# Improvement of Pipe Holding Mechanism and Inchworm Type Flexible Pipe Inspection Robot

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***Abstract*— In wet condition of complex pipe, pipe inspection robots using fluidic flexible actuators have advantages because of no electrical leakage and easy traveling into pipe while deforming its body. In the previous study, a robot that can travel in a complex pipe with inner diameter of 100 mm by changing pipe holding position like an inchworm was proposed and tested. However, the pipe holding mechanism using extension type flexible pneumatic actuator could not hold the pipe surly because of its small contacting area with pipe. In this paper, to make sure to surely the hold pipe with smaller diameter of 75 and 50 mm, the development of a holding mechanism with large contacting area with pipe is described. The improved holding mechanism has similar construction of automobile tire wheel to decrease volume change for expanding. In addition, a thinner type sliding/bending mechanism using a novel extension type flexible pneumatic actuator for the pipe diameter of 50 mm is proposed and tested. The pipe inspection robots using both pipe holding mechanisms for the pipe diameter of 75 and 50 mm are also developed. The driving test of pipe inspection robots using both holding mechanisms is carried out. As a result, it can be confirmed that both robots can travel smoothly in a complex pipe that includes corner and tee joints.**

***Index Terms*— tire wheel type pipe holding mechanism, extension type flexible pneumatic actuator, pipe inspection robot, sliding/bending mechanism**

## I. INTRODUCTION

In 2014, about 12.1% of the total length of Japan's water supply pipelines of 660,000 km has surpassed 40 years of statutory life [1]. Only 0.76% of the entire pipe is replaced once in every year. It takes 130 years to replace the entire pipe in calculation. Consequently, many water leakage accidents are reported in Japan. In addition, Japan terrain is mostly rugged and mountainous causes the water pipelines in Japan to be very complex with numerous corners and joints. It makes the pipe inspection more difficult. Therefore, various inspection methods such as a fiber scope have been developed. However, a manipulated fiber scope has a disadvantage that searching area is not so large because of pipe complexity. Therefore, pipe inspection robots that can travel by themselves have been developed by various companies and researchers [2-4]. These inspection robots need high mobility in the pipeline. It is also more desirable because the shape of the robot's body can change naturally due to low energy consumption and can reduce the travel time. In addition, a fluidic actuator is convenient to apply in damp and wet conditions such as a water supply pipe [5-8]. There is no risk of electric leakage and short circuit. Based on this concept, a pipe inspection robot that consists of a sliding propulsion mechanism and a holding mechanism using extension type flexible pneumatic actuators (we call it "EFPAs" for short) has been proposed and tested in the previous study [9,10]. The robot could successfully travel in the pipe with the inner diameter of 100 mm [10]. However, the tested pipe holding mechanism could not hold the pipe surely, because the contacting area with pipe is small. The holding force affects carrying force and inspection area of robot. Therefore, it is necessary to improve the pipe holding mechanism so that its contact area with the pipe becomes larger. In addition, from viewpoint of response, it is better to make the volume change of the mechanism smaller.

In this study, a novel pipe holding mechanism that has larger contact area with pipe of smaller inner diameter of 75 and 50 mm and small volume change is proposed and tested. In this paper, the construction and holding characteristics of these pipe holding mechanisms will be described. Also, the mobility of the pipe inspection robot using both pipe holding mechanisms and a novel thin sliding/bending mechanism will be explained through the driving test of the robot in narrow and complex pipes.

## II. PREVIOUS PIPE INSPECTION ROBOT

Fig. 1 shows the view of the whole pipe inspection robot developed in the previous study [10]. The robot consists of a sliding/bending mechanism and two holding mechanisms using EFPAs. Two holding mechanisms are set at both ends of the sliding/bending mechanism. The coil type tube can supply air to the top end of holding mechanism from the end of robot. The total length and

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weight of the robot are about 0.3 m and about 0.49 kg, respectively. The robot is connected to a valve unit controlled by a control unit that consists of an embedded controller (Renesas electronics Co. Ltd. SH7125) and transistors. Fig. 2 shows the view and inner construction of the EFPA. The EFPA consists of a silicone rubber tube (with an inner diameter of 8 mm and outer diameter of 10 mm) covered with a bellows-shaped ruffled fabric sleeve made of nylon strings and two acrylic end connectors with a supply port. The bellows-shaped ruffled fabric sleeve will prevent it from expand toward radial direction, thus the actuator will lengthwise longitudinally when the supply pressure is applied. The actuator can extend more than about 2.5 times of its original length. This high extension ratio of 250 % is one of the strongest points of EFPAs.

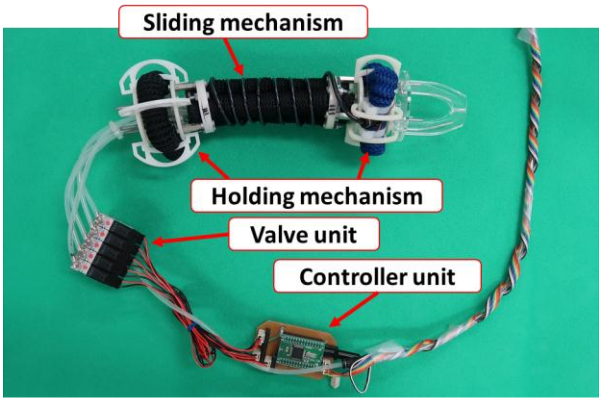



Figure 1. Previous pipe inspection robot using EFPAs.

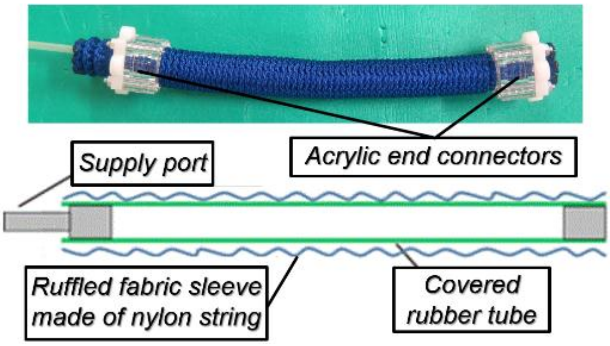



Figure 2. View and inner construction of the EFPA.

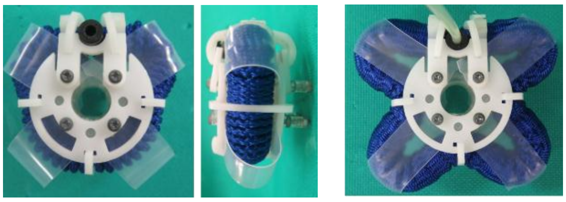


Figure 3. The holding mechanism using EFPA

Fig.3 shows the pipe holding mechanism using the EFPA. The left and right sides on Fig. 3 show the view of the tested mechanism when the supply pressure of 0 and 500 kPa is applied, respectively. The mechanism consists of a ring-shaped EFPA that both ends of the EFPA are connected to a tee joint. The operating principle of the holding mechanism is as follows. When the supply pressure is applied to EFPA in the mechanism, non-fixed area of the EFPA expands toward radial direction and the stiffness of the EFPA increases. The expanding area of the mechanism can hold the pipe. The maximum outer diameter is 114 mm. The holding force is about 44 N in the case when four expanding parts catch the pipe with an inner diameter of 100 mm [10].

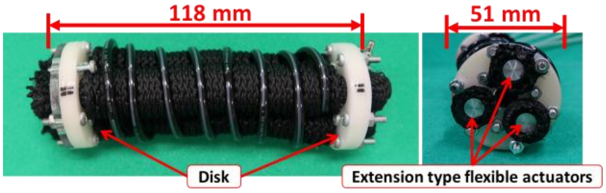



Figure 4. Sliding/bending mechanism using three FFPAs.

Fig. 4 shows the construction of the sliding/bending mechanism using EFPAs. In the mechanism, three EFPAs are set in parallel between both disks in every 120 degrees and have a radius of 12 mm from the central axis of the robot. Fig.5 shows the operation of the robot. The operating principle of the robot is as follows. First, the pipe holding mechanism at the end of the robot expands so that it can hold the pipe. In the condition, the sliding mechanism is extended by pressurizing three EFPAs. When the sliding mechanism extends up to a maximum length, the top pipe holding mechanism expands to hold the pipe. After that, the end pipe holding mechanism and the sliding mechanism contracts by exhausting input pressure, and end holding mechanism moves forward. By repeating these operations, the robot can move forward as an inchworm. The backward motion can also be realized by applying the opposite operation mentioned above. To steer the robot toward desired direction in pipe joint, after bending motion is applied by pressurizing one or two EFPAs in the sliding/bending mechanism, it can be realized by all three EFPAs are pressurized. By this method, the robot can select six radial directions by pressurized one or two EFPAs in the sliding/bending mechanism.

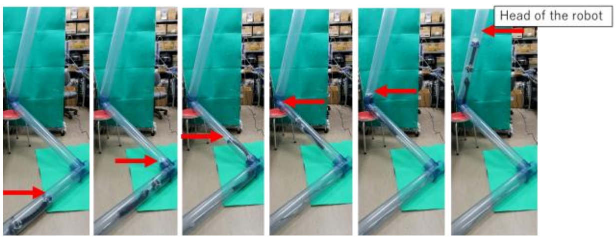



Figure 5. Transient view of movement of the previous robot in case when the robot travels in complex pipe.

Fig. 5 shows transient view (from left to right) of the previous robot's movement when traveling in a complex pipe with an inner diameter of 100 mm. In the experiment, first, the robot travels in the straight pipe with length of 1 m set on the floor. Before the robot reaches at an elbow or tee joint, the robot bends toward the desired direction. From this condition, three EFPAs in the sliding/bending mechanism are pressurized. Then, the robot can move forward while deforming its shape naturally according to pipe shape because of its flexibility. After that, the robot climbs the straight pipe with an inclined angle of 25 deg. It also turns the elbow joint. Also, it climbs the pipe with an inclined angle of 75 deg. From the experiment, it could be confirmed that the robot could pass through a complex pipe with a total length of 3 m within 4 minutes. The average moving speed is 14 mm/s.

However, in some cases, the pipe holding mechanism could not catch the inner pipe surely especially when the robot passes through the bending joint due to the top holding mechanism being oblique to pipe axis once the robot is bends. In addition, the unique mechanism using ring-shaped EFPA prevents to reduce outer diameter of the holding mechanism. In the next section, a novel pipe holding mechanism that can hold smaller pipe with large contact area will be described.

## III. Improved Pipe Holding Mechanism

### A. Construction

Pipes with smaller inner diameter of 75 and 50 mm that are commonly used as main pipe diameter were selected as a tested pipe in this experiment to improve pipe holding mechanisms. In order to get a larger contact area with pipe without a larger volume change, a novel pipe holding mechanism that has similar construction of tire wheel is proposed and tested. Fig. 6 and 7 show the construction of the improved pipe holding mechanisms for pipe diameter of 75 and 50 mm, respectively. Both mechanisms consist of a tire wheel type cylindrical rubber tube holder made by laminated acrylic plates, the rubber tube and two disk shaped holding plates and clamping rings for rubber tube. The rubber tubes with outer diameter of 60 and 29 mm are used in the holding mechanism for pipe diameter of 75 and 50 mm, respectively.

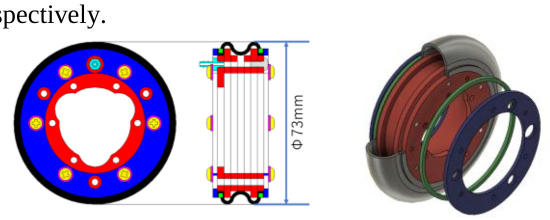



Figure 6. Construction of improved pipe holding mechanism for pip diameter of 75 mm.

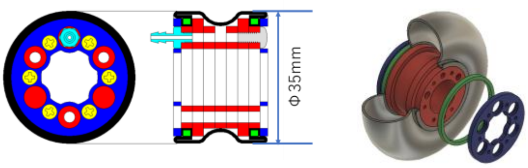



Figure 7. Construction of improved pipe holding mechanism for pip diameter of 50 mm.

In both mechanisms, the rubber tube is set over the wheel type holder. Both ends of each tube are clamped by the tube holder and disk-shaped holding plates through two clamping rings. By this method, the volume change of inner chamber surrounded by rubber tube for input pressure is limited toward only radial direction of the mechanism. Then, to decrease the volume change and to increase the contacting area, the outer diameter of both holding mechanism are set 73 and 35mm for pipe of 75 and 50 mm, respectively. The mass of the tested mechanism for pipe diameter of 75 and 50 mm are 68.8 and 28.8 g, respectively.

### B. Pipe Holding Characteristics

Figs. 8 and 9 show the relations between supplied pressure and pipe holding force of tested mechanisms for pipe diameter of 75 and 50 mm, respectively. In the experiment, the pipe holding force is measured as a pulling force when the slip has occurred under the condition when the mechanism in the pipe is pulled. In both figures, symbol shows the average values of holding force of 20 times measurements. The vertical bar shows the measured data distribution. The maximum pressure supplied was decided through a preliminary experiment to investigate the rupture pressure of the mechanism. From both figures, it can be seen that both mechanisms can generate pipe holding force of about 160 N. This value is about 4 times higher than the previous one [10]. As the contact area with pipe is circumferential area, the improved holding mechanism can hold pipe more surely. The pipe holding force of 160 N is enough to apply to pipeline inspection robot using EFPAs, because the maximum generated pulling force of the sliding/bending mechanism in the robot is about 60 N.

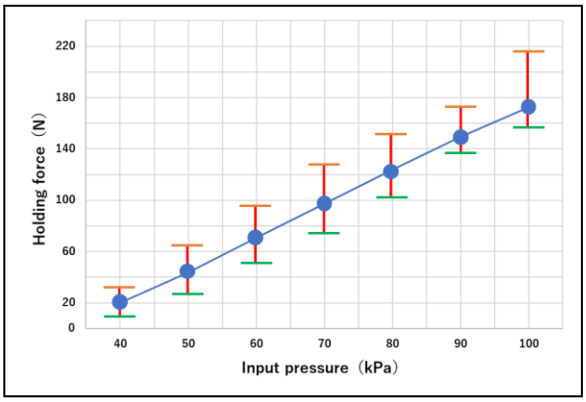



Figure 8. Relation between supplied pressure and pipe holding force of the mechanism for pipe diameter of 75 mm.

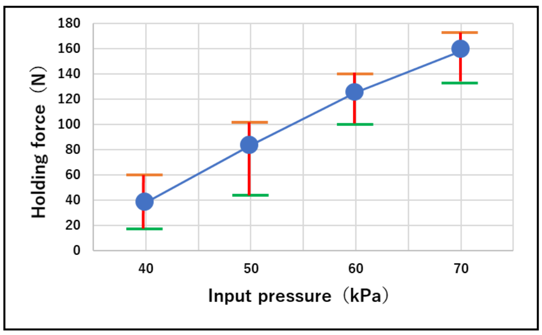



Figure 9. Relation between supplied pressure and pipe holding force of the mechanism for pipe diameter of 50 mm.

## IV. Improved Pipe Inspection Robot

### A. Construction

Figs. 10 and 11 show the construction of the improved pipe inspection robots using the improved holding mechanism for pipe diameter of 75 and 50 mm, respectively. In each robot, two holding mechanisms are set to both ends of the sliding/bending mechanism. In both sides of the holding mechanism, there are plastic guide to prevent stacking at a corner as shown in Fig. 10 and 11. In the case using the holding mechanism for pipe diameter 75 mm, the outer guide uses an arc-shaped claws with length of 21.7 mm and the inner guide uses a short arc-sloped claws with length of 14.7 mm to fill the gap between the holding mechanism and the sliding mechanism. On the other hand, the case using the mechanism for 50 mm, in the outer side of robot, the arc-shaped claws are also used with length of 19.7 mm meanwhile the inner side, a round plate with an outer diameter of 44.2 mm is used instead of claw type guide. The design of these guides was carried out according to the tee joint and corner that have a shaped edge in the joint as shown in Fig. 12 by trail and error.

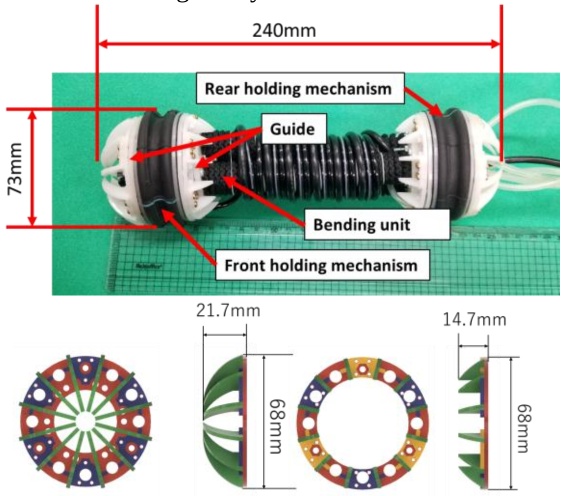



Figure 10. Improved pipe inspection robot and support guide for pipe diameter of 75 mm.

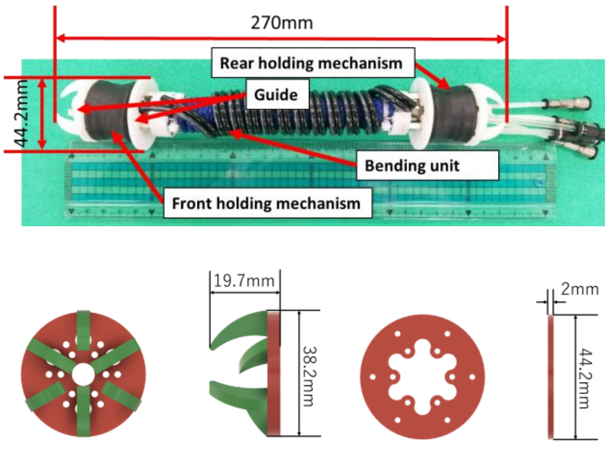
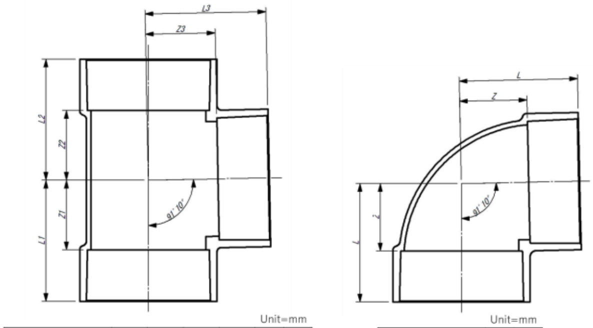



Figure 11. Improved pipe inspection robot and support guide for pipe diameter of 50 mm




Unit=mm

| Part number | Z1 | Z2 | Z3 | L1 | L2 | L3 |
|---|---|---|---|---|---|---|
| VU-DT-TOUMEI_50 | 34 | 34 | 34 | 59 | 59 | 59 |
| VU-DT-TOUMEI_75 | 48 | 49 | 48 | 88 | 89 | 88 |
| VU-DT-TOUMEI_100 | 62 | 63 | 62 | 112 | 113 | 112 |

Unit=mm

| Part number | Z | L |
|---|---|---|
| VU-DL-TOUMEI_50 | 33 | 58 |
| VU-DL-TOUMEI_75 | 48 | 88 |
| VU-DL-TOUMEI_100 | 62 | 112 |

Figure 12. Sectional diagram of typical tee joint and corner.

In addition, in the case of the robot for pipe diameter of 50 mm, a thinner type sliding/bending mechanism is used. Fig. 13 shows the inner construction of the thinner type sliding/bending mechanism using a novel EPFA. Compared with the previous sliding mechanism, three silicone rubber tubes with inner diameter of 4 mm and outer diameter of 6 mm are installed into one bellows type ruffled fabric tube. Both end of the EFPA has connectors that can clamp three rubber tube at same time. The mechanism can also extend and bend by changing pressurized rubber tube. The maximum generated pulling force is as same as one EFPA, that is 31 N.

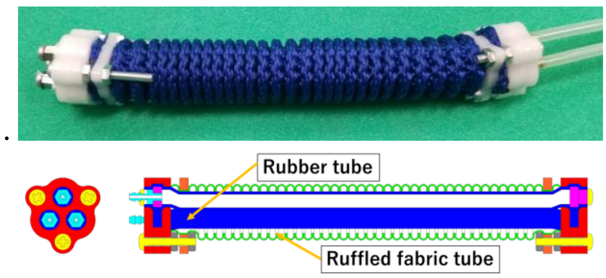



Figure 13. Inner construction of thinner type sliding/bending mechanism.

### B. Control System and Driving Test

Fig. 14 shows the schematic diagram of control system to drive the tested pipe inspection robot. The system consists of the tested robot, five on/off control valves (Koganei Co. Ltd., G010HE1) and an embedded controller (Renesas Electronics, SH7125). Three valves are used for the sliding mechanism, and they are operated through transistor and I/O port in the embedded controller. Two valves are used for pipe holding mechanisms and operated through transistor and PWM control port in the controller. In order to use same supplied pressure of 500 kPa for both sliding and holding mechanisms, the holding mechanisms are driven by lower duty ratio signal so as to reduce operating pressure of the mechanism. The optimal duty ratio of each holding mechanism for pipe diameter of 75 and 50 mm was investigated by trial and error through driving test of the robot. In the experiment, duty ratio 50 and 30% were used for the holding mechanism of pipe diameter of 75 and 50 mm, respectively. The control procedure is as follows. The operator sends digital code through a serial communication cable using a personal computer. The embedded controller selects to drive suitable valve according to the sequential program that is preinstalled into the controller. The timing of valve operation is adjusted by using of timer function in the embedded controller.

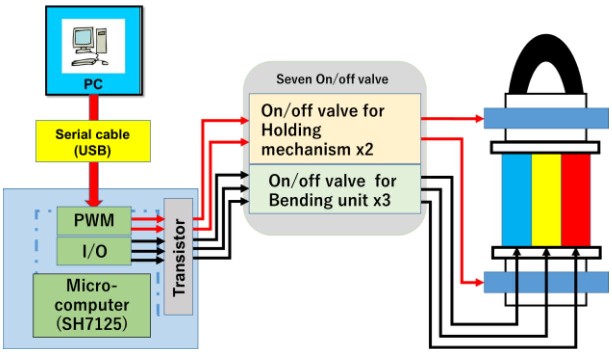



Figure 14. Schematic diagram of control system to drive the mechanism.

Fig.15 shows the experimental setup for driving test of the tested robot. Fig. 16 and 17 shows the results of driving test when the tested inspection robots pass through a complex pipe as shown in Fig. 15. In the experiment, the complex pipe has same configuration of the previous one as shown in Fig. 5. Fig. 16 shows the case using the robot for pipe diameter of 75 mm. Fig. 17 shows the result for pipe diameter of 50 mm. In each experiment, three straight pipes with a length of 1 m and a corner and a tee joint were used. In addition, the valve unit was located on outside of pipes as shown in Fig. 15. Between the robot and valve unit, there is parallel arranged five small pipes with outer diameter of 4 mm and inner diameter of 2.5 mm. From both Figs. 16 and 17, it can be seen that both robots can pass through smoothly the complex pipe with a total length of 3 m within 4 minutes. Interestingly, through observation, robots are not stuck in corner and tee joints. This is mainly because of the improved higher holding force. As a result, it can be confirmed that the improvised pipe holding mechanism is useful to be apply to the pipe inspection robot. It is also confirmed that the pipe inspection robot for pipe diameter of 75 and 50 mm can be successfully developed.

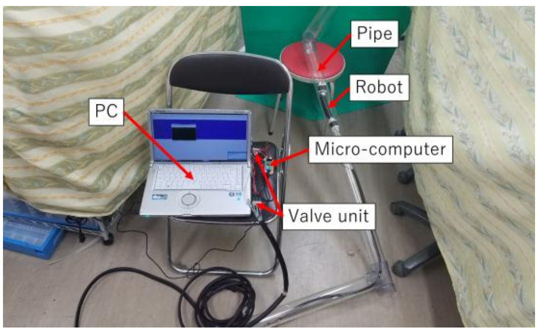



Figure 15. Result of driving test using the tested robot for pipe diameter of 75 mm.

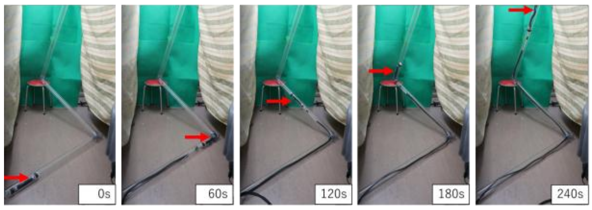



Figure 16. Result of driving test using the tested robot for pipe diameter of 75 mm.

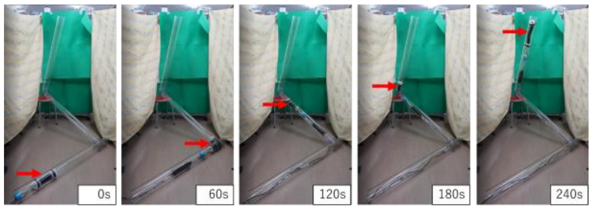



Figure 17. Result of driving test using the tested robot for pipe diameter of 50 mm.

## V. CONCLUSIONS

This study aiming to improve a pipe holding mechanism for traveling small pipe and holding pipe surely can be summarized as follows.

To hold pipe surely without large volume change, two sizes of tire wheel type pipe holding mechanisms were proposed and tested. One is used for pipe diameter of 75 mm. Another is for diameter of 50 mm. The holding characteristics of both mechanisms were investigated. As a result, the holding force of about 160 N could be obtained in both mechanisms. This value is about 4 times higher than that of the previous pipe holding mechanism.

To develop the pipe inspection robot for pipe diameter of 50 mm, the thinner type sliding/bending mechanism was proposed and tested. The pipe inspection robots using improved pipe holding mechanisms and the thinner sliding mechanism were also proposed and tested. The control system that it can adjust different operating pressure by using PWM method from same supply pressure was proposed and tested. The driving test using both robots was also carried out. As a result, it can be confirmed that both robots can pass through a complex pipe smoothly with moving speed of about 14 mm/s without stuck.

As a future work, the driving test using tested pipe inspection robots with various condition of pipe will be carried out. The driving system using tap water will also be developed as a familiar fluid pressure source.

## ACKNOWLEDGMENT

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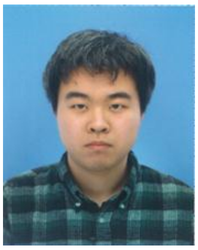

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