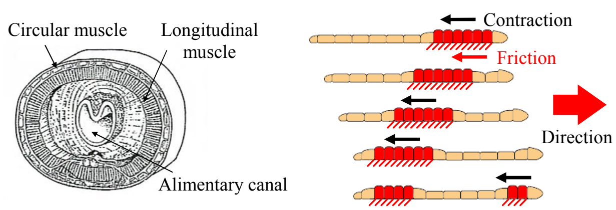
II. Peristaltic Crawling of Earthworms

Peristaltic crawling is used by life forms such as earthworms and inchworms for moving forward. The robot developed in this paper emulates the earthworm's motion.

An earthworm consists of 110–200 segments. Figure 2 (a) shows the structure of an individual segment. The earthworm has two muscle layers: a circular muscle that is arranged inside of a skin circumferentially, and a longitudinal muscle that is arranged inside the circular muscle in the axial direction. The former elongates and the latter contracts the segments in the axial direction [14]. Figure 2 (b) shows the earthworm's peristaltic crawling pattern. The earthworm contracts and expands as follows. First, the earthworm contracts an anterior segment using the longitudinal muscles. Next, this contraction is transmitted to rear segments while the anterior segments are elongated by the circular muscles simultaneously. Finally, the contraction segments generate frictional force between the segments and a surface. Because of this frictional force, a reaction force to elongate contraction segments is generated.

Thus, the earthworm can move because of the repetition of thick-short and thin-long motion.



(a) Inner structure [14]. (b) Peristaltic crawling.

Figure 2. Peristaltic crawling pattern of an earthworm.

III. Peristaltic Crawling Robot

A. Structure of the Robot

Figure 3 shows the structure of a peristaltic crawling robot. As stated earlier, this robot was developed by emulating the motion of an earthworm. The robot consists of several units, each of which is equal to a segment of an earthworm. A unit consists of two flanges, a chamber, aluminum sheet, a silicon-tape-coated compression spring, and artificial muscle. When air is supplied to the chamber, the artificial muscle contracts in the axial direction and expands in the radial direction. When air is discharged from the chamber, the artificial muscle extends in the axial direction. Thus, the robot repeats the extension and contraction motion in the same way as an earthworm's motion.

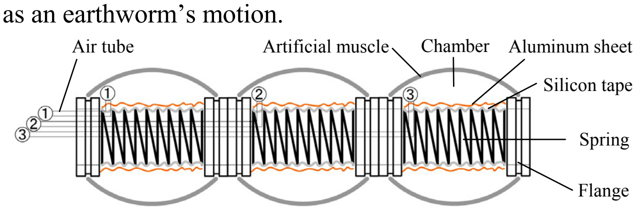
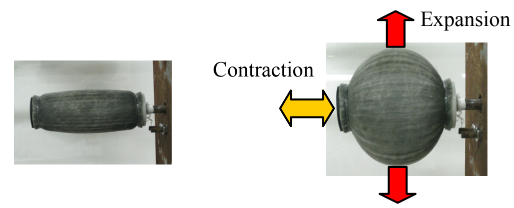


Figure 3. Structure of a peristaltic crawling robot.

B. Straight-Fiber Artificial Muscle

We use a straight-fiber artificial muscle as the actuator for the robot [15]. Figure 4 shows an overview of the artificial muscle, which is made of low-ammonia natural-rubber latex and micro-carbon fiber. This construction offers the following advantages: lightness, low price, flexible, and high output. The materials are formed in a tube, and a micro-carbon sheet is inserted into the tube in the long-axial direction. The range of the sheet extends when the rubber elongates [16].

This actuator is controlled by air pressure. When air is supplied to the actuator, the artificial muscle contracts in the axial direction and expands in the radial direction because the film expands but the carbon sheet maintains its shape.



(a) Unpressurized. (b) Pressurize.

Figure 4. Straight-fiber artificial muscle.

C. Method of Operation

Figure 5 shows the robot's control system. The robot is controlled by a H8-3052F microcomputer. Digital signals output from the H8 microcomputer are converted into analog signals using a digital-analog converter. These analog signals are then input to a proportional solenoid valve. The air pressure that is supplied to the robot via a manifold from a compressor is proportional to the input voltage. Thus, the units are free to extend and contract independently.

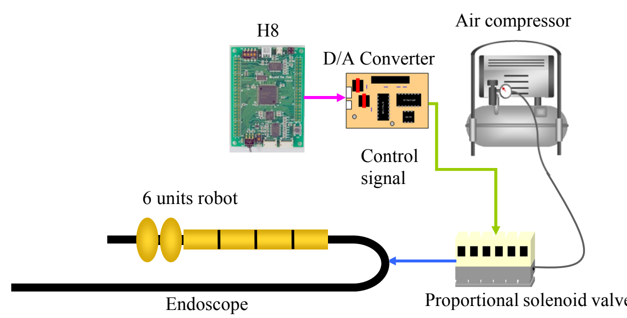


Figure 5. Control system of the pneumatic robot.

D. Motion Patterns

By altering the extension or contraction of each unit, several motion patterns can be achieved. Motion patterns consist of a wavelength, propagation speed, and waves. Here, wavelength is the number of units extended in the axial direction. The propagation speed is the number of units propagated in the rear. Here l, s, n, and N are the wavelength, propagation speed, number of waves, and number of units, respectively. Henceforth, we identify the basic motion patterns as motion l-s-n. For example, motion 4-1-1 (wavelength–propagation speed–number of waves) is shown in Figure 6. Each of the parameters must satisfy the following equations:

$$(l+s)\times n < N. \tag{1}$$

$$N-l > s. \tag{2}$$

$$l \geq s. \tag{3}$$

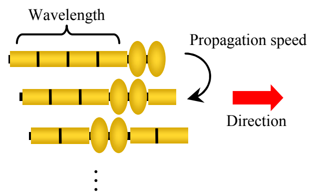


Figure 6. Motion pattern 4-1-1.

IV. Peristaltic Crawling Robot for Single Elbow

A. *Peristaltic Crawling Robot for Single Elbow*

Figure 7 shows an image of the robot, which consists of six units, five joints, and a head section, which guides the robot when it passes through an elbow. The robot weighs 98 g and has a length of 480 mm when fully extended. It is equipped with an endoscope.

This robot can pass through a horizontal and vertical elbow.

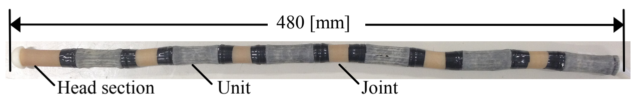


Figure 7. Peristaltic crawling robot for single elbow.

B. *Unit*

Figure 8 shows an image of a unit and Table 1 shows the specifications. As already mentioned, a single unit consists of two flanges, aluminum sheet and silicon tape-coated compression spring, and artificial muscle. A fluorine tube (outer diameter: 1.4 mm, inner diameter: 0.9 mm) is used as an air tube.

(a) Extension. (b) Contraction.
Figure 8. Unit.

TABLE I. Unit Specifications

Weight [g]		6.8
Length [mm]	Extension	46.6
	Contraction	35.6
Width [mm]	Extension	15.4
	Contraction	37.7

C. *Joint*

Figure 9 shows an image of the joint. This joint connects units to enable the robot to bend as it passes through an elbow. This joint consists of a natural rubber tube and a compression spring and has a length of 30 mm and an outer diameter of 12 mm.

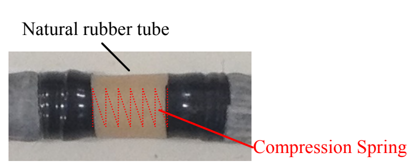


Figure 9. Joint.

D. *Head Section*

Figure 10 shows an image of the head section. This head section is connected to the first unit to guide the robot when the robot passes through an elbow. The head section consists of a hemispherical ABS resin section and natural rubber tube. The ABS resin section is hollow to allow an endoscope to be attached.

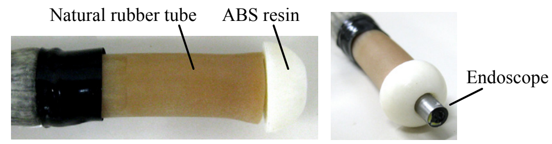


Figure 10. Head section.

E. *Problems in Passing Through Elbows*

In real-life environments, continuous elbows are encountered between gas meters and the main pipe that lies under the road. To pass through continuous elbows, the robot faces two problems:

(1) The robot cannot pass smoothly through an elbow. Therefore, it cannot pass through continuous elbows.

(2) The robot cannot pass through narrow elbows, which are frequently found in real-life environments.

First, we explain problem (1). Figure 11 shows an image of the robot passing through an elbow. As shown in the figure, the robot bends passively. Therefore, friction between the robot and the pipe occurs and, as the surface of the robot is rubber, friction between the robot and the pipe is high. In addition, the steps between a unit and a joint of the robot constitute an obstruction to traveling. To solve this problem, we need to reduce the friction of the robot.

Second, we explain problem (2). Figure 12(a) shows the elbow (JIS K 6775, Rc = 1.0 ID) of a gas pipe from Sekisui Chemical Company. This pipe is commonly used for buried 1-inch gas pipes. Figure 12(b) shows two types of elbows, both having a narrow width. Figure 13(a) shows the state when the head section of the robot is passing through a narrow elbow. As mentioned, the head section comprises a hemispherical ABS resin section and a rubber tube. As seen in Figure. 13(a), the rubber tube buckles, and the head unit eventually smash into the elbow. The approach angle of the robot into a narrow elbow is obviously smaller than for a wide elbow, as shown in Figure. 13(b), and thus the head unit collides with a narrow elbow more than it would with a wide elbow. Therefore, the robot cannot pass through a narrow elbow while it can pass through a wide elbow. To solve this problem, we need to alter the head section.

Thus, to restate the above, for a robot to be able to pass through continuous elbows that are found in real-life environments, we need to reduce the friction of the robot and alter the head section.

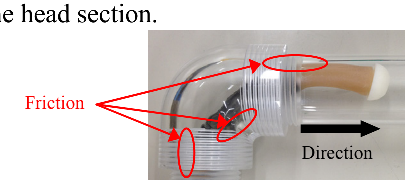
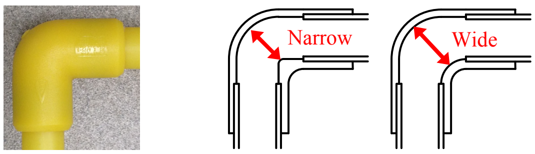
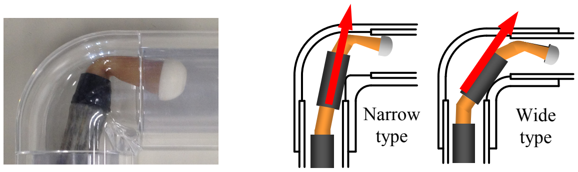


Figure 11. Image of a robot passing through an elbow.



(a) Elbow from Sekisui Chemical Company (PE). (b) Two types of elbow.

Figure 12. Types of elbow.



(a) Head unit colliding with a narrow elbow. (b) Effect of elbow type on approach angle.

Figure 13. Image of the head section passing through an elbow.

V. Low-Friction Robot for Smooth Traveling

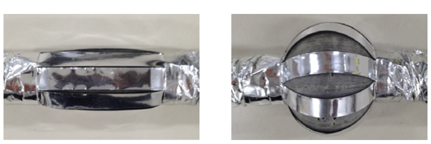
A. Low-Friction Robot

Figure 14 shows an image of a low-friction robot. The robot is coated with aluminum sheet to reduce friction and the steps between a unit and a joint of the robot.

Figure 14. Low friction type robot.

B. Variable Friction Unit

The robot was modified into a low-friction device so that it could pass smoothly through an elbow. However, doing so reduces the maximum friction force and speed of the robot in a straight pipe. Therefore, we developed a variable friction unit that can pass smoothly through an elbow while retaining maximum friction force and speed of the robot in a straight pipe, as shown in Figure. 15. As shown in the figure, the aluminum sheet is cut in the axial direction, so the artificial muscle is exposed when the unit contracts so that the robot develops friction between itself and the pipe.



(a) Extension. (b) Contraction.

Figure 15. Variable friction unit.

C. Experiment of Maximum Friction Force

Figure 16 shows the setup for the experiment of maximum friction force. The number of contracted units is varied from one to six. The maximum friction force is measured by a push-pull scale. First, the units of the robot were contracted in a horizontal pipe and isolated from electrical supply to maintain contraction. Then, we connected the robot to the push-pull scale using a cord and pulled the acrylic pipe along a guide in a straight line. At the point where the acrylic pipe slips from the robot, the friction force is the maximum friction force. An air pressure of 0.1 MPa was applied to the unit.

Table 2 shows the experimental results from which we can see that the maximum friction force of the aluminum-sheet-coated robot does not decrease more than 10% compared to its uncoated counterpart. Upon the contraction of two units, the robot broke because it was unable to withstand the load.

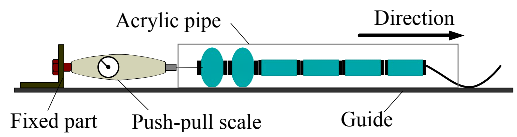


Figure 16. Experimental setup for measuring frictional force.

TABLE II. Experimental Results of Maximum Frictional Force

The number of contracting units		1	2
Maximum friction force [N]	Without aluminum sheet	61	(80)
	With aluminum sheet	56	(78)

D. Experiment of Locomotion Speed

We measured the locomotion speed of the robot proceeding using Motion 4-1-1. These experiments were conducted in a 1-inch acrylic pipe, and an air pressure of 0.1 MPa was applied to the unit.

Figure 17 shows the experimental result. From the result, we observe that the locomotion speed of the aluminum-sheet-coated robot does not decrease compared to its uncoated counterpart.

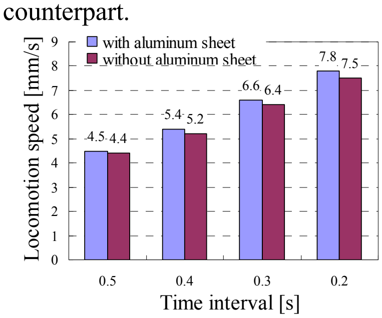


Figure 17. Locomotion speed in a 1-inch acrylic pipe.

E. Experiment in a Horizontal Elbow

To confirm that the aluminum-sheet-coated robot can pass smoothly through an elbow, we measured the locomotion speed through a 90-degree elbow (Rc = 1.0 ID). These experiments were conducted in a 1-inch acrylic pipe, using Motion 4-1-1 with a time interval of 0.2 s. An air pressure of 0.1 MPa was applied to the unit.

Figure 18 shows the experimental result, which shows that the aluminum-sheet-coated and uncoated robot passed through an elbow at 75 and 125 s, respectively. Therefore, the locomotion speeds of the aluminum-sheet-coated and uncoated robot are 6.8 and 4.1 mm/s, respectively, which means the aluminum-sheet-coated robot passes through the elbow 1.7 times faster than the uncoated robot. Thus, we confirmed that the aluminum-sheet-coated robot can pass through an elbow smoothly. Thus, the proposed approach leads to reduced friction and steps of the robot, and is thus effective in enabling the robot to smoothly pass through an elbow.

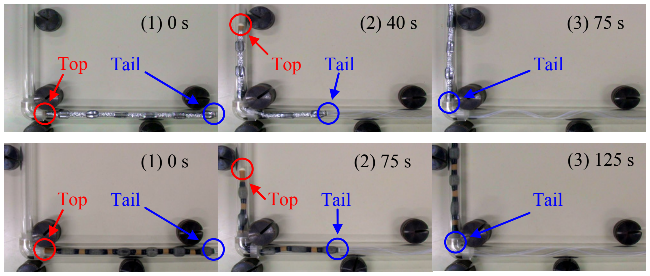


Figure 18. Passage time of each robot in a horizontal elbow.

VI. New Head Section

In this section we explain the requirement for the head section to guide the robot when the robot is passing through an elbow. Figure 19 shows an image of the head section climbing over a step that is between an elbow and a straight pipe. First, to climb over the step, the ABS part needs to proceed in the direction of travel, therefore the tip of the head section needs to be flexible. Figure 20 shows an image after the head section has climbed over the step. If the head section is flexible, the base of the head section buckles, therefore the head unit collides with the elbow. Thus, the base of the head section needs a pulling force that pulls it backward because the head unit needs to proceed in the direction of traveling.

Figure 21 shows an image of the new head section we developed, and Table 3 shows the specifications. The new head section climbs over the step using the flexibility of a compression spring, and pulls itself backward by using the pulling force of the extension spring. We determined this length (140 mm) so that the head section can pass through a continuous elbow first as the robot passes through a continuous elbow.

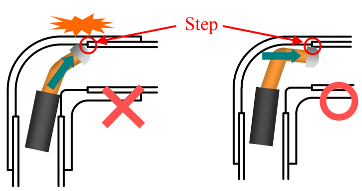


Figure 19. Head section climbing over a step.

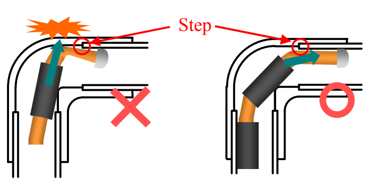


Figure 20. Image after the head section has climbed over the step.

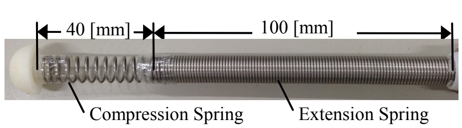


Figure 21. New head section.

TABLE III. New Head Section Specifications

	Outer diameter [mm]	Inner diameter [mm]
Compression spring	10.0	8.0
Extension spring	8.4	6.0

VII. Peristaltic Crawling Robot for Continuous Elbows

Figure 22 shows an image of the robot developed for continuous elbows and Table 4 shows the specifications of the unit. As shown in the table, the unit length became its shortest so that the unit can grasp the elbow, enabling the robot to pass smoothly through an elbow.

The locomotion speed of the robot is 10.2 mm/s in a 1-inch acrylic pipe, using Motion 4-1-1 with a time interval of 0.2 s. Air pressure of 0.12 MPa was applied to the unit. As the unit length became short, the length contraction of in the pipe increase. Therefore, the locomotion speed in a pipe increases compared to a low-friction robot.

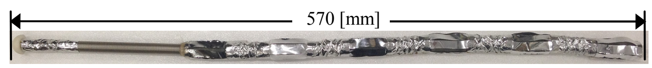


Figure 22. Peristaltic crawling robot for continuous elbows.

TABLE IV. Unit Specifications

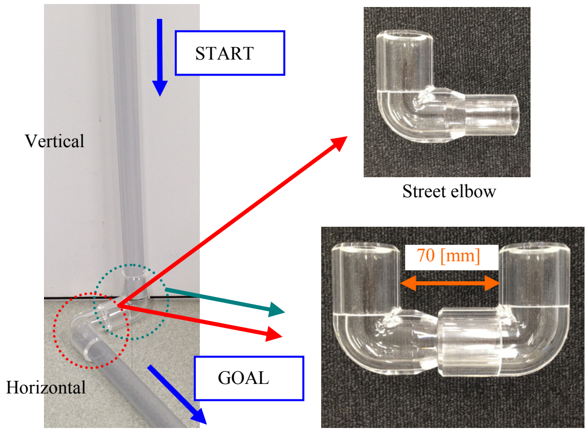
Weight [g]		6.8
Length [mm]	Extension	42.8
	Contraction	32.8
Width [mm]	Extension	15.0
	Contraction	34.6

VIII. Experiment in Continuous Elbows

We conducted an experiment in which the developed robot attempts to pass through (narrow) continuous elbows.

Figure 23 shows an image of the experimental environment and connected elbows. This array is the same as that encountered in real-life environments. If the pressure in the pipes that is connected to both ends of an elbow differs, the elbow may be broken by the pressure of the pipe and the expansion and contraction of pipe. To prevent this, an elbow and a street elbow are combined.

This experiment is conducted in a 1-inch acrylic pipe (made based on pipe manufactured by Sekisui Chemical Company) using Motion 4-1-1 with a time interval of 0.2 s. Air pressure of 0.12 MPa was applied to the unit. Figure 24 shows the experimental results, which shows the robot passed through a narrow elbow, and the continuous elbows in 163 s. Therefore, the locomotion speed of the robot is 4.2 mm/s in continuous elbows; however, this is less than half the speed of a counterpart's 10.2 mm/s in a straight pipe. The reason for this is that because the alignment of the elbows is complex, a large amount of friction between the robot and pipe arises when the robot passes through the continuous elbows. Therefore, the robot undergoes a deflection, which comes back behind the robot when it switches to the next motion cycle and the last unit leaves the pipe. Thus, a loss of procession of the robot arises. We think that to solve this problem, we need to increase the number of units to increase the robot's travel distance per motion cycle. Thus, the robot penetrates further when it undergoes a deflection.



(a) Continuous elbows pipe. (b) Combined elbows.

Figure 23. Experiment environment.

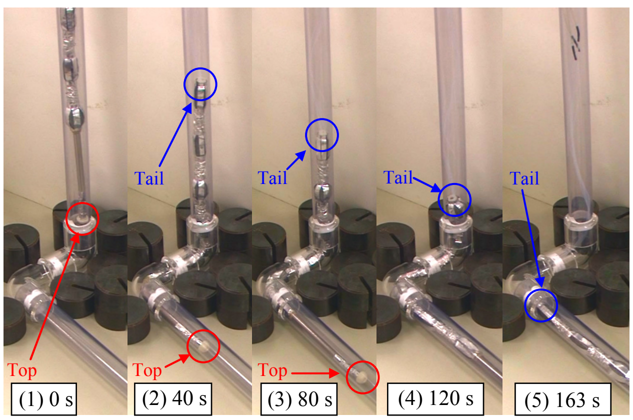


Figure 24. Experiment in continuous elbows.

IX. Conclusion and Future Work

A. Conclusion

We developed a peristaltic crawling robot for in-pipe inspection of 1-inch gas pipes that can pass through continuous elbows using pneumatic artificial muscles. Our results were as follows:

(1) The robot passed through an elbow 1.7 times faster than its predecessor while retaining maximum friction force and speed in a straight pipe by reducing friction, and developing a variable friction unit.

(2) The robot could pass through a narrow elbow of a type commonly found in real-life environments by developing a head section that combines a compression spring and an extension spring.

(3) As a result, the robot could pass through continuous elbows.

B. Future Work

In order to pass smoothly through continuous elbows, we should increase the number of units.

Moreover, to use the robot in real-life environments, we should enable the robot to travel long distances.

References

[1] A. Kuwada, K. Tsujino, K. Suzumori, and T. Kanda “Intelligent actuators realizing snake –like small robot for pipe inspection,” in 2006 Proc. IEEE International Symposium on Micro-nano Mechatronics and Human Science, pp. 1-6.

[2] P. Li, S. Ma, B. Li, and Y. Wang, “Development of an adaptive mobile robot for in-pipe inspection task,” in Proc. ICMA International Conference on Mechatronics and Automation, pp. 3622-3627, 2007.

[3] T. Okada and T. Sanemori, “MOGRER: A vehicle study and realization for in-pipe inspection tasks”, IEEE Journal of Robotics and Automation, Vol. RA-3, No. 6, pp. 573–582, Dec. 1987.

[4] A. H. Heidari, M. Mehrandezh, R. Paranjape and H. Najjaran, “Dynamic analysis and human analogous control of a pipe crawling robot,” Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 733-740, 2009.

[5] M. Konyo, K. Hatazaki, K. Isaki and S. Tadokoro, “Development of an active scopecamera driven by ciliary vibration mechanism”, Proc. of the 12th ROBOTICS symposia, pp.460-465, 2007.

[6] K. Suzumori, T. Miyagawa, M. Kimura, and Y. Hasegawa, “Micro inspection robot for 1-in pipes”, *IEEE/ASME Trans. Mechatronic*s, vol. 4, pp. 286-292, Sep.1999.

[7] S. Hirose, H. Ohno, T. Mitsui, and K. Suyama, “Design of in-pipe inspection vehicles for ø25, ø50, ø150 pipes”, in *Proc. IEEE International. Conference. Robotics, Automation*, 1999, pp. 2309-2314.

[8] M. Ikeuchi, T. Nakamura, and D. Matsubara, “Development of an in-pipe inspection robot for narrow pipes and elbows using pneumatic artificial muscles”, *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012.

[9] T. Nakamura, T. Kato, T. Iwanaga and Y. Muranaka, “Development of a peristaltic crawling robot using servo motors based on the locomotion mechanism of earthworms”, Proceedings of IEEE International Conference on Robotics and Automation (ICRA 2006), pp.4342-4344, 2006.

[10] T. Nakamura and T. Iwanaga, “Locomotion strategy for a peristaltic crawling robot in a 2-dimensional space”, Proc. IEEE International Conference on Robotics and Automation, 2008, pp. 238–243.

[11] N. Saga and T. Nakamura, “A prototype of peristaltic robot using pneumatic artificial muscle”, The 8th Conference on Intelligent Autonomous System (IAS-8), 2004.

[12] H. Omori, T. Hayakawa and T. Nakamura, “Locomotion and turning patterns of a peristaltic crawling earthworm robot composed of flexible units”, Proceedings of IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems, pp.1630-1635, 2008.

[13] S. Horii, T. Nakamura and K. Aoki, "Development of an in-pipe peristaltic crawling mobile robot and derivation of theoretical model", Proceedings of 1st International Conference on Applied Bionics and Biomechanics (ICABB-2010), 2010.

[14] H. Sugi, “Evolution of muscle motion,” The University of Tokyo Press, p. 72, 1977 (in Japanese).

[15] T. Nakamura, and H. Shinohara, “Position and force control based on mathematical models of pneumatic artificial muscles reinforced by straight glass fibers,” Proceedings of IEEE International Conference on Robotics and Automation (ICRA 2007), pp. 4361- 4366.

[16] T. Nakamura, N. Saga, and K. Yaegashi, “Development of pneumatic artificial muscle based on biomechanical characteristics,” Proceedings of IEEE International Conference on Industrial Technology (ICIT 2003), pp. 729-734.