Pipe Inspection Robot Using an Inch-Worm Mechanism with Embedded Pneumatic Actuators

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Abstract: The outlet feeder pipe thinning in a PHWR (Pressurized Heavy Water Reactor) is caused by high pressure steam flow inside the pipe, which is a well known degradation mechanism called FAC (Flow Assisted Corrosion). In order to monitor the degradation, the thickness of the outlet bends closed to the exit of the pressure tube should be measured and analyzed at every official overhaul. This paper develops a mobile feeder pipe inspection robot that can minimize the irradiation dose of human workers by automating the measurement process. The robot can move by itself on the feeder pipe by using an inch worm mechanism, which is constructed by two gripper bodies that can fix the robot body on the pipe, one extendable and contractable actuator, and a rotation actuator connected the two gripper bodies to move forward and backward, and to rotate in the circumferential direction

Keywords: inch-worm, pipe inspection, feeder pipe, nuclear robot

1. Introduction

The outlet feeder pipe thinning in a PHWR (Pressurized Heavy Water Reactor) is caused by high pressure steam flow inside the pipe, which is a well known degradation mechanism called FAC (Flow Assisted Corrosion). In order to monitor the degradation, the thickness of the outlet bends closed to the exit of the pressure tube should be measured and analyzed at every official overhaul. However, collecting high quality data is a challenge, mainly due to lack of space around the pipes, especially for 2.5 inch pipes and the roughness of feeder pipes. Moreover, although the reactor is shutdown in the overhaul period, the radiation dose is severe near the feeder pipe because they are located in front of the reactor.

Ontario Hydro's SIMD department developed SIMD bracelet and used it in Gentilly-2 from 1997 to 1999 for inspecting the feeder pipe thinning problem [1]. However, the SIMD bracelet can only be applied at 2 inch feeder pipes and especially on the first bends because of the limited space around the feeders. Therefore, the data quality of the inspection is not enough for guaranteeing the safety of the feeder pipes.

Hydro Quebec research center (IREQ) developed an inspection system, METAR and used it in Gentilly-2 from 1999 to 2000 [1]. METAR has 14 ultrasonic sensors mounted on holders in each sensor. The holder maintains the sensor to be attached perpendicular with respect to the feeder pipe and allows some amount of freedom by using a flexible collar to fixing the holders. The SIMD bracelet and METAR are operated manually, that is, since the inspection systems have no motorizing capabilities, a human worker should install the system and stay in front of the feeder pipe while completing the measurement, which increases the irradiation dose of the workers.

This paper develops a mobile feeder pipe inspection robot that can minimize the irradiation dose of a human worker by automating the measurement process. The robot can move by itself on the feeder pipe by using an inch worm mechanism [2][3], which is constructed by two gripper bodies that can fix the robot body on the pipe and one extension/contraction actuator and a rotation actuator connected the two gripper bodies to move forward and backward and to rotate in the circumferential direction. Those actuators are drived pneumatically which are embedded inside the robot body to reduce the size of the robot so that it is applicable to the actual feeder pipes in the PHWR.

The design method of the robot is presented based on the analysis of the working environment in a PHWR to determine the size and functions of the robot. The kinematic analysis gives an insight of the relation between the robot size and allowable feeder pipe curvature. The control system is developed by using five directional control valves and a microcontroller with five MOSFET solenoid drivers. The proposed inspection robot is applied to a mockup of a feeder pipe to illustrating the feasibility of the inspection.

2. Working environment analysis

The PHWR in Korea has 380 pressure tubes. The feeder pipes are attached in each pressure tube whose diameters are 1.5, 2.0, 2.5 inches with the number by 33, 183, 164, respectively. The direction and curved angle of the feeder pipe is various. Figure 1(a) shows a part of the pressure tube array. The pressure tubes are arranged circularly with the interval distance by 286 mm each other. The distance to reach the feeder pipe from the front face of the pressure tube is about 413 mm. The robot should be able to pass the space among the pressure tubes and the guides to fix the feeder pipes to reach the surface of the feeder pipe, whose size is approximately 155 $mm \times 204$ mm.

Figure 1(b) shows the interference of a feeder pipe with other feeder pipes, pressure tubes, and guides, when the inspection robot travels the feeder pipe. The cross section view of a 2.5 inch feeder pipe is described because it has more severe interference than 2.0 and 1.5 inch pipes. Therefore, in order

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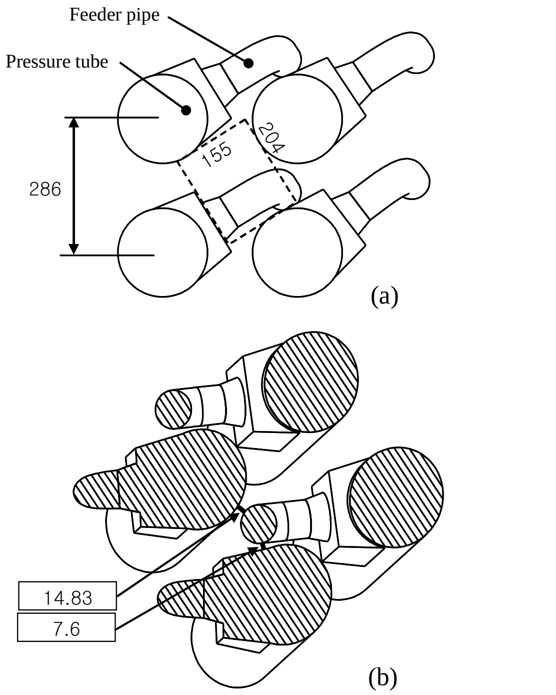

Fig. 1. (a) Feeder pipe array in a PHWR (b) The cross-section view of a closest gap in the array.

to inspect the feeder pipe, the robot can travel such gaps. The inner part of the curved pipe has more space than the outer part. In conclusion, the robot should be able to pass through 7.6 mm gaps and the thickness of the robot body should not exceed more than 14.63 mm.

Since the feeder pipe in the PHWR is made by bending a special steel pipe of 1.5, 2.0, and 2.5 inch sizes, the cross-section of the pipe at the curved part becomes elliptical shape, that is, the in-plane curved part of the feeder pipe has wide diameter, and the out-plane curved part has small diameter compared with the nominal diameter. Figure 2 shows the distance and contact angle changes of the ultra-sonic sensor to maintain perpendicularity with respect to the feeder pipe. This contact distance and angle variation should be considered for designing the robot and the sensor mechanism. Table 1 shows the measured diameter of an actual 2.5 inch feeder pipe at the first and second parts of bending. Since the curvature of the feeder pipe is various, only the maximum case is described. The maximum diameter change is 6.3 mm at the second bending as shown in the table.

When the sensor is located at the angle θ, if the pipe is perfectly a circle, the ultra sonic sensor is located at s_1. If the pipe is changed to an elliptical shape, the sensor is located at

Table 1. The diameter change caused by the bending of the pipe.

unit (mm)	Nominal	first bend	second bend
minimum	73.1	68.15	66.8
maximum	-	77.25	77.1
curvature	-	92.25	-

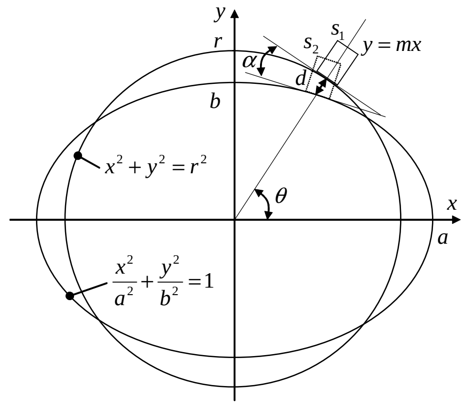

Fig. 2. (a) The measurement of the diameter at the 1st and 2nd bending in a feeder pipe mockup (b) The variation of ultra-sonic sensor attachment caused by the bending.

s_2, and the position and contact angle of the sensor should be changed by d and α, respectively, to maintain the perpendicular contact with the pipe. The relation between the amount of the diameter change with the required distance and angle of the sensor can be obtained from the geometric analysis. The distance change caused by the bending is

$$d = r - \sqrt{\frac{(1+m^2)a^2b^2}{b^2+a^2m^2}}. \tag{1}$$

The contact angle variation is

$$\alpha = \tan^{-1}\left(-\frac{1}{m}\right) - \tan^{-1}\left(-\frac{b^2}{a^2}\frac{1}{m}\right) \tag{2}$$

where $m = \tan\theta$.

Assume that the area of the pipe is not changed caused by bending, the contact distance and angle changes with respect

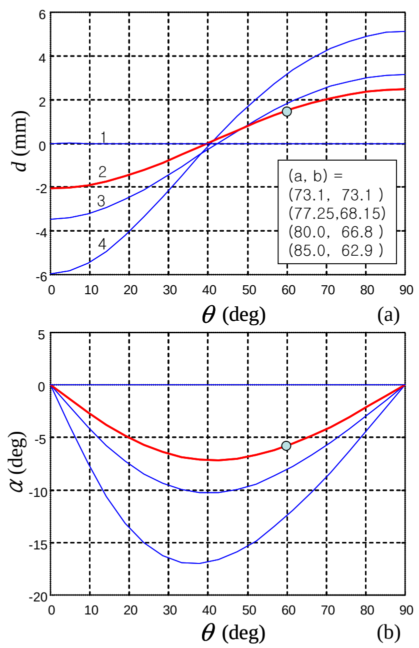

Fig. 3. (a) The distance variation (b) contact angle variation caused by the pipe distorsion.

to various pipe distortions are analyzed as shown in Fig. 3 which is from Eq. (1) and Eq. (2). The plot 2 is the result for the actual feeder pipe. The distance and angle change will be by 1.48 mm and 5.8 deg when θ becomes 60 deg, respectively.

3. Structure of the Feeder Pipe Inspection Robot

3.1. Structure of the robot

There are various actuation mechanism to design a robot such as electrical motor, pneumatic cylinders, hydraulic actuators, and material forces, and so on. Although the electrical system has many benefits, the smaller the actuator, the smaller the actuator force. That is, we can make the robot as small as possible, but the robot may not working in an actual environment which has various harsh conditions that require large force. The material forces generated by a piezoelectric and magnetostrictive material are a good actuator only for sub-millimeter or sub-micrometer applications. The hydraulic actuators is relatively large forces with small volume, but the contamination is the main problem. The pneumatic actuators are good at generating a large force and preventing from contamination. Therefore, the pneumatic actuators are used for robot design.

The working environment of the robot is one of the most hazardous environment that a robot can meet because of the large radiation dose, complex mechanical constraints, and requirement of high precision measurement. The robot can be able to travel along that environment. In this paper, we designed a robot using pneumatic actuators which is embedded into the robot body, which reduces the robot size dramatically.

An inch-worm mechanism is used for the moving mechanism as shown in Fig. 4. The robot is constructed by four actuation parts. Two gripper actuators are located at the front and rear parts of the robot body for fixing the robot to the feeder pipe. Each gripper actuator has two half-circle shaped gripper hand to encloses the pipe. The gripper hand is drived by two pneumatic cylinders with opposite direction. When air pressure is applied to the gripper body, the cylinder expands and moves the gripper hands in the fixing direction. When the air is released, the cylinder moves back by spring force.

The gripper is designed to be able to be opened by applying external force so that it can be easily installed as shown in Fig. 5. The human worker or installation equipment just push the robot for installation and pull the robot for releasing.

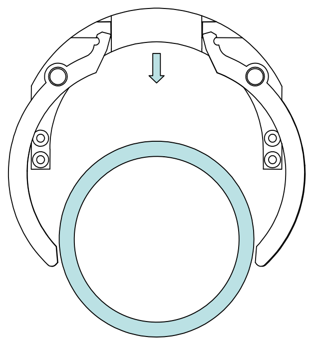

Fig. 5. The installation of the feeder pipe inspection robot.

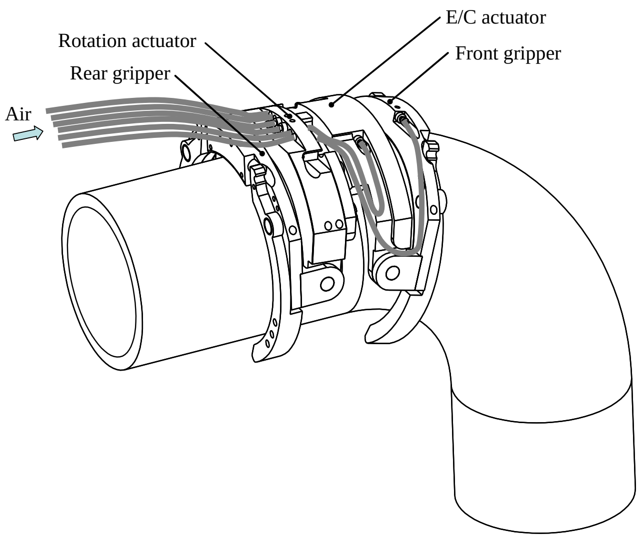

Fig. 4. Feeder pipe inspection robot using an inch-worm mechanism.

A motorizing mechanism connects the two gripper bodies, which is constructed as an extendable/contractable actuator (E/C actuator) and a rotation actuator in the middle of the two gripper bodies for moving forward and backward, and for rotating circularly along the circumference direction of a feeder pipe, respectively.

In order to adopt to various radius of curvature of the feeder pipes, the grippers and the motorizing mechanism are connected by free revolute joints so that the front and rear grippers can be formed any angle with respect to the motorizing mechanism by mechanical constraints with the curved feeder pipe. This mechanism gives self-adjusting of the orientation of the robot body so that the robot body is always placed at the outer side of the curved feeder pipe, which is an ideal case like the inner diameter of the gripper is almost same as the outer diameter of the feeder pipe and the feeder pipe has no variation on the diameter, even though at the curved section. However, since the inner diameters of the grippers are limited by the maximum diameter of a curved feeder pipe as shown in Fig. 2, there are some amount of gaps between the grippers and feeder pipes, which prevents the self-adjusting of the orientation. Therefore, a motorizing mechanism is required to adjust the orientation of the robot.

Figure 6(a)-(c) show the moving principle of the inch-worm feeder pipe robot. In order to move to the right direction, the rear gripper is fixed by extending the cylinder, then, extending the E/C actuator, fixing the front gripper, releasing the rear gripper, contracting the E/C actuator. This operation is continued to move further and the operation is reversed if the direction is left. Figure 6(d)-(f) show the rotation principle. In order to rotate in cw (clock wise) direction, the rear

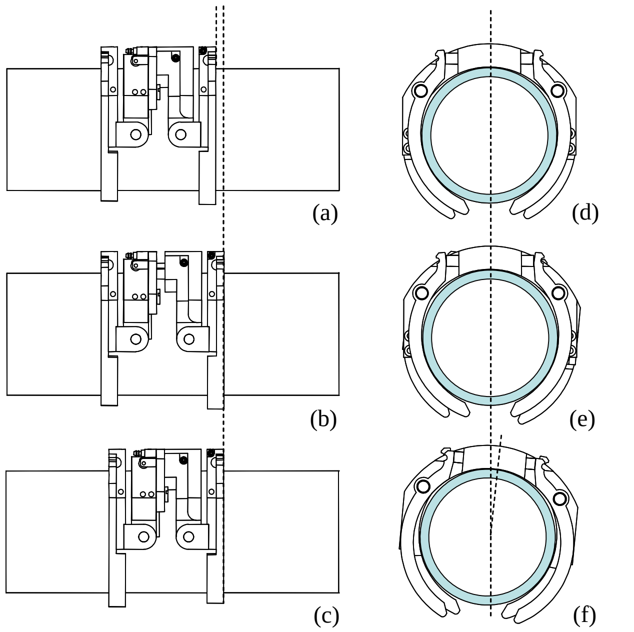

Fig. 6. Feeder pipe inspection robot using an inch-worm mechanism.

gripper is fixed, then, rotating the rotation actuator in cw direction, fixing the front gripper, releasing the rear gripper, rotating the rotation actuator in ccw (counter clock wise) direction. This operation is continued to rotate further and the operation is reversed if the direction is cw. Since the robot can move freely in the longitudinal and circumferential directions of a feeder pipe, we can measure most of the part on the feeder pipe if the space is allowed except the inner part of the curved feeder pipe, which cannot be accessed because of the mechanical constraints.

3.2. Robot Design

The robot should be move along a curved pipe with relatively small curvature as listed in Table 1. In order to determine the size of the robot that can be travel along the target feeder pipe, a kinematic analysis is performed as shown in Fig. 7. The vector $\mathbf{P_3}$ can be represented as

$$\mathbf{P_3} \quad = \quad \mathbf{v_1^0} + \mathbf{A_1^0 v_2^1} + \mathbf{A_1^0 A_2^1 P_3^2}. \tag{3}$$

Assume that the θ_1 is $\pi/2$, that is, the robot is located at the top of the circular pipe, then the x position of the P_3 should be larger than zero ($P_{3x} > 0$) and the mechanical constraints, that is, the gripper is aligned perpendicularly with respect to the feeder pipe gives

$$\frac{l_1}{2} + l_3 \cos\theta_2 - r_3 \sin\theta_2 > 0 \tag{4}$$

$$r_1 \sin\theta_2 - \frac{l_1}{2}\cos\theta_2 - l_2 = 0. \tag{5}$$

where, $r_3 = r_p + l_g + l_h$, $l_2 = l_3 + l_w/2$. Here, r_p, l_g, l_h, and l_w are radius of the feeder pipe, the gap between the outer radius of the feeder pipe and the inner radius of the robot, the height of the gripper, and the length of the gripper bodies, respectively. l_3, r_3, and l_2 are the x and y position of $\mathbf{P_2}$ and $\mathbf{P_3}$ with respect to $x_2 - y_2$ coordinate system. Changing the inequality of Eq. (4) to an equality condition for plotting the graph and rearranging Eqs. (4) and (5) gives

$$\begin{bmatrix} l_1 \\ l_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \cos\theta_2 \\ -\frac{1}{2}\cos\theta_2 & -1 \end{bmatrix}^{-1} \begin{bmatrix} r_3 \sin\theta_2 \\ \frac{l_w}{2} - r_1 \sin\theta_2 \end{bmatrix}. \tag{6}$$

Computing the Eq. (6) with respect to θ_2 and plotting the result with respect to the l_1 and l_3 gives Fig. 8. Seven cases of the feeder pipe bending curvature are plotted, which are 60, 65, 70, 80, 90, 92.25, and 100 mm. The right area of each plot represents the feasible region, for example, assume that the designed robot's l_1 and l_3 are 27 mm and 9 mm, which are at the left side of the plot representing the bending curvature of 70 mm, so the robot can travel the curved pipe whose curvature is larger than 70 mm. However, since the design is at the right side of the plot representing the bending curvature of 65 mm, the robot cannot travel along the pipe. The designed robot is at the left side of the curvature with 92.25 mm, it can travel along the feeder pipe that are going to be inspected.

4. Controller Design

The robot has six degree of freedom including four active joints controlled by the body embedded pneumatic actuators

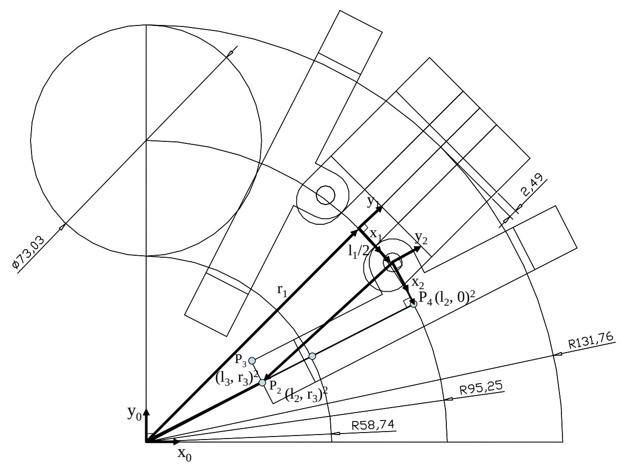

Fig. 7. The kinematic analysis for verifying the relationship between the robot size and the pipe curvature.

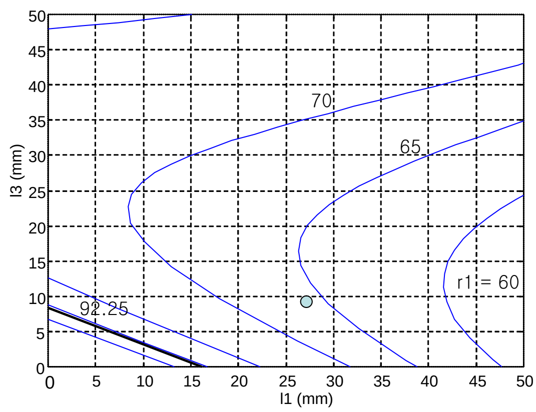

Fig. 8. The relation between the pipe curvature and the size of the robot.

and two free joint which are constrained by the curved pipe. The four active joints are composed of six pneumatic cylinders. Two for front and rear grippers, two for E/C actuator, and two for rotation actuator. The gripper has gripping and releasing motion, which can be controlled by using one five ports directional control valve. The E/C actuator has expansion and contraction motion, which can be controlled by one five ports directional control valve. The rotation actuator has cw rotation, ccw rotation, and center position, which is controlled by two five port directional control valves. Therefore, five valves are used for robot control. Figure 9 shows the block diagram of the robot controller. The valves are drived by using five MOSFETs. The switching sequence of the MOSFETs are controlled by using an ATMega128, an AVR microcontroller made by the Atmel co. ltd. The command can be transferred from PC through RS-232 port and from control panel composed of switches for movement and rotation direction control, and a potentiometer for velocity control.

Table 2 shows the switching sequence for forward and backward movement. the sequence 0 is a normal condition that fixes the robot to the feeder pipe so that the robot cannot be slipped down. The 'H' and 'L' mean that the valve is switched on and off, respectively, which mean that the air pressure is supplied or not. Table 3 shows switching sequence for cw and ccw rotation motion. In case of rotation, the nominal condition is the center position of the rotation actuator. Since no air pressure is applied at sequence 0, the position is determined by the spring forces. These sequence tables are included in the control program.

Table 2. The switching sequence for forward and backward movement.

Seq.	Forward			Backward		
	RG	E/C	FG	RG	E/C	FG
0	H	L	H	H	L	H
1	H	L	L	L	L	H
2	H	H	L	L	H	H
3	H	H	H	H	H	H
4	L	H	H	H	H	L
5	L	L	H	H	L	L

Table 3. The switching sequence for cw and ccw rotation.

Seq.	cw				ccw			
	RG	CW	CCW	FG	RG	CW	CCW	FG
0	H	L	L	H	H	L	L	H
1	H	L	L	L	H	L	L	L
2	H	H	L	L	H	L	H	L
3	H	H	L	H	H	L	H	H
4	L	H	L	H	L	L	H	H
5	L	L	L	H	L	L	L	H

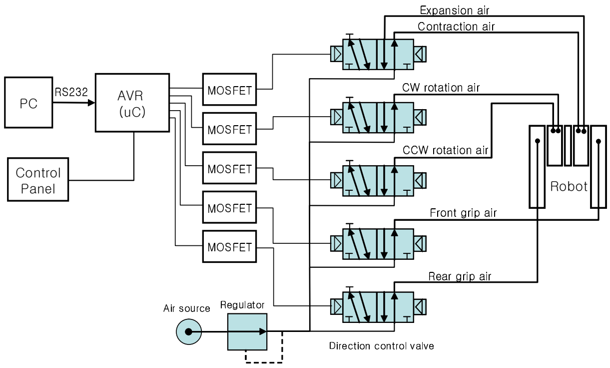

Fig. 9. Pneumatic feeder pipe inspection robot.

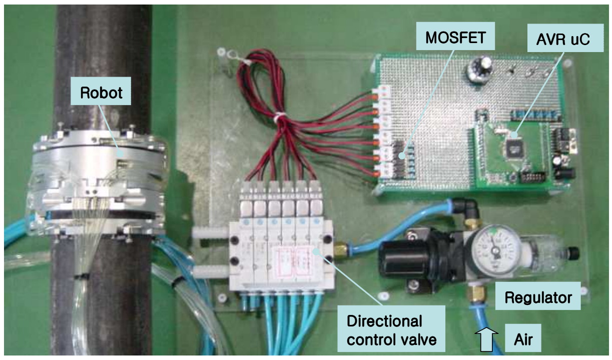

Fig. 10. The experimental setup.

5. Experiments

Figure 10 shows the experimental setup for motion control. The air supply by the air compressor flows through the regulator that is equipped with the air filter. The filtered air is supplied to the directional control valves. The MOSFETs controlled by the AVR microcontroller control the air flow that is applied to the robot.

Figure 11 shows the designed feeder pipe inspection robot. The robot bodies are made by aluminium to reduce the weight, and the piston and joints are made by steel to have enough mechanical roughness. A flexible 3.2 mm pneumatic tube is used for connecting the controller and robot. The piston diameters of the embedded pneumatic actuators are 6 mm, then, when the air pressure is 5 kgf/cm^2, the gripper force is 1.4 kgf.

The robot is tested to travel along the straight pipe and curved pipe. In case of the straight pipe, both the motion of longitudinal and circumferential directions are possible, the robot can travel in that direction well. In case of curved pipe, the motion in longitudinal direction is possible, but circumferential direction is possible only small amount because of the mechanical constraints.

Figure 12 shows the measuring displacement of forward and backward movements of the robot in a horizontal pipe when the robot moves five steps with interval time by 0.25, 0.5, and 1.0 sec per each step, respectively. The corresponding average velocities are by 20.8, 9.0, and 3.6 mm/sec. Al low speed, the robot moves its step distance for each step. At high speed, however, the robot extends and contracts before

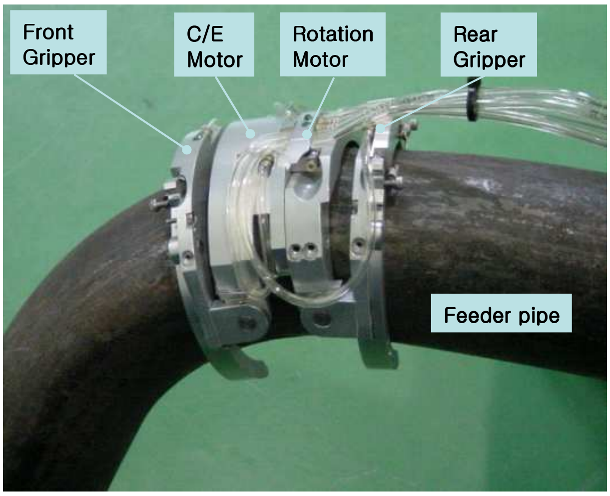

Fig. 11. The controller for pneumatic feeder pipe inspection robot.

the gripper fixes the robot tightly on the pipe, then the inertia force makes a slip and causes the displacement become large as the speed increases. The gripper force is important in the inch worm mechanism because it is directly concerned with the resolution of the position control. If the gripper force is not enough, the inertia force caused by the motion of the front or rear body makes slipping on the robot movement, which causes the position error. Moreover, when the robot moves a vertical pipe, it cannot climb up, and when the robot is hanged below the pipe, it cannot recover to the up standing position.

In order to increases the gripper force, one of the easy solution is increasing the pressure of the air, but it is limited by the capabilities of the air pump and directional control valves. The other is increasing the piston diameter, which causes larger robot size. The robot size and the air pressure should be considered for designing a robot that can be applicable to the actual power plant.

6. Conclusions

This paper proposed a mobile robot for inspecting feeder pipes in a PHWR by using an inch-worm mechanism. A pneumatic robot is designed and manufactured so that the pneumatic cylinders are embedded into the robot body to reduce the size. This design scheme reduces the robot dramatically with slim shape. The experimental results show that the mechanism can be applicable to curved pipe inspection with small size, which can be applied not only the nuclear industry, but also other pipe inspection applications.

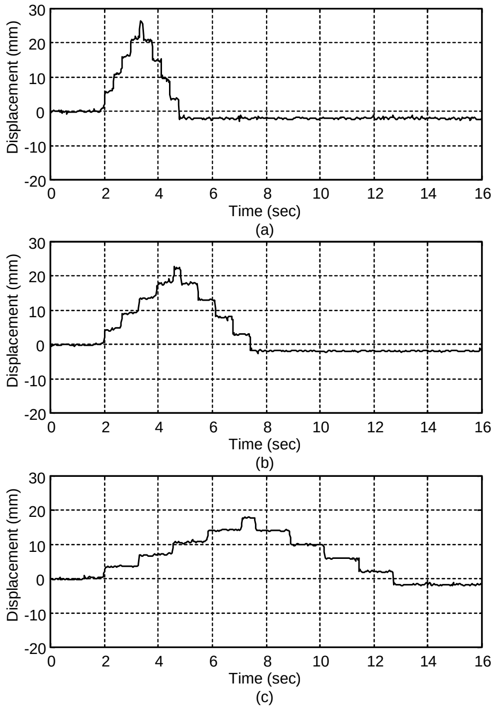

Fig. 12. The displacement of forward and backward movement of the robot.

References

[1] Eric Lavoie, Gilles Rousseau, Jean Lessard, and Alain Drolet, "Hydro-Quebec Meter Inspection Bracelet," Canadian Nuclear Society's 5th Int. Conf. on CANDU Maintenance.

[2] Byungkyu Kim, Kyoung-Dae Kim, Jinhee Lee, Jong-Oh Park, Soo-Hyun Kim and Yeh-Sun Hong, "Locomotive Mechanism based on pneumatic actuators for the semi-autonomous endoscopic system," ICASE 2001.

[3] Chang-Hwan Choi, Seung-Ho Jung, Yong-Chil Seo, Kyung-Min Jeong, Ho-Chul Shin, and Seung-Ho Kim, "Small mobile feeder pipe inspection robot for pressurized heavy water reactor with inch-worm mechanism," Korean Patents, 10-2003-0059819.

[4] Development of video probe system for inspection of feeder pipe support in calandria reactor, KAERI Report, KAERI/RR-2058/99.