Development of Pipe Holding Mechanism and Bending Unit Using Extension Type Flexible Actuator for Flexible Pipe Inspection Robot

Keichi Kusunose, Tetsuya Akagi, Shujiro Dohta, Wataru Kobayashi, and Kengo Nakagawa
Okayama University of Science, Okayama, Japan
Email: t14r019kk@ous.jp, {akagi, dohta, kobayashi}@are.ous.ac.jp, t17rm04nk@ous.jp

***Abstract*—To reduce the inspection cost of water supply pipe, various pipe inspection robots have been developed. In the previous study, a novel pipe inspection robot using a flexible pneumatic cylinder and pipe holding mechanism that could move forward along to the pipe by changing the robot's body naturally was proposed and tested. In this paper, to improve its mobility and responsibility, a pipe holding mechanism using an extension type flexible pneumatic actuator whose volume change is smaller than the previous one using a balloon is proposed and tested. In addition, to change the travelling direction of the robot, a compact bending unit using shorter extension type flexible actuators is proposed and tested. As a result of its driving test, the tested thin holding mechanism can hold a pipe without increasing its longitudinal length. The tested bending unit can bend 90 deg. toward every radial direction with the length of the unit becomes two-third short from the previous one.**

***Index Terms*— holding mechanism; compact bending unit; extension type flexible pneumatic actuator; pipe inspection robot.**

I. Introduction

In Japan, it is found that about 5% of the total length of water supply pipe have been already past the statutory useful life of 40 years [1]. Water pipe lines are very complex and include numerous corners and joints. If an excavating work is used to inspect these pipes, a huge cost is needed. Therefore, various inspection methods such as a fiber scope have been developed. However, a manipulated fiber scope has a limit of searching area. In particular, complex pipelines include angles and tee joints preventing the examination. Therefore, pipe inspection robots have been developed by various companies and researchers [2-4]. The cost of pipe inspection can also be reduced by using these robots. The inspection robots require high mobility. In ideal, it is more desirable that the shape of the robot body changes naturally because of the low energy consumption and reducing the time for traveling. In our pervious study, a pipe inspection robot that consists of a flexible sliding mechanism using a flexible pneumatic cylinder have been proposed and tested [5-8]. The tested robot could travel in the narrow space smoothly by changing the body according to the shape of the pipe.

In the next step, it is necessary to improve its mobility for corners and tee joints. In this paper, a thin pipe holding mechanism using an extension type flexible pneumatic actuator is proposed and tested. As a desired holding mechanism, it is necessary to develop a mechanism that increases in diameter without increasing its longitudinal length. It also needs to develop a compact bending unit that can change the moving direction of the inspection robot. In particular, to pass through elbow and pipe tee the bending unit with a shorter length of less than 100 mm and a bending angle of more than 90 deg. is required. In this paper, the construction and the operating principle of the tested holding mechanism and bending unit are described. The holding performance of the mechanism and bending ability of the unit will be investigated.

II. Previous Pipe Inspection Robot

A. Flexible Pneumatic Cylinder

As an actuator of an inspection robot that moves in a narrow space while changing body naturally, a flexible pneumatic cylinder is used. Fig. 1 shows the construction of the flexible pneumatic cylinder developed in our previous study [9]. The cylinder consists of a flexible tube as a cylinder, a steel ball with outer diameter of 9 mm as a cylinder head, and two slide stages. The 9 mm steel ball as a cylinder head is pinched by two pairs of brass rollers from both sides. This allows the ball to move freely when air enters into the cylinder. The operating principle of the flexible cylinder is as follows.

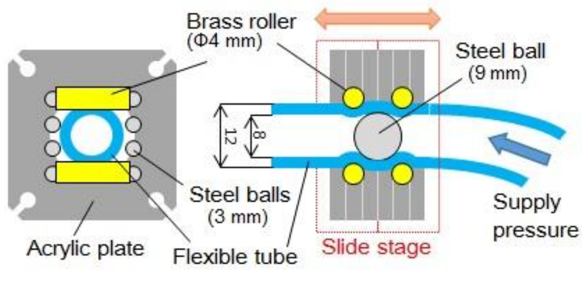


Figure 1. Construction of the flexible cylinder.

Manuscript received March 9, 2018; revised December 14, 2018.

doi: 10.18178/ijmerr.8.1.129-134

When the pressure is applied to one side of the cylinder, the 9 mm steel ball which is in the middle of the slide stage is pushed and moved accordingly. At the same time, the steel ball pushes the brass rollers and then the slide stage moves while it deforms the tube. The slide stage can move even if the cylinder bends. The generated force of the cylinder is about 15 N when supplied pressure of 500 kPa is applied.

B. Pipe Inspection Robot

Fig. 2 shows a flexible sliding mechanism using the flexible pneumatic cylinder and two open/close units as a holding mechanism developed in the previous study [6]. The coil type pneumatic supply tube is used as a supply pipe to the open/close unit on the slide stage and to the top end chamber of the cylinder. The open/close unit can expand the claw toward radial direction using the mechanism like an umbrella shape and is driven by the typical pneumatic cylinder. The initial diameter of the unit with no supply pressure is 48 mm. The unit has the maximum diameter of 120 mm when it opens and the maximum length of 140 mm when it closes. The flexible pneumatic cylinder is located into the coil tube. By using coil type tubes, the smart configuration of air supply pipes from the end of the mechanism can be realized.

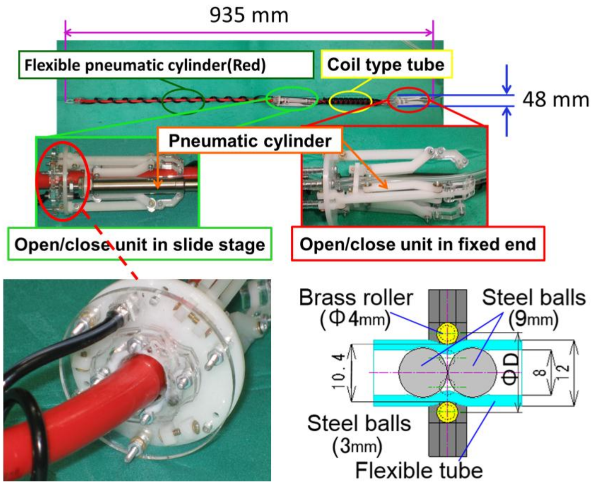


Figure 2. Flexible sliding mechanism for inspection robot.

Fig. 3 shows the operating principle of the sliding mechanism. The operating principle is as follows. First, the open/close unit at the end of the mechanism opens so that the claw can hold the pipe as shown in Fig. 3 (2). Next, the right-side chamber of the flexible cylinder is pressurized, then, the slide stage with the open/close unit can slide toward the top end of the cylinder (3). When the slider reaches at the end of the cylinder, the open/close unit opens to hold the pipe (4). Then, the open/close unit at the end of mechanism closes (5), and the left side chamber of the cylinder is pressurized. At the same time, the flexible cylinder with the end open/close unit can move forward (6). By repeating these operations from (2) to (6), the mechanism can move forward as an inchworm.

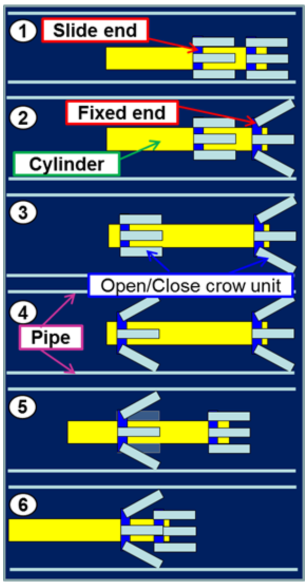


Figure 3. Operating principle of sliding mechanism.

Fig. 4 shows the view movement of the tested inspection robot using the sliding mechanism when the robot passes through the pipe with the inner diameter of 100 mm. The size of the robot is 1.1 m in length with 48 mm of outer diameter. The total mass of the robot including the pneumatic driving system is 0.78 kg. The motion for passing through a pipe is as follows. First, from the far front of pipe tee (A, C), the bending unit of the robot is bent toward the desired direction (2). While keeping the bending motion, the robot moves forward. Then, the acrylic guide is inserted into the desired pipe. The robot can move forward along to the pipe by changing the robot's body naturally. Fig. 4(3) shows the case when the robot passes through an elbow (B). In the same manner as the case of the pipe tee, by bending toward the desired direction in the far front of the corner, the robot can easily move at the corner. The moving speed passing through both corners is almost same speed of moving straight (about 140 mm/s). However, it is noted that sometimes open / close units have been trapped in the corner while the robot was bending. Therefore, it needs to develop a pipe holding mechanism with shorter longitudinal length. In addition, to realize quick response for holding the pipe as same as the previous, the unnecessary volume change of a holding mechanism should be decreased.

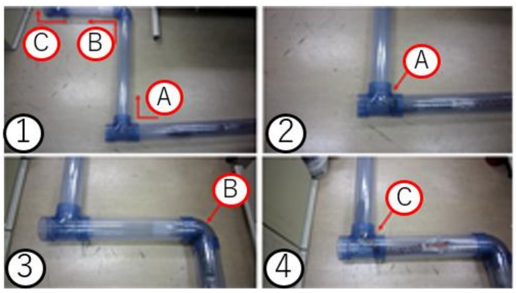


Figure 4. View of movement of inspection robot in complex pipe.

III. Pipe Holding Mehcanism Using Flexible Extension Type Actuator

A. Flexible Extension Type Actuator

In order to improve the mobility of the robot, a thin holding mechanism with quick response is required. If a balloon type holding mechanism is used, the response time of the mechanism is depending on the volume change and supplied flow rate of the balloon. In ideal, a flexible expanding mechanism toward radial direction without expanding toward longitudinal direction is required. In this study, therefore, as a pneumatic actuator whose volume change occurs toward only one direction, an extension type flexible pneumatic actuator is proposed and tested. Fig. 5 shows the schematic diagram of the proposed extension type flexible actuator. The tested actuator consists of a silicone rubber tube covered with a ruffled fabric sleeve made of nylon strings and two acrylic end connectors with a supply port. The rubber tube has an inner diameter of 8 mm and outer diameter of 10 mm.

The operating principle of the actuator is as follows. When the air is supplied to the actuator, the inner rubber tube expands toward radial and longitudinal directions. As the ruffled fabric sleeve can only deform toward longitudinal direction while preventing to expand toward radial direction, the actuator extends longitudinally. The actuator can extend more than about 2.5 times of the original length when the input pressure of 400 kPa is applied.

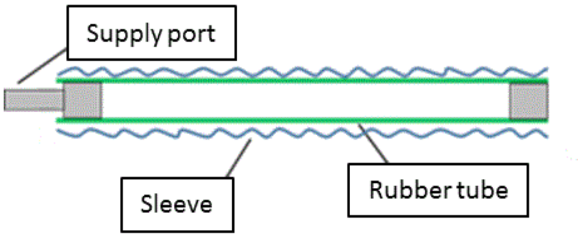


Figure 5. Schematic diagram of tested extension types flexible actuator.

B. Proposed Pipe Holding Mechanism

Fig. 6 shows the side view of the improved pipe holding mechanism using the extension type flexible actuator proposed in this study. Fig. 7 shows the view of the improved pipe holding mechanism using the tested actuator mentioned above. The mechanism consists of a ring-shaped extension type flexible actuator that both ends of the actuator are connected with a tee joint. The actuator is placed to close and cover the plastic winding frame located at the center of the mechanism. The ring-shaped actuator is fixed on the plastic frame by using five plastic hooks. It is covered by 4 pieces of silicon rubber films with thickness of 0.5 mm to prevent slipping on the pipe. The size of the mechanism is 78 mm in outer diameter and 45 mm in length without supplied pressure. Compared with the previous open/close unit, the longitudinal length becomes shorter from 140 mm to 45 mm. By using the flexible actuator, the rigid parts can be reduced on the circumference face.

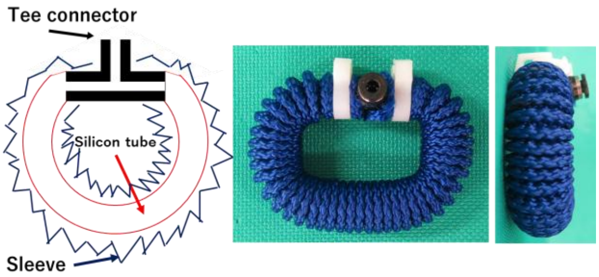


Figure 6. Construction and view of extension type flexible actuator.

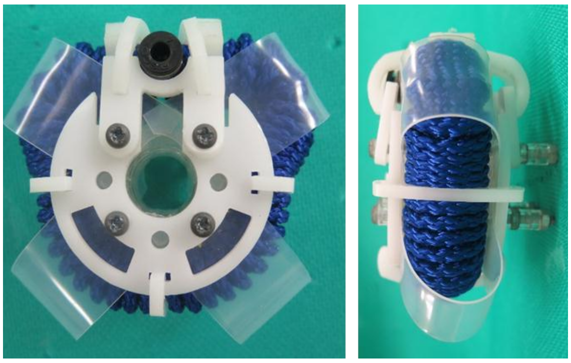
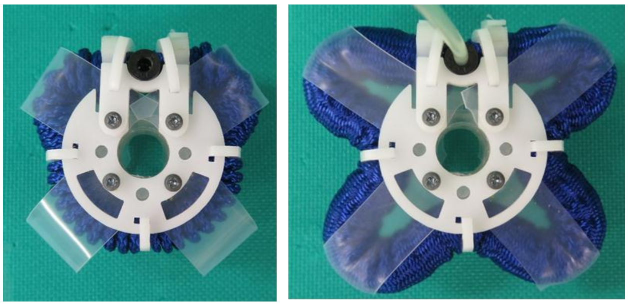


Figure 7. View of the improved pipe holding mechanism.

Fig. 8 (a) and (b) show the view of the operation of the tested holding mechanism when the supplied pressure of 0 and 500 kPa are applied, respectively. The operating principle of the pipe holding mechanism is as follows. When the air is supplied into the actuator, the actuator expands toward its longitudinal direction. As the actuator is fastened by hooks toward the center, the non-fixed area of the actuator expands toward radial direction as shown in Fig. 8. At the same time, the stiffness of the actuator increases according to supplied pressure and the expanding area of the actuator can hold the pipe. The maximum outer diameter of 114 mm can be obtained when the supply pressure of 500 kPa is applied. In the opposite way, when the supply pressure is released, the actuator will naturally shrink back, and the flexible holding pipe actuator will return to its original form. This is because the silicone rubber tubes used have elastic deformations that will change in shape at a certain stress that is recoverable after the stress is removed. In such a deformation, the longitudinal length of the mechanism does not change and there is no unnecessary volume change of the actuator to expand toward radial direction. It can be expected that the tested holding mechanism does not interfere the robot passing through a pipe elbow because of its shorter longitudinal length and flexibility on circumference face compared with the previous open/close unit. In addition, silicone rubber sheet is covered on the actuator to reduce the frictional force between the actuator and wall surface of pipes.



(a) no supplied pressure (b) supplied pressure of 500 kPa

Figure 8. View of operation of pipe holding mechanism with supplied pressure of 0 and 500 kPa.

Fig. 9 shows the relation between the supplied pressure and the generated holding force of the tested mechanism. In the experiment, the generated force of the mechanism was measured by the force sensor (NIDEC-SHIMPO Corporation, FGPX-20) under the condition that the mechanism was installed into a pipe with an inner diameter of 100 mm. In Fig. 9, circles show the average holding force calculated by 20 times measurements. Fig. 9 also shows the maximum and minimum holing force for each supplied pressure. From Fig. 9, it can be seen that the average holding force of 44 N can be obtained when the input pressure of 500 kPa is applied. This force is enough to hold the inspection robot which weight less than 1 kg.

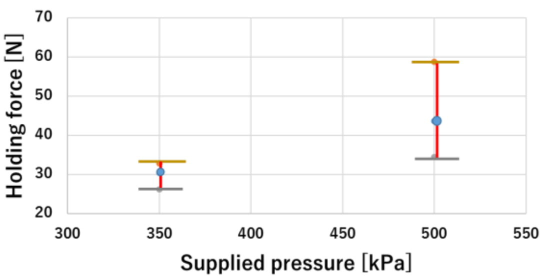


Figure 9. Relation between supplied pressure and generated holding force of the mechanism.

IV. Bending Unit

Fig. 10 shows the view of the previous bending unit using McKibben artificial muscles developed in our previous study [7]. The unit consists of three McKibben artificial muscles. The muscles consist of silicon rubber tube which are made of nylon mesh with the inner diameter of 2 mm and the outer diameter of 4 mm. Three muscles are set parallel at the end of disk in every 120 deg., and from the center of the disk with the radius of 12 mm. They are protected by the flexible plastic cover. The whole size of the bending unit is 175 mm in length and 45 mm in outer diameter. The mass of the unit is 98 g. The bending unit can bend 60 deg. toward every radial direction. The unit can change the direction of the inspection robot.

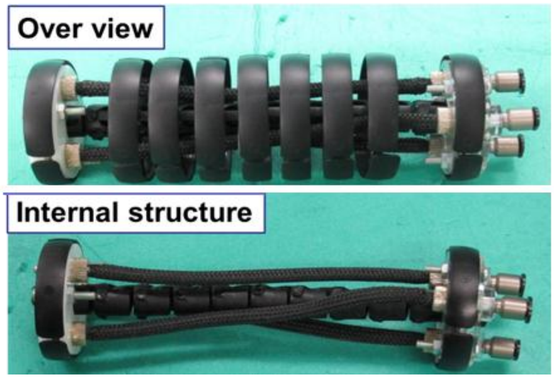


Figure 10. Previous bending unit using McKibben artificial muscles.

To avoid being trapped in the corners and improve a steering ability of the inspection robot, a shorter bending unit with larger bending angle is required. Therefore, the bending unit using the extension type of flexible actuator which has the longer stroke than its original length is proposed and tested. Fig. 11 shows the view of the tested bending unit with a camera unit. The camera unit consists of a CCD camera (Shenzhen Sonice Technology Corporation, SJC-220) and acrylic guides to protect the CCD camera. The bending unit consists of three extension type flexible actuators with the length of 99 mm and two plastic disks. The actuators are set parallel between both disks in every 120 deg. and have the radius of 17 mm from the center of the disk. The bending unit has a length of 194 mm and an outer diameter of 60 mm. The total mass of the unit without the camera unit is 161 g.

Fig. 12 shows the transient view of movement of the tested bending unit when the pressurized actuator is changed every 2 seconds. From Fig. 12, it can be seen that the improved bending unit can bend toward every radial direction with bending angle of about 90 deg.

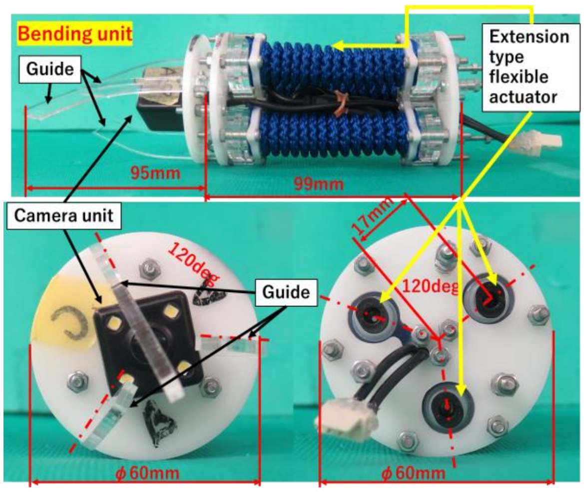


Figure 11. Bending unit using extension type flexible actuators.

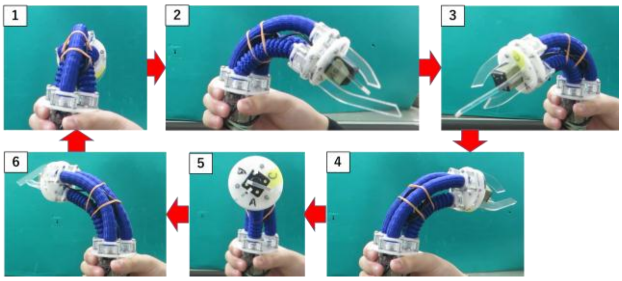


Figure 12. Transient view of movement of the bending unit.

V. Whole Pipe Inspection Robot Uisng Improved Holoding Mechanisms and Bending Unit

A. Whole Inspection Robot

Fig. 13 shows the view of the whole pipe inspection robot using the improved holding mechanisms and the bending unit. The robot consists of the sliding mechanism using a low-friction type flexible pneumatic cylinder [10], the improved bending unit with the camera unit, two holding mechanisms mentioned above and air supplied tubes. One of holding mechanisms is connected with the slide stage on the sliding mechanism by using four screws. The other is connected to the end of the sliding mechanism. As same as the previous robot, the coil type tubes with electric signal lines are used so that air pressure can be supplied from the end of the robot. The electric line is used to transmit the electricity and to broadcast video signal from the CCD camera. The size of the whole robot is 1.06 m in length and 78 mm in outer diameter. The mass of the whole robot is 0.63 kg without the controller and supplied pipes.

Figure 13. Whole inspection robot using the improved holding mechanisms and bending unit.

B. Control System of the Robot

Fig. 14 shows the schematic diagram of the control system of the robot. The system consists of the tested robot mentioned above, seven on/off control valves (SMC Corporation, S070C-SDG-32), a micro-computer (Renesas Electronics Corporation, SH7125) as a robot controller and a personal computer (PC for short) for sending commands to the robot. The micro-computer works as an interface between the operator command via PC and the robot. The control procedure is as follows. First, the PC sends the binary character code to the micro-computer through the serial communication cable and port by the operator. The micro-computer selects to drive the valve based on the control algorithm for input code through the I/O port and the transistors. By simplifying the complex motion of the robot such as moving forward or backward, the controller can realize the sequential motion of the robot by sending only one-character code. The sequential motions moving forward and backward are executed for about 40 seconds per cycle. As a result of preliminary driving test of the robot using the tested controller, it can be confirmed that each elements of the robot can be successfully driven through the tested controller.

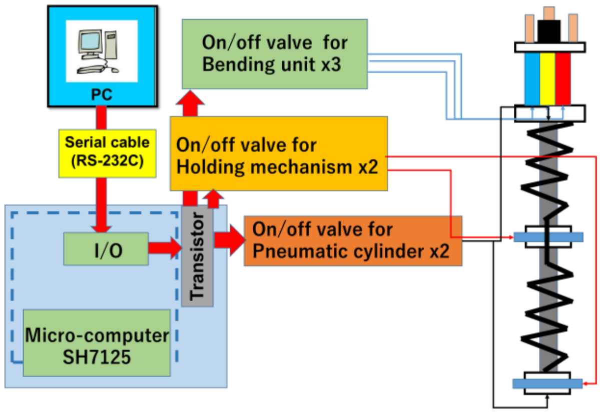


Figure 14. Schematic diagram of the control system of the pipe inspection robot.

VI. Conclusions

In order to improve the mobility of the pipe inspection robot using flexible pneumatic cylinders, the thin holding mechanism using the extension type flexible actuator was proposed and tested. The holding performance of the tested mechanism was investigated. As a result, it was confirmed that the tested holding mechanism could generated enough holding force of 44 N without unnecessary volume change of the inner actuator. Compared with the previous holding mechanism with a length of 140 mm, the longitudinal length of the improved thinner holding mechanism became shorter, that is 45 mm (about 32% of the previous one).

In order to improve the steering ability of the robot, the shorter bending unit using three flexible extension type actuators was proposed and tested. Driving test of the tested bending unit was carried out. As a result, the tested bending unit could bend more than 90 deg. even the length of the unit became two-third compared with the previous one.

As future work, the design and protector sleeve for the holding mechanisms so as to easily pass the corners and tee joints will be performed. In addition, we are going to carry out the driving test using the tested robot.

ACKNOWLEDGMENTS

This study was supported by the Education Ministry of Japan through a Financial Assistance Program for QOL Innovative Research (2012-2016) and a Grant-in-Aid for Scientific Research (C) (Subject No. 16K06202).

REFERENCES

[1] "Water pipe: 38,000 kilograms, lifetime exceeding financial difficulties (in Japanese), renewal does not progress", Mainichi Newspaper (7th May 2010), Available: https://4348.co.jp/pdf/toku2/s-04.

[2] J. Yuan et al., "Development of an inspection robot for long distance transmission pipeline on-site overhaul," *Int. J. Industrial Robot*, vol. 36, pp. 546-550, 2009.

[3] E. Dertien et al., "Development of an inspection robot for small diameter gas distribution mains," *Proc. 2011 IEEE Int. Conf. R&A*, pp. 281-294, 2011

[4] K. Nagatani et al., Development of a transformable mobile robot with a variable wheel diameter," *J. Robotics and Mechatronics*, vol. 19, no. 3, pp. 252-257, 2007.

[5] T. Kawasaki et al., "Development of a flexible sliding mechanism using flexible pneumatic cylinder for rescue robot," in *Proc. FLUCOME2011*, 41.pdf, pp. 1-6, 2011.

[6] T. Akagi et al., "Development of sliding type inspection robot using flexible pneumatic cylinder," *Int. J. Advanced Mechatronic Systems*, vol. 5, pp. 87-94, 2013.

[7] T. Akagi et al., "Pipe inspection robot using flexible pneumatic cylinder built-in pneumatic driving system," *Proc. Int. Forum on Systems and Mechatronics*, pp. 1-6, 2014.

[8] K. Choi et al., "Development of pipe holding mechanism for pipe inspection robot using flexible pneumatic cylinder," in *Proc. IC4M2016*, pp. 529-536, 2016.

[9] T. Akagi and S. Dohta, "Development of a rodless type flexible pneumatic cylinder and its application," *Transactions of JSME*, Series C, vol. 73, no. 731, pp. 2108-2114, 2007.

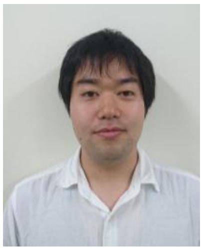
[10] W. Kobayashi, J. Guo, T. Akagi, S. Dohta, and N. Kato, "Development of simplified wearable wrist rehabilitation device using low-friction type flexible pneumatic cylinders," *International Journal of Mechanical Engineering and Robotics Research*, vol. 6, no. 3, pp.253-257, 2017.

Keichi Kusunose is undergraduate student, studies in Okayama University of Science since 2014. His research topics are focused on development of pipe holding mechanism and bending unit using extension type flexible actuator for flexible pipe inspection robot using flexible pneumatic actuators.

Tetsuya Akagi is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Okayama University of Science in 1998. He started at Tsuyama National College of Technology, Japan as a research associate on 1998. Then, he joined Okayama University of Science as a lecturer from 2005. He received Young Scientists' Prize from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. His research interests include mechatronics and robotics; especially wearable control systems using microcomputers and wearable control devices such as flexible pneumatic actuator, soft sensor and wearable control valve.

Shujiro Dohta is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He is also currently a Vice-president of Okayama University of Science. He joined Okayama University of Science as a research associate on 1974. Then, he became an Exchange Faculty of Wright State University, U.S.A. from 1984 to 1985. He received his doctor degree in Engineering from Kobe University in 1990. His major in mechatronics is focusing on the development of robotics, wearable devices for rehabilitation purpose. Prof. Shujiro Dohta is currently a member of The Japan Society of Mechanical Engineers (JSME), The Society of Instrument and Control Engineers (SICE), The Robotics Society of Japan (RSJ), and The Japan Fluid Power System Society (JFPS).

Wataru Kobayashi is currently an assistant professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Shibaura Institute of Technology in 2015. His research interests are robust control theory and aqua drive system; especially rehabilitation and life support systems. He is a member of The Japan Society of Mechanical Engineers, The Society of Instrument and Control Engineers, The Japan Fluid Power System Society, and The Society of Life Support Engineering.



Kengo Nakagawa is graduate student at Okayama University of Science. He received the Bachelor of Engineering from Okayama University of Science in 2017. His research interests are focusing on the improvement of pipe holding mechanism for pipe inspection robot using flexible pneumatic cylinder.