

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

Changhwan Choi, Seungho Jung, and Seungho Kim

Abstract: The outlet feeder pipe thinning in a PHWR (Pressurized Heavy Water Reactor) is caused by a high pressure steam flow inside the pipe, which is a well known degradation mechanism called a FAC (Flow Assisted Corrosion). In order to monitor the degradation, the thickness of the outlet bends close to the exit of the pressure tube should be measured and analyzed at every official overhaul. This paper describes a mobile feeder pipe inspection robot that can minimize the irradiation dose to 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 to the pipe, one extendable and contractible actuator, and a rotation actuator connected to the two gripper bodies to move forward and backward, and to rotate in a circumferential direction.

Keywords: Inch-worm, pipe inspection, PHWR.

1. INTRODUCTION

The outlet feeder pipe thinning in a PHWR (Pressurized Heavy Water Reactor) is caused by a 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 close to the exit of the pressure tube should be measured and analyzed at every official overhaul.

Lots of pipe inspection robots have been developed that can be applicable for inspecting the feeder pipe. The drive mechanism can be classified as crawler or wheel mechanisms [1,2], articulated wheel mechanisms [3], and bio-mimetic mechanisms that originate a snake or inch worm [4-7]. Since the feeder pipe inspection should be performed without cutting the pipe and without any severe radiation contamination to the robot, the out-pipe inspection methods are preferred. However, collecting high quality data is a challenge, mainly due to a lack of space around the pipes, especially for 2.5 inch pipes and the roughness of the feeder pipes.

Ontario Hydro's SIMD department developed the SIMD bracelet and used it in Gentilly-2 from 1997 to

1999 [8]. However, the SIMD bracelet can only be applied to two inch feeder pipes and especially on the first bends because of the limited space around the feeder pipes. Therefore, the data quality of the inspection is not enough for guaranteeing the safety of the pipes.

Hydro Quebec research center (IREQ) developed an inspection system, METAR and used it in Gentilly-2 from 1999 to 2000 [8]. METAR has 14 ultrasonic sensors mounted on holders in each sensor. The holder ensures the sensor is attached perpendicular with respect to the feeder pipe and allows some amount of freedom by using a flexible collar to fix it to the holders. The SIMD bracelet and METAR are operated manually, that is, since the inspection systems have no motorizing capabilities, a human operator should install the system and stay in front of the feeder pipe while completing the measurement, which increases the irradiation dose to the workers.

This paper describes a mobile feeder pipe inspection robot that can minimize the irradiation dose to a human operator by automating the measurement process. The robot can move by itself on the feeder pipe by using an inch worm mechanism [9,10], which is constructed by two gripper bodies that can fix the robot body on to the pipe and one extension/contraction actuator and a rotation actuator connected to the two gripper bodies to move forward and backward and to rotate in a circumferential direction, respectively. These actuators are driven pneumatically and are embedded inside the robot body to reduce the size of the robot so that it is applicable to the actual feeder pipes in a PHWR.

The design method of the robot is presented based

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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 into the relationship between the robot size and the allowable feeder pipe curvature. The attaching force generated by the pneumatic actuator is also analyzed for various pipe and robot configurations. The control system is developed by using five directional control valves and a digital signal processor with five MOSFET solenoid drivers. The proposed inspection robot is applied to a mockup of a feeder pipe to illustrate the feasibility of the inspection.

2. WORKING ENVIRONMENTS

The PHWR in Korea has 380 pressure tubes. The feeder pipes are attached to each pressure tube whose diameters are 1.5, 2.0, 2.5 inches with the number of 33, 183, 164, respectively. The direction and curved angle of the feeder pipe is various. Fig. 1(a) shows a part of the pressure tube array. The pressure tubes are arranged circularly with an interval distance of 286 mm between them. 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 that fix the feeder pipes, to reach the surface of the feeder pipe. The size is approximately 155 mm × 204 mm.

Fig. 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 a more severe interference

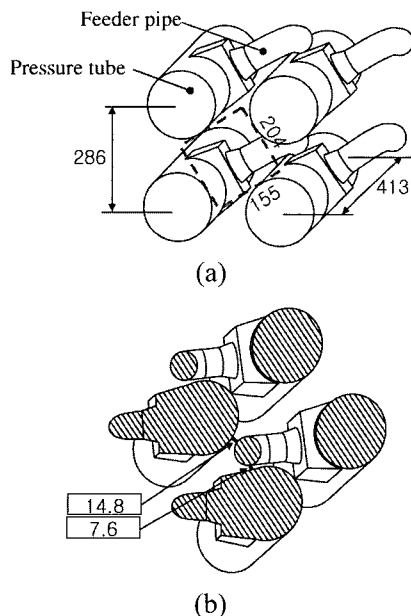


Fig. 1. (a) The feeder pipe array in a PHWR (b) the cross-section view of a closest gap in the array.

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

unit (mm)	Nominal	first bend	second bend
min. dia.	73.1	68.15	66.8
max. dia.	73.1	77.25	77.1
curvature	∞	92.25	92.25 (min)

than the 2.0 and 1.5 inch pipes. Therefore, in order to inspect the feeder pipe, the robot must overcome such gaps. In conclusion, the robot should be able to pass through 7.6mm gaps and the thickness of the robot body should not exceed more than 14.8 mm.

Since the feeder pipes in a PHWR are 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 an elliptical shape, that is, the in-plane curved part of the feeder pipe has a small diameter, and the out-plane curved part has a large diameter when compared with the nominal diameter. Table 1 shows the measured diameter of a 2.5 inch feeder pipe at the first and second parts of a bending. Since the curvature of the feeder pipe is various at the second bend, only the minimum case is described. The maximum diameter change is from a nominal value which is 6.3 mm as shown in the table. These diameter variations should be considered in the robot design.

3. PRINCIPLE OF THE ROBOT

3.1. Robot structure

There are various actuation mechanisms to design a robot such as electrical motors, pneumatic cylinders, hydraulic actuators, and material forces, and so on. Although the electrical system has many benefits, the smaller the actuator, the smaller the actuation force. That is, we can make the robot as small as possible, but the robot may not work in an actual environment

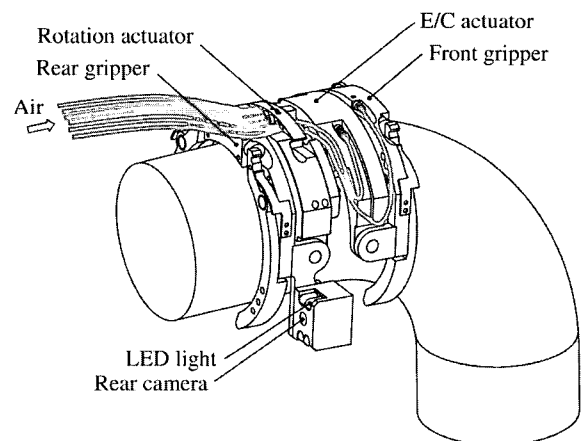


Fig. 2. The feeder pipe inspection robot using an inch-worm mechanism.

Table 2. The specifications of the robot.

Descriptions	Value
Mass	350 g
Max. moving speed	14.2 mm/s
Max. rotating speed	13.8 deg/s
Moving resolution	6.25 mm/step
Rotating resolution	7.6 deg/step
Min. allowable pipe curvature	66 mm

which has various harsh conditions that require a large force such as a large slope of the pipe and a cable tension force. The material forces generated by piezoelectric or magnetostrictive materials is a good actuator only for sub-millimeter or sub-micrometer applications. The hydraulic actuator has a relatively large force with a small volume, but a contamination is the main problem. The pneumatic actuators are good at generating a large force and preventing a contamination. Therefore, the pneumatic actuators are used for the robot design.

The working environment of the robot is one of the most hazardous environments that a robot can meet because of the large radiation dose, complex mechanical constraints, and the requirement of a high precision measurement. The robot should be able to travel through that environment.

In this paper, we designed a robot using pneumatic actuators which are 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. 2. 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 on to the feeder pipe. Each gripper actuator has two half-circle shaped gripper hands to enclose the pipe. The gripper hand is driven by two pneumatic cylinders for each finger. When an air pressure is applied to the gripper body, the cylinder expands and moves the gripper hands so that it fixes the robot to the pipe. When the air is released, the cylinder moves back by a spring force.

The gripper finger is designed to be able to be opened by applying an external force so that it can be easily installed. The human operator or installation tool pushes the robot for an installation and pulls the robot for releasing it. The spring force holds the robot to the pipe during failure conditions.

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 it to the various radius of a pipe curvature, the grippers and the motorizing mechanism

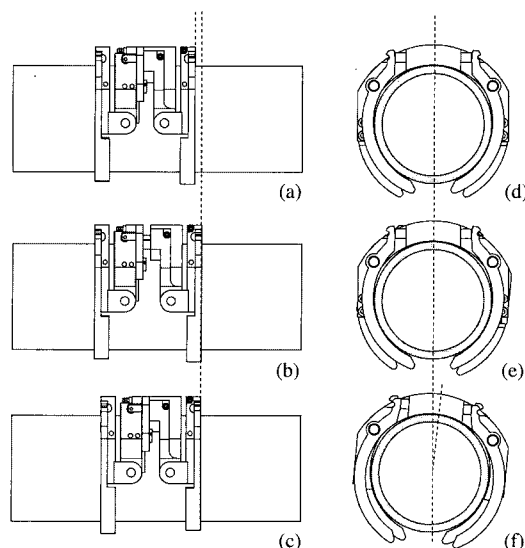


Fig. 3. The moving and rotating principles of the inch-worm feeder pipe robot.

are connected by free revolute joints so that the front and rear grippers can be formed at any angle by the mechanical constraints between the curved feeder pipe and the robot. Table 2 shows the specification of the robot.

3.2. Working principle

Figs. 3(a)-(c) show the moving principle of the inch-worm feeder pipe robot. In order to move in the right direction, drive the actuators in a sequence of fixing the rear gripper, extending the cylinder, extending the E/C actuator, fixing the front gripper, releasing the rear gripper, and contracting the E/C actuator. This operation is continued to move forward and the operation is reversed if the direction is left. Figs. 3(d)-(f) show the rotation principle. In order to rotate in a cw (clock wise) direction, fixing the rear gripper, rotating the rotation actuator in a cw direction, fixing the front gripper, releasing the rear gripper, and rotating the rotation actuator in a ccw (counter clock wise) direction. This operation is continued to rotate further and the operation is reversed if the direction is a cw. Since the robot can move freely in the longitudinal and circumferential directions of a feeder pipe, we can measure most of the parts on the feeder pipe if the space is allowed for except for the inner part of the curved feeder pipe, which cannot be accessed because of the mechanical constraints.

4. ROBOT DESIGN AND ANALYSIS

4.1. Robot body sizing

The robot should move along the curved pipe with a relatively small curvature as listed in Table 1. In order to determine the size of the robot that can travel along the target feeder pipe, a kinematic analysis is

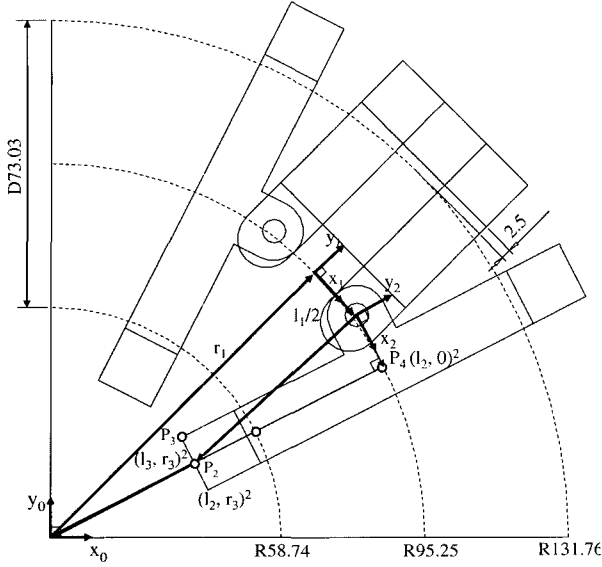


Fig. 4. The kinematic analysis for verifying the relationship between the robot size and the pipe curvature.

performed as shown in Fig. 4. Two conditions are required; one is that the front and rear gripper should not collide. The other is that the grippers should be aligned perpendicularly with respect to the pipe. As for the first condition, considering the point P_3^0 at the front gripper and the corresponding point at the rear gripper, the vector P_3^0 can be represented as

$$P_3^0 = v_1^0 + A_1^0 v_2^1 + A_1^0 A_2^1 P_3^2, \quad (1)$$

where v_1^0 and v_2^1 are the vectors indicating the origin of the reference coordinate system with orientation angles of ϕ_1 and ϕ_2 , respectively. A_1^0 and A_2^1 represent the coordinate transformation matrices. Here, the subscript represents the point index and the superscript represents the reference coordinate system. Assume that the θ_1 is $\pi/2$, that is, the robot is located at the top of the circular pipe, then the condition becomes $P_{3x}^0 > 0$

$$\frac{l_1}{2} + l_3 \cos \theta_2 - r_3 \sin \theta_2 > 0, \quad (2)$$

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 the 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 positions of P_2 and P_3 with respect to the $x_2 - y_2$ coordinate system.

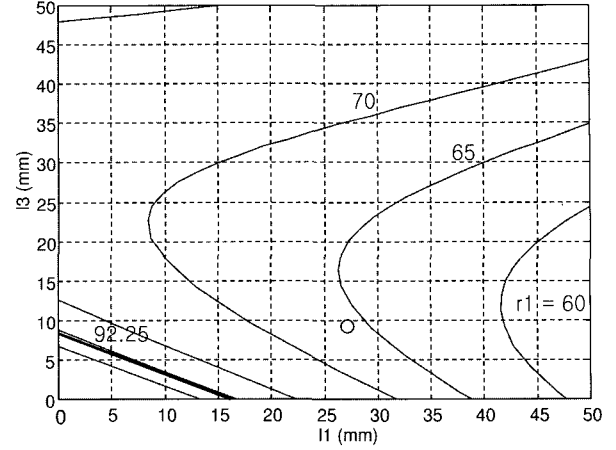


Fig. 5. The relation between the pipe curvature and the size of the robot.

As for the second condition, the line connecting the points P_2 and P_4 should meet the origin of the $x_0 - y_0$ coordinate system, which gives a relation, $P_{2x}^0 P_{4y}^0 - P_{2y}^0 P_{4x}^0 = 0$, then the following condition should be satisfied.

$$r_1 \sin \theta_2 - \frac{l_1}{2} \cos \theta_2 - l_2 = 0. \quad (3)$$

Changing the inequality of (2) to an equality condition for plotting the graph and rearranging (2) and (3) gives

$$\begin{bmatrix} l_1 \\ l_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \cos \theta_2 \\ -\frac{1}{2} \cos \theta_2 & -1 \end{bmatrix}^{-1} \begin{bmatrix} r_3 \sin \theta_2 \\ \frac{l_w}{2} - r_1 \sin \theta_2 \end{bmatrix}. \quad (4)$$

Computing (4) with respect to θ_2 and plotting the result with respect to the l_1 and l_3 gives Fig. 5. Seven cases of the feeder pipe bending curvature are plotted, which are 60, 65, 70, 80, 90, 92.25, and 100 mm. The left side 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 as indicated in the circle, which are located between the bending curvature of 65 mm and 70 mm. Which means that the robot can travel a pipe whose bending curvature is larger than 66 mm. Since the bending curvature of the first bend is 92.25 mm, it can travel along that feeder pipe.

4.2. Robot gripper analysis

The grippers are one of the essential parts of the robot for a stable movement which fix the robot body to the feeder pipe. The cross-section of a feeder pipe is circular at a straight part, however, it becomes

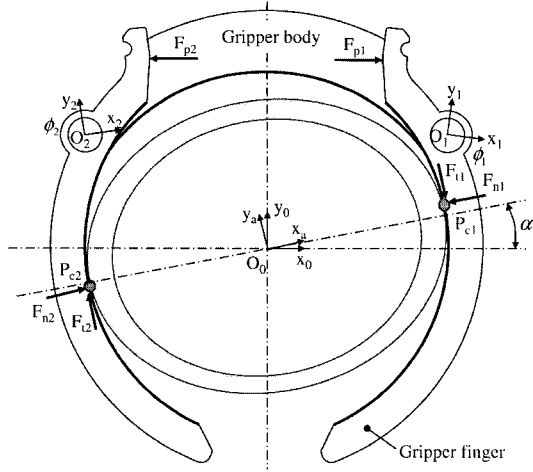


Fig. 6. The gripper analysis when the feeder pipe is an elliptical shape.

elliptical at the first and second bend caused by the bending operation. Then, at the curved part, the contact points between the feeder pipe and the gripper body become three or two according to the shape distortion of the pipe. Fig. 6 shows the configuration of the feeder pipe and the gripper body. Assume that the robot is rotated along the circumferential direction of the feeder pipe by the angle α . The figure shows that situation based on the robot body fixed coordinate system, $x_0 - y_0$. When a pneumatic pressure is applied to the gripper, forces F_{p1} and F_{p2} are generated and push the grippers to grip the pipe. Then, the gripper fingers are rotated based on the points O_1 and O_2 with the angles ϕ_1 and ϕ_2 . The grippers grip the feeder pipe at the contact points $P_{c1} = (c_1, d_1)^0$ and $P_{c2} = (c_2, d_2)^0$ with the gripping forces by F_{n1} and F_{n2} which are perpendicular to the surface of the pipe, and with tangential forces by F_{t1} and F_{t2} . The $x_1 - y_1$ and $x_2 - y_2$ denote the body fixed reference coordinate systems which are attached on the gripper fingers.

The equation of the outer surface of the elliptical pipe when the robot is rotated by α is

$$\frac{x_a^2}{r_1^2} + \frac{y_a^2}{r_2^2} = 1, \quad (5)$$

where

$$\begin{bmatrix} x_a \\ y_a \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (6)$$

and r_1 and r_2 are the principle radius of the ellipse.

The equation of the inner circle of the gripper is

$$(x_i + a_i)^2 + (y_i + b_i)^2 = r_g^2, \quad (7)$$

where $i=1,2$ and 1 means the right side gripper and 2 the left, and

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} \cos \phi_i & \sin \phi_i \\ -\sin \phi_i & \cos \phi_i \end{bmatrix} \begin{bmatrix} x - a_i \\ y - b_i \end{bmatrix}. \quad (8)$$

In order to be inscribed between the feeder pipe and the gripper hand, the angle of the normal vector from the origin to the contact point seen by (5) and (7) should be the same, which gives

$$\tan^{-1} \left(-\frac{x_i + a_i}{y_i + b_i} \right) + \phi_i - \tan^{-1} \left(-\frac{r_2^2 x_a}{r_1^2 y_a} \right) - \alpha = 0. \quad (9)$$

At the contact point $(c_i, d_i)^0$, (5)-(9) should be simultaneously satisfied. Substituting $(c_i, d_i)^0$ to the (x, y) of (6) and (8), provides three nonlinear equations with three unknown variables such as c_i, d_i, ϕ_i . These nonlinear equations are solved by using the MATLAB, 'fsolve' function. The solving algorithm is a subspace trust region method and is based on the interior-reflective Newton method. Each iteration involves the approximate solution of a large linear system by using the method of preconditioned conjugate gradients (PCG) [11].

Fig. 7 shows the gripper contact angle β_i and the normal forces applied to the pipe with various pipe diameters when the cross-section shape of the feeder pipe is circular, and 'A' denotes the contact point when the feeder pipe diameter is 60, 65, 70, and 75 mm. Since the friction coefficient is dependent on

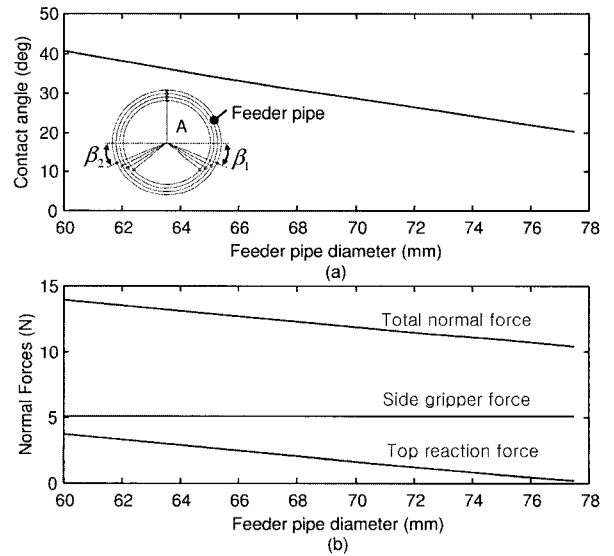


Fig. 7. (a) The gripper contact angle β_i (b) the forces applied to the pipe with various pipe diameters when the cross-section shape of the feeder pipe is circular.

various surface conditions, we denote the gripping force by using the normal force for a generality. In this case, the gripper is fixed by three contact points, which are at the inner surface of the gripper body and that of the two gripper fingers. When the diameter of a pipe is small, the contact angle β_i is large, that is, the contact points P_{ci} are at the lower side of the pipe as shown in 'A'. As the diameter increases, the contact point moves up to the side of the pipe. This makes the moment arm established by O_i to P_{ci} to be almost constant. Then, the force applied by the gripper finger to the side of the pipe becomes almost constant. The reaction force caused by the contact of the gripper body can be obtained from the force equivalence, and the total normal forces exerted on

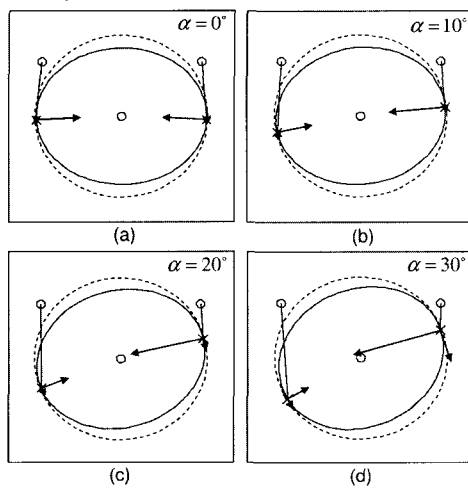


Fig. 8. The gripping force applied to the pipe with respect to the robot orientation angle.

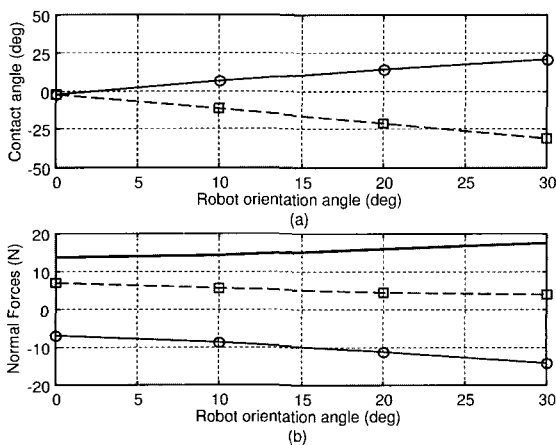


Fig. 9. (a) The gripper contact angle β_i (b) the forces applied to the pipe with respect to robot orientation angle α when the cross-section shape of the feeder pipe is elliptical. (solid line when $i=1$, dashed line when $i=2$).

the pipe can be obtained by summing the top reaction force and the two side gripper forces as shown in Fig. 7(b). Since the friction force is a multiplication of the normal force by a friction constant, as the diameter of the pipe increases, the normal force decreases, which means that the gripper can fix its body more tightly when the pipe diameter is small.

For the robot in this paper, the inside of the gripper is coated with silicon rubber to increase the friction, and the nominal value of the friction coefficient is 1.60 which was obtained from the experiments is a reasonable value because the friction coefficient of rubber and steel are known to be between 1.0 to 4.0. Then for a feeder pipe with a diameter of 73.03mm, the gripping force is 1.8kgf for each gripper while the weight of the robot is 335g. Therefore, the gripper can fix the robot body even in a vertical pipe in static conditions.

At the bending part of a pipe, the cross-section of the pipe is an elliptical shape. In this case, one of the worst cases is that there is only two contact points, which means the gripping force is small and a slip can occur easily. Depending on the orientation angle of the robot, there are various configurations as shown in Fig. 8, which shows the gripping force applied to the pipe with respect to the robot orientation angle. When the robot is aligned with the outer surface of the curved pipe, that is $\alpha = 0^\circ$, the contact point is near the longest side of the pipe. As the robot rotates along the pipe in a counter clock wise direction, the left side contact point moves down, which increases the moment arm and decreases the press force, On the contrary, the right side contact point moves up, which decreases the moment arm and increases the press force. Fig. 9 shows the gripper contact angle, β_i and the normal forces applied to the pipe. The amount of the total normal force is changed by 25% from 0 deg to 30 deg, which is acceptable because the friction force is relatively large.

5. CONTROLLER DESIGN

The robot has six degrees of freedom including four active joints controlled by the embedded pneumatic actuators in the bodies and two free joints which are constrained by the curved pipe. The four active joints are composed of four single acting cylinders in two grippers and cw and ccw rotation actuators, and one double acting cylinder in the expansion and contraction (E/C) actuator. The two grippers and the E/C actuator are controlled by three five port directional control valves for each, and the rotation actuator has a cw rotation, ccw rotation, and a center position, which is controlled by two five port directional control valves. Therefore, five valves are used for the robot's control.

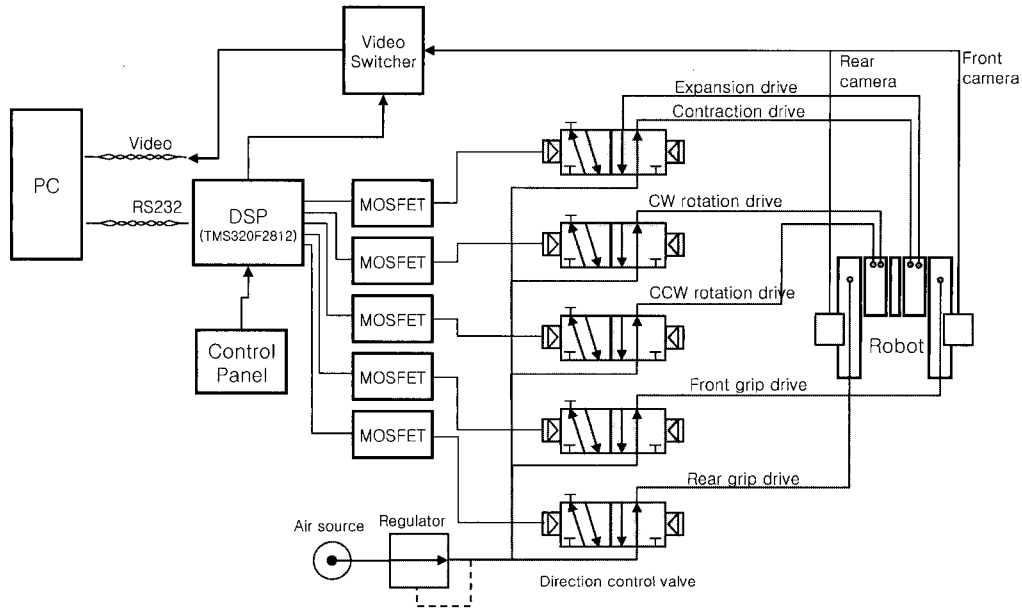


Fig. 10. The controller block diagram for the feeder pipe robot.

Fig. 10 shows the block diagram of the robot controller. The valves are driven by using five MOSFETs. The switching sequence of the MOSFETs is controlled by using TMS320F2812, a DSP made by the Texas Instruments co. ltd. The command can be transferred from a PC through the RS-232 port and from a control panel composed of switches for the movement and rotation direction, and for a velocity control. In order to control it remotely, the visual information is provided by two cameras with LED lights, one for the forward movement and the other for the backward movement. The human operator can switch on the video remotely.

Table 3 shows the switching sequence for the forward and backward movements. Sequence 0 is a normal condition that fixes the robot to the feeder pipe so that the robot cannot slip. The ‘H’ and ‘L’ mean that the valve is switched on and off, respectively, which means the air pressure is supplied or not.

Table 4 shows the switching sequence for the cw and ccw rotation motions. In the case of a 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 3. The switching sequence for the 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 4. The switching sequence for the rotation.

Seq.	cw				ccw			
	RG	LR	RR	FG	RG	LR	RR	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

6. EXPERIMENTS

Fig. 11 shows the experimental setup for investigating the robot’s motions. A small mirror is attached on top of the robot body, which is used for measuring the robot’s movement by using a laser displacement sensor. The displacement is captured by using a distal storage oscilloscope.

Fig. 12 shows the designed feeder pipe inspection robot. The robot’s bodies are made of aluminium to reduce the weight, and the piston and joints are made

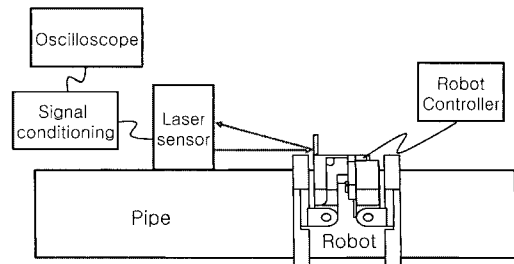


Fig. 11. The experimental setup.

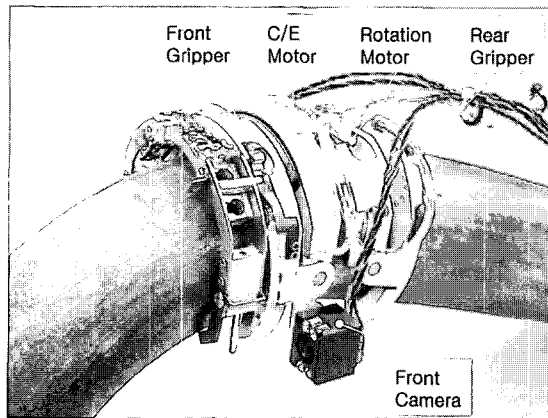


Fig. 12. The pictures of the feeder pipe inspection robot.

of steel to have enough mechanical roughness. A flexible 3.2mm pneumatic tube is used for connecting the controller and the robot. The piston diameters of the embedded pneumatic actuators are 6mm . When the air pressure is 5kgf/cm^2 , the gripper force is 1.4kgf .

Fig. 13 shows the measuring displacement of the forward and backward movements of the robot on a horizontal pipe when the robot moves five steps with an interval time of 1.5, 1.2, 0.6 seconds per each step, respectively. The corresponding average velocities are 4.9, 6.3, and 12.4mm/s . As shown in the figure, the robot follows the command sequence well. The forward and backward repeatability from the original position is the same. However, if the speed increases more, the robot could extend and contract before the gripper fixes the robot tightly on to the pipe, then the robot could slip by the inertia force and cause a position error as the speed increases. The gripper force is important in the inch worm mechanism because when the robot moves on a vertical pipe, it cannot climb up it, and when the robot is hung below the pipe, it cannot recover to the upright position.

Fig. 14 shows the measuring displacement of the forward and backward movements of the robot on a pipe with a 45deg slope when the robot moves five steps. Although the robot gripping force is large enough to fix the robot on to the pipe, the displacement is smaller than that of the horizontal pipe. Which is caused by the free revolute joints of the gripper. If the E/C actuator is driven when the robot is sloped, the free joint is rotated slightly, which diminishes the displacement when climbing up. Moreover the displacement in the downward direction becomes large because of the inertia force generated by the impact of the E/C actuators.

In order to reduce this effect, the gripping force needs to be increased by increasing the air pressure or increasing the piston diameter. In addition, the impact

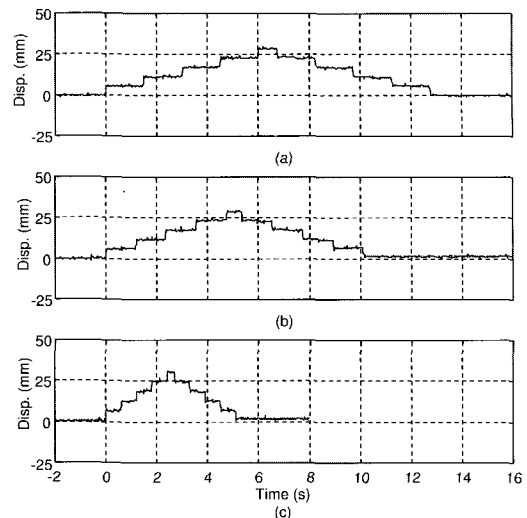


Fig. 13. The forward and backward five step movement in a plane pipe.

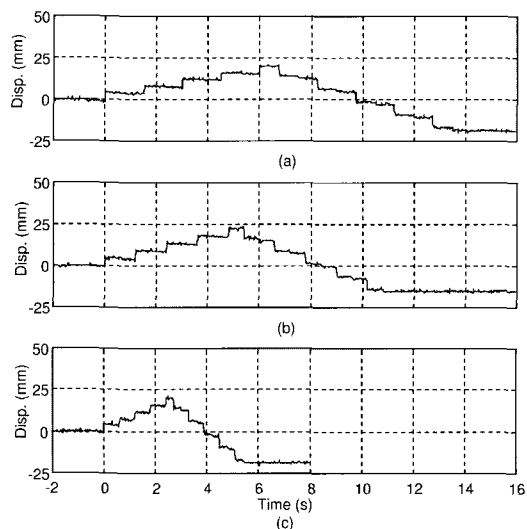


Fig. 14. The forward and backward five step movement in a sloped pipe of 45deg .

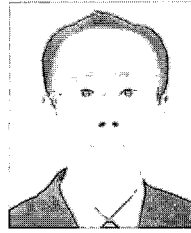
like driving force in the E/C actuator needs to be smooth by using pressure control values.

7. 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 size dramatically with a slim shape. The experimental results show that the mechanism can be applicable to a pipe inspection with a small size, which can be applied not only in the nuclear industry, but also other pipe inspection applications.

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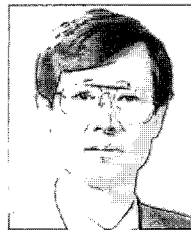
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