

Improvement of Pipe Inspection Robot Using Extension Type Flexible Pneumatic Actuators

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Abstract

In moisture and wet conditions, the pipe inspection robot using pneumatic actuators is needed, as it has a high security feature that can prevent electric leakage as well as clean energy consumption. In the previous study, a pipe inspection robot using flexible pneumatic cylinders with two holding mechanisms that could move forward like an inchworm along the pipe by deforming the robot's body naturally had been proposed and tested. In that study, a pipe holding mechanism using an extension type flexible pneumatic actuator where volume change was small was developed. A compact bending unit using three extension type flexible pneumatic actuators was also developed. In this paper, to increase the driving force of the robot, an improved sliding mechanism that can extend, contract and bend in every direction is proposed and tested. Then the compact pipe inspection robot with the improved sliding mechanism using the flexible pneumatic cylinder will be presented and tested. The driving test of the robot travels in a complex pipe will also be carried out. As a result, it can be confirmed that the improved pipe inspection robot can pass through the complex pipe smoothly even if the pipe is set vertically.

Keywords: Extension type flexible pneumatic actuator, Pipe inspection robot, Pipe holding mechanism, Extension / contraction/ bending mechanism

INTRODUCTION

In 2014, about 12.1% which is 660,000 km from the total length of the water supply pipeline in Japan had surpassed the statutory life of 40 years [1]. On the other hand, only 0.76% of the total pipes are refurbished each year and this means it will take 130 years to renew the entire pipeline here. Water pipelines are very complex and include numerous corners and joints. If excavation works are selected to inspect the entire pipe, it will require high cost and time. Therefore, various inspection methods such as a fiberoptic, have been developed. However, the manipulated fiber scope has the disadvantage that the search area is not very large because of the complex shape of the pipe, including the corners and tee joints. Therefore, pipe inspection robots that can travel by themselves have been developed by various companies and researchers [2-4]. The cost of pipe inspection can also be reduced by using these robots. Yet, the inspection robots need high mobility in a pipe. 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 addition, the fluidic actuators are useful for application in high and wet humidity conditions such as in water supply pipes. This is because the fluidic actuators do not use electricity as their primary energy and have no risk of electrical leakage. Based upon this concept, a pipe inspection robot that consists of a flexible sliding mechanism using a flexible pneumatic cylinder have been proposed and tested in our previous study [5-8]. The tested robot could travel in the narrow space smoothly by naturally changing the shape of the robot according to the shape of the pipe. However, the generated force of the

flexible pneumatic cylinder is not so large, that is 15 N at a 500 kPa supply pressure. Furthermore, as a result of several driving tests using the tested robot, it has been found to be stuck in the corners and tee joints in the pipe.

For the next plan, it is necessary to improve the traveling force of sliding mechanism. In this paper, a novel sliding mechanism using three extension type flexible pneumatic actuators is proposed. The proposed mechanism has functions of extension, contraction and bending. The compact pipe inspection robot using the improved sliding mechanism and compact valve unit is also proposed and tested. The test drive for the tested robot moving in a complex pipe having elbows, tee joints and vertical pipes will be described.

II. PREVIOUS PIPE INSPECTION ROBOT USING FLEXIBLE PNEUMATIC CYLINDER

Figure 1 shows the inner construction of the flexible pneumatic cylinder developed in our previous study [9,10]. 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 slide stage has 12 steel balls that have a diameter of 3 mm set on around 9 mm steel balls to press and change the shape of the tube. These steel balls are held by two slide stages from both sides of the ball. The operating principle of the cylinder is as follows. When the compressed air is applied to one side of the cylinder, the ball is pushed. The slide stage is also pushed while deforming the tube. The slide stage can move even if the cylinder bends.

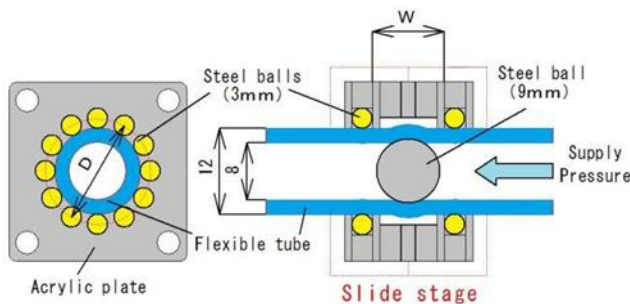


Fig. 1: Inner construction of flexible pneumatic cylinder.

The generated force of the cylinder is about 16 N when the supplied pressure of 500 kPa is applied [10]. In the previous robot, the cylinder was used as a sliding mechanism by attaching two pipe holding mechanisms at the point of the slide stage and the one end of the cylinder.

Figure 2 shows the pipe holding mechanism using the extension type flexible pneumatic actuator developed in our previous study [11]. The left side on Fig. 2 shows the view of the tested pipe holding mechanism. The right side on Fig. 2 shows the view of the mechanism when supply pressure of 500 kPa is applied. The mechanism consists of a ring-shaped extension type flexible pneumatic actuator that both ends of the actuator are connected to a tee joint. Figure 3 shows the view and the inner construction of the extension type flexible pneumatic actuator. The actuator 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 operating principle of the actuator is as follow. When the supplied pressure is applied, the inner rubber tube expands toward both radial and longitudinal directions. As the bellows-shaped ruffled fabric sleeve prevents to expand toward radial direction, the actuator extends longitudinally. The actuator can extend more than about 2.5 times of its original length. The extension type flexible pneumatic actuator is located so that it can cover a plastic circumference frame. The ring-shaped actuator is fixed on the plastic frame by using five plastic hooks. The actuator is also covered by 4 sheets of silicon rubber films with thickness of 0.5 mm to prevent slipping on the pipe. The mechanism has the outer diameter of 78 mm and the thickness of 45 mm without supplied pressure. The operating principle of the pipe holding mechanism is as follows. When the supply pressure is applied to the actuator, non-fixed area of the actuator expands toward radial direction as shown in right side on Fig. 2. As the stiffness of the actuator increases according to supplied pressure, the expanding area of the actuator can hold the pipe. The maximum outer diameter is 114 mm when the supply pressure of 500 kPa is applied. On the opposite case when the input pressure is released, the actuator naturally contracts by means of elastic deformation of the inner rubber tube. In addition, the holding force of the mechanism is about 44 N in the case when the mechanism holds the pipe with an inner diameter of 100 mm [11]. The average holding force of 44 N is enough to be applied to the inspection robot with a mass of less than 1 kg.



Fig. 2: Holding mechanism using extension type flexible pneumatic actuator

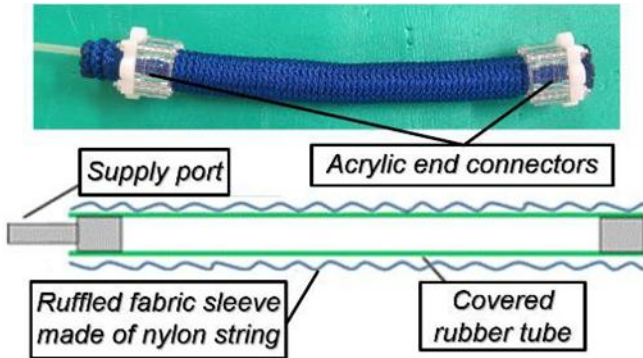


Fig. 3: View and inner construction of extension type flexible pneumatic actuator

Figure 4 shows the view of the previous pipe inspection robot. The robot consists of the sliding mechanism using a low-friction type flexible pneumatic cylinder [10], a bending unit with the camera unit, two holding mechanisms and air supplied pipes. Figure 5 shows the view of the bending unit with a camera unit. The camera unit consists of a CCD camera (Shenzhen Sonice Technology Corporation, SJC-220) and an acrylic protector. The bending unit consists of three extension type flexible pneumatic actuators with a original 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. On the robot, one of the holding mechanisms is set at the slide stage and another one is set at the end of the sliding mechanism.

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 previous robot is 1.06 m in length with the 78 mm of outer diameter. The mass of the robot is 0.63 kg without the controller, valve unit and supplied pipes. From the result of driving test, it is found that the traveling speed of the inspection robot in a straight pipe with an inner diameter of 100 mm was about 10 mm/s. It can also be verified that the robot can travel in complex pipes with tee and elbow joints with a total length of 2 m in about 12 minutes. However, the robot is also sometimes stuck in the elbow joints due to lack of traveling force of the sliding mechanism.

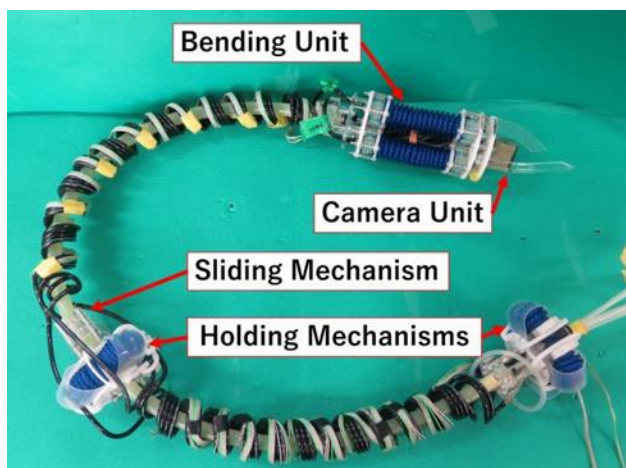


Fig. 4: View of the previous pipe inspection robot

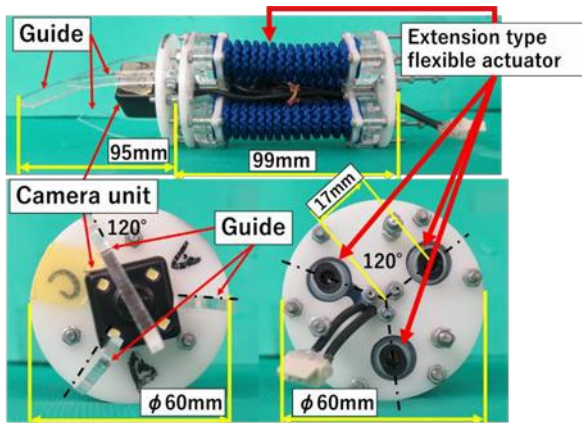


Fig. 5: Bending unit using three extension type flexible actuators

III. IMPROVED SLIDING MECHANISM AND IMPROVED PIPING INSPECTION ROBOT

In the previous robot, the lack of pushing/pulling force of the flexible pneumatic cylinder as a traveling force of the sliding mechanism makes the robot move slowly. In addition, a long robot body with a length of more than 1 m is easy to cause problems such as being stuck in the pipe joint. Therefore, it is necessary to make the robot more compact and increase the generated force of the sliding mechanism. In this study, we aim to develop a pipe inspection robot fabricated by only using extension type flexible actuator.

Figure 6 shows the construction of the improved sliding mechanism using extension type flexible pneumatic actuators. From view point of functionality, it can be said that the mechanism needs to have extension, contraction and bending. The construction of the improved sliding mechanism as shown in Fig. 6 is almost same as the bending unit in Fig. 5. Compared with the previous bending unit, there is no core cable to prevent the extension between two end disks in the improved mechanism. Instead of core cable, three extension type flexible actuator are covered by the coil type air supply tube and are arranged to gather at the center. They are set on the circumference with the radius of 12 mm from the center of the disk. By pressurizing or decompressing three actuators

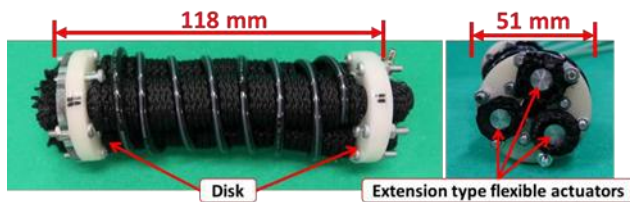


Fig. 6: Improved sliding mechanism using extension type flexible pneumatic actuators

simultaneously, they can extend and contract. It can be expected that the maximum pulling force is about 40 N theoretically. The size of the sliding mechanism is 118 mm in length and 51 mm in outer diameter.

Figure 7 shows the view of the whole improved pipe inspection robot. The robot consists of the improved sliding mechanism using extension type flexible pneumatic actuator and two holding mechanisms. Two holding mechanisms are set on both ends of the sliding mechanism. The coil type tube can supply air to the top end of holding mechanism from the end of robot. The total length and mass of the robot are about 0.3 m and 0.49 kg, respectively. The length of the robot becomes one third from the previous robot and the mass of the robot becomes half. 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. In order to realize smooth moving of the robot, it is necessary to develop a compact valve unit with larger flow rate. Figure 8 shows the view of the compact valve unit. The unit consists of five on/off type control valves (Koganei Co. Ltd., G010HE-1) with larger flow rate and an acrylic common flow passage for supply and exhaust. By this method, the valve unit can be used in the water.

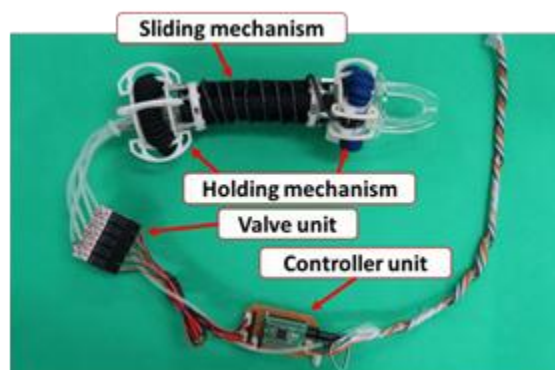


Fig. 7: Improved pipe inspection robot using extension type flexible pneumatic actuators

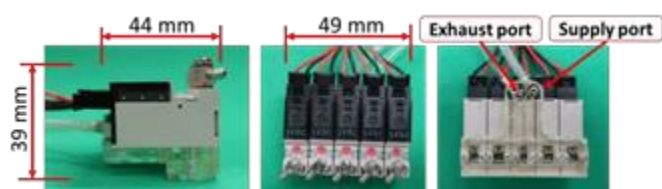


Fig. 8: Compact valve unit using 5 on/off valves and plastic flow passages

Figure 9 shows the schematic diagram of the control system of the improved pipe inspection robot. The system consists of the embedded controller, the improved sliding mechanism, the valve unit and two holding mechanisms. For the valve unit, two valves are used for holding mechanisms and another three valves are used for the sliding mechanism. Each actuator of the robot is operated by an on/off valve through I/O port or PWM port in the embedded controller. The control procedure is as follows. First, the Personal Computer sends the binary code to the embedded controller through the serial communication cable. The embedded controller selects to drive the valve according to the command.

Figure 10 shows the operating principle of the improved 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 (1). Next, three actuators in the sliding mechanism are pressurized, then, the sliding mechanism extends (2). When the actuators reach at maximum length, the top of pipe holding mechanism expands to hold the pipe (3). Then, the pipe holding mechanism at the end of robot contracts (4). Then, the compressed air in chambers of three actuators is exhausted. At the same time, the sliding mechanism contracts and end holding mechanism moves forward (5). By repeating these operations from (1) to (5), the robot can move forward as an inchworm. On the other hand, the backward motion can be realized by using the opposite operation mentioned above. In the case to steer the robot toward desired direction in pipe joint, first, bending motion of the sliding mechanism is generated by pressurizing one or two extension type flexible pneumatic actuators. Next, from this condition of bending motion, three actuators in the sliding mechanism are pressurized. Then, the robot can move forward while changing moving direction. The robot can move to six directions by pressurized one or two extension type flexible pneumatic actuators on the sliding mechanism.

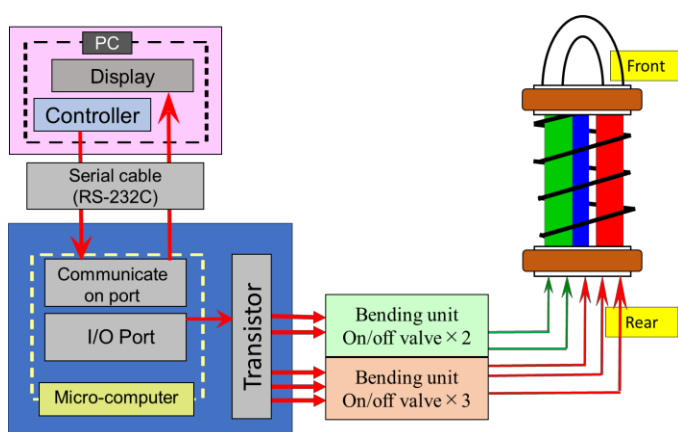


Fig. 9: Schematic diagram of control system of the robot

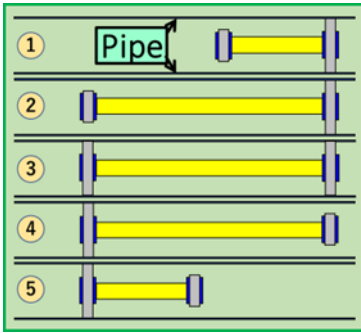


Fig. 10: Operating principle of the improved robot

Figure 11 shows the relationship between the bending angle of the sliding mechanism and the input duty ratio to the valve. In Fig. 11, the blue line shows the bending angle when only one extension type flexible pneumatic actuator is driven. The red line shows the result in the case of driving two actuators of extension type flexible actuators. The PWM period of 25 ms can be realized by using timer function and I/O port of the embedded controller. From Fig. 11, it can be seen that the bending angle of the mechanism is increased according to the input duty ratio. It seems that the optimum duty ratio for bending at elbow joint, is 90 deg., which is about 24%. By using this method, the bending angle of the robot can be controlled by only using on/off valves.

Figure 12 shows the transient view of the improved robot in case when the robot travels in a complex pipe with an inner diameter of 100 mm. In the experiment, three straight pipes, an elbow joint and a tee joint were used. First straight pipe set on horizontal plane. And it connects to the second straight pipe with inclined angle of about 25 degrees from the horizontal plane through the tee joint. The third straight pipe is set with inclined angle of about 75 degrees and it is connected to the second pipe through elbow joint. In addition, the tee and elbow joints used in the experiment are conventional plastic pipe on the market. There are sharp step with a tip angle of 90 degrees in the inner wall of the joint. The operating procedure of the robot is as follows. First, the robot passes through the straight pipe. Before the robot reaches at elbow or tee joint, the robot bends toward the desired direction. From this condition, three actuators in the sliding mechanism are pressurized. Then, the robot can move forward while deforming the shape of its body according to the shape of the inner pipe naturally because of its flexibility. As a result, the

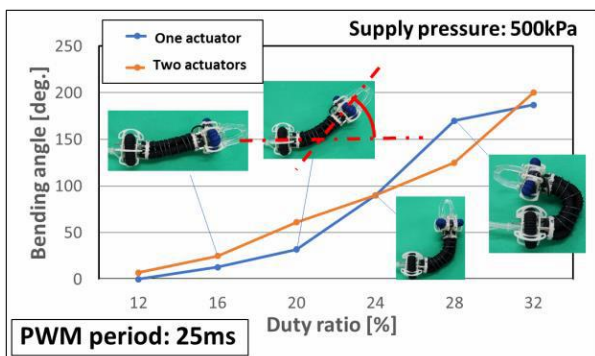


Fig. 11: Relation between input duty ratio and bending angle

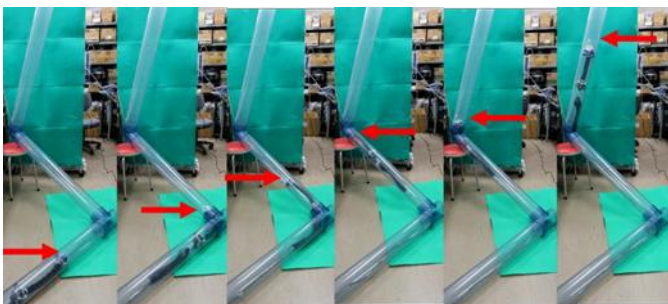


Fig. 12: Transient view of the improved robot in case when the robot travels in complex pipe

robot can pass through joints toward desired passages without stuck. After that, the robot climbs the straight pipe with an inclined angle of 25 deg. It also turns the elbow joint. And climbs the pipe with an inclined angle of 75 deg. As shown in Fig. 11, the tested robot can pass through the complex pipe that includes various joints and vertical pipes smoothly. From the experiment, it can be confirmed that the robot pass through complex pipe with a total length of 3 m within 4 minutes. The average speed of the robot is 1.4 cm/s.

IV. CONCLUSIONS

This study aiming to improve the mobility of the pipe inspection robot that can be used in moisture and wet conditions is summarized as follows.

To improve the mobility of the pipe inspection robot in a joint, the sliding mechanism using the extension type flexible pneumatic actuator was proposed and tested. As a result, it was confirmed that the tested sliding mechanism could generate enough pushing or pulling force to move the robot, that is more than 120 N. It was confirmed that the tested mechanism could also extend, contract and bend toward every direction by changing pressurized actuator in the mechanism.

The compact valve unit with larger flow rate that consist of 5 on/off valves was also proposed and tested. In addition, the relation between the bending angle of the tested sliding mechanism and the input duty ratio for on/off valve in the compact valve unit was investigated. As a result, the optimal input duty ratio of around 25 % could be obtained in the case of passing through the joint with 90 degrees angle.

The improved pipe inspection robot that consists of the improved sliding mechanism, two holding mechanisms and compact valve unit was proposed and tested. The control system using the embedded controller that can operate the robot through a serial communication was also proposed and tested. The driving test of the whole pipe inspection robot was carried out. As a result, it was confirmed that the robot could pass through a complex pipe smoothly even the traveling passages includes critical corner and vertical pipe.

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REFERENCES

- [1] https://www.mhlw.go.jp/seisakunitsuite/bunya/topics/bukyoku/kenkou/suido/newvision/chiikikondan/10/suishin_kondan_10-1.pdf. (in japan)
- [2] J. Yuan, X. Wu, Y. Kang and C. Huang, "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, S. Stramigioli and K. Pulles, "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, M. Kuze and K. Yoshida, "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, T. Akagi, S. Dohta and K. Harihara, "Development of a Flexible Sliding Mechanism Using Flexible Pneumatic Cylinder for Rescue Robot", *Proc. FLUCOME2011*, 41.pdf, pp.1-6, 2011.
- [6] T. Akagi, S. Dohta, L. Wang and T. Kawasaki, "Development of sliding type inspection robot using flexible pneumatic cylinder", *Int. J. Advanced Mechatronic Systems*, Vol.5, pp. 87-94, 2013.
- [7] T. Akagi, S. Dohta and H. Qiu, "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, S. Dohta, T. Akagi and S. Ninomiya, "Development of pipe holding mechanism for pipe inspection robot using flexible pneumatic cylinder", *Proc. of 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.
- [11] K. Kusunose, T. Akagi, S. Dohta, W. Kobayashi and K. Nakagawa, "Development of pipe holding mechanism and bending unit using extension type flexible actuator for flexible pipe inspection robot", in press.