The Design and Analysis of a Feeder Pipe Inspection Robot With an Automatic Pipe Tracking System

Changhwan Choi, Byungsuk Park, and Seungho Jung

Abstract—The feeder pipes in a pressurized heavy water reactor (PHWR) suffer from flow-assisted corrosion (FAC), which makes the wall thickness of the pipes thin. This effect is a well-known degradation mechanism of a carbon pipe with high pressure and high flow rate. Therefore, the weak parts of the pipe should be measured to guarantee the safety. This paper describes a mobile out-pipe inspection robot with an automatic pipe tracking system for a feeder pipe inspection in a PHWR. The robot is composed of dual inch worm mechanisms. One is for a longitudinal motion along a pipe, and the other is for a rotational motion in a circumferential direction to access all of the outer surfaces of a pipe. A design method for a gripper actuator is proposed by using a kinematic and force analysis. The proposed mechanism shows a more stable gripping capability than the previous one [21]. An automatic pipe tracking system is proposed based on machine vision techniques to make the mobile robot follow the exact outer circumference of a curved feeder pipe as closely as possible, which is one of the requirements of a thickness measurement system for a feeder pipe. The proposed sensing technique is analyzed to verify its feasibility and to develop a calibration method for an accurate measurement. A mobile robot and control system are developed, and the automatic pipe tracking system is tested in a mockup of a feeder pipe.

Index Terms—Feeder pipe inspection, nuclear robot, pressurized heavy water reactor (PHWR).

I. INTRODUCTION

THE feeder pipes in a pressurized heavy water reactor (PHWR) suffer from flow-assisted corrosion (FAC), which makes the wall thickness of the pipes thin. This effect is a well-known degradation mechanism of a carbon pipe with high pressure and high flow rate. Therefore, the weak parts of the pipe should be measured to guarantee the safety, which is a mandatory requirement in nuclear power plant maintenance.

Pipe inspection systems have been developed for many years due to their demands in various industries not only to nuclear power plants [1], but also other industries such as gas [2] or water [3] supply systems. The inspection methods can be categorized into two groups based on their installation and operation concepts. One is an in-pipe inspection and the other is an out-pipe inspection. An in-pipe inspection method is relatively simple, because the internal status of most pipes is usually uniform and there are not many obstacles in the insides of pipes. However, a pipe needs to be cut or another special inlet needs to be established for an installation, and an inspection system can be contaminated by materials inside of the pipe. In the case of out-pipe inspection, there are many obstacles such as flanges, fixtures, and other pipes, which make it difficult to inspect, but its installation is simple and it has a low possibility of contamination, which are positive factors for applying this method in the nuclear industries, because a radiation contamination and a nondestructiveness are the most important requirements.

Various locomotion mechanisms have been developed for pipe inspection systems. These mechanisms can be classified as conventional pig mechanisms [4], crawler or wheel mechanisms [5]–[9], articulated wheel mechanisms [10], and biomimetic mechanisms that originate from a snake, an inch worm, and a spider [11]–[16]. Fukuda et al. developed a series of out-pipe inspection robots by using an inch-worm mechanism which can pass over flanges and T-joints [17], [18]. Since a feeder pipe inspection should be performed without cutting pipes and without any severe radiation contamination to the robot, an out-pipe inspection methods are preferred. As applications to the feeder pipe in a PHWR, Ontario Hydro (Canada)’s Specialized Inspection and Maintenance Department developed the SIMD bracelet and used it in Gentilly-2 from 1997 to 1999, and Hydro Quebec research center (IREQ) developed an inspection system, METAR and used it in Gentilly-2 from 1999 to 2000 [19], and several crawler robots have also been constructed and tested [20].

This paper describes a mobile out-pipe inspection robot with an automatic pipe tracking system for a feeder pipe inspection in a PHWR. The robot is composed of dual inch worm mechanisms. One is for a longitudinal motion along a pipe, and the other is for a rotational motion in a circumferential direction. This 2-DOF motion makes it possible to access all the outer surfaces of a pipe. Since a gripping mechanism is important for a stable robotic motion in an inch worm mechanism, a design method for a gripper actuator is proposed by using a kinematic and force analysis. The proposed mechanism shows a more stable gripping capability than the previous one [21]. An automatic pipe tracking system is proposed based on machine vision techniques to make the mobile robot follow the exact outer circumference of a curved feeder pipe as closely as possible, which is one of the requirements of a thickness measurement system for a feeder pipe because a thickness variation needs to be monitored at the same measurement points in every overhaul. The proposed sensing technique is analyzed to verify its feasibility and to develop a calibration method for an
accurate measurement. The mobile robot and control systems are developed, and the automatic pipe tracking system is tested in a mockup of a feeder pipe. The advantages of the proposed robot over the conventional robots are as follows. First, the proposed locomotion mechanism is small enough to be applicable to a real environment while having a large driving force by using pneumatic actuators. Second, a novel sensing system is developed to provide an accurate positioning of the robot attitude.

In Section II, the working environment, the proposed robot mechanism, and the design and analysis method for the gripper actuator are described. Section III describes the automatic pipe tracking system with its analysis and sensor calibration technique. Sections IV and V describe the experimental setup and the results, respectively.

II. ROBOT DESIGN AND ANALYSIS

A. Working Environment

The PHWR in Korea has 380 pressure tubes. The feeder pipes are attached to each pressure tube whose diameters are 1.5, 2.0, and 2.5 in with the numbers of 33, 183, and 164, respectively. There are various pipes with different bending curvatures and installation angles. Fig. 1 shows a part of the pressure tube array. The feeder pipes generally have two bends. The distance to reach the first bending of the feeder pipe from the front face of a pressure tube is about 413 mm. The location of the second bending is far from the first one and has various shapes.

After installing a robot at a first bending of a pipe, the robot should be able to pass through the narrow spaces limited by the pressure tubes and other feeder pipes to reach a second bending, which requires the height of an inspection robot to be below 14.8 mm. Since feeder pipes are made by bending a steel pipe, the shape at the bent part is distorted, that is, the cross section of the pipe becomes an elliptical shape. This working environment is one of the most hazardous environments that a robot can meet because of the high radiation dose, complex mechanical constraints, and the requirement of a precision measurement. After reaching the measurement position, the robot should measure the thickness of the feeder pipes, mostly in bent region of the pipe, by using an array of ultrasonic sensor.

B. Robot Structure

An inch-worm mechanism is used for the locomotion mechanism, as shown in Fig. 2. The robot is composed of four actuation parts, two gripper actuators, and a locomotion mechanism that consists of translation and rotation actuators. Fig. 3(a)–(c) shows the moving principle of the inch-worm robot. In order to move it to the right, drive the actuators in a sequence to fix the rear gripper, extend the translation actuator, fix the front gripper, release the rear gripper, and contract with the translation actuator. This operation continues to move it forward and the operation is reversed if the direction is changed. Fig. 3(d)–(f) shows the rotation principle. In order to rotate it in a clockwise (cw) direction, fix the rear gripper, rotate the rotation actuator in a cw direction, fix the front gripper, release the rear gripper, and rotate the rotation actuator in a counter cw (ccw) direction. This operation is continued to rotate further and the operation is reversed if the
direction is changed. Since the robot can move freely in the longitudinal and circumferential directions of a feeder pipe, we can measure most parts of the feeder pipe if the space is available except for the inner part of the curved feeder pipe, which cannot be accessed because of the mechanical constraints in the robot mechanism.

The two gripper actuators are located at the front and rear parts of the robot body to fix the robot on to a feeder pipe. Fig. 4 shows the gripper actuator and its cross-sectional view. The gripper actuator is composed of two gripper links and two fingers connected in each gripper link with a slide joint to improve the contact condition. The gripping spring pushes two gripping cylinders so that some amount of gripping force can be applied when no air pressure is applied for safety, which make the robot be attached at a pipe when the air pressure is released inadvertently. The plate spring make the gripper in shape if there is no air pressure. If an air is applied, the gripping cylinders push each gripper link, and the finger is rotated to grip the pipe. The gripper actuator should be able to fix itself to a pipe rigidly for a stable motion of a robot.

A locomotion mechanism connects the two gripper actuators which has a translation and a rotation actuators for moving forward and backward, and for rotating along the circumferential direction of a pipe, respectively. In order to adopt to various radii of a pipe curvature automatically, the grippers and the locomotion mechanism are connected by free revolute joints so that the front and rear grippers can be adapted to any angle by the mechanical constraints between the feeder pipe and the robot. Fig. 5 shows the translation actuator and its cross-sectional view. The translation actuator is composed of two pneumatic cylinders one is for extension motion and the other is for contraction motion. If an air is applied at the extension cylinder while releasing the air in contraction cylinder, it pushes the connection bar to extend. The contraction motion is similar. Normally, the connection bar is located at the center position where the spring force of each spring is balanced.

C. Kinematic Analysis

The gripper actuator fixes the robot body on to the pipe and it sustains the inertia, gravity forces, and tension force caused by the cable. If the grip is weak, the robot’s movement is not uniform due to a slippage. The proposed mechanism in Fig. 7 shows an improved version of the author’s previous grippers [21]. In the previous version, the gripper link and finger were constructed as one body. That means, the gripper finger is rotated at the $O_1$ pivot point that causes a two-point support between
the gripper and the pipe because of a pipe distortion at the bent part, which results in a slippage when moving the robot. Therefore, in the proposed mechanism, the gripper finger is separated into two links. The gripper link pushes the finger by a linear contact and the finger rotates with respect to the $O_2$ pivot point, which always guarantees a three-point contact for practical pipe distortions.

In order to design a reliable gripper actuator, kinematic and force analysis are performed. $L_1$ and $L_2$ indicate the trajectory of the contact point, $P_1$ between the pneumatic cylinder and the surface of the gripper link, and the slide line of the pivot point, $P_2$ between the gripper link and finger, respectively. $x_1 - y_1$ and $x_2 - y_2$ indicate the body-fixed coordinate system attached to the joint at the gripper link and the finger, respectively. The origin positions are $O_1$ and $O_2$, and the rotation angles are $\theta_1$ and $\theta_2$, respectively. $C_1$, $C_2$, and $E_1$ represent the inner circle of the gripper body, that of the finger, and the ellipse of the pipe outer surface, respectively.

In order to simplify the derivation of the equation, let us define a function denoting the solution of an algebraic equation. Suppose that there is an equation expressed as an analytic function $f(x_1, x_2, \ldots, x_n) = 0$, then we can obtain an identical expression with respect to one of its parameters as $x_i = G(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n)$ from an implicit function theorem. Rewrite the expression as $x_i = S_{x_i}(f)(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n)$, which means that the $x_i$ is computed from $f$ with respect to other variables except $x_i$. Here, $S_{x_i}(\cdot)$ can be expressed as a closed-form equation in a simple case, but, in general, it may not be possible, nevertheless we can compute the $x_i$ numerically.

The coordinate transformation matrix between the body-fixed frame and the global frame is

$$R_{\theta_i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & O_{x_i} \\ \sin \theta_i & \cos \theta_i & O_{y_i} \\ 0 & 0 & 1 \end{bmatrix}$$

where $i = 1, 2$.

Representing $L_1$ and $L_2$ in their body-fixed coordinate systems, that is $x_1 - y_1$ and $x_2 - y_2$, gives

$$a^T P_{1i}^1 = 0$$

$$b^T P_{2i}^2 = 0$$

where $a = [a_1, a_2, a_3]^T$ and $b = [b_1, b_2, b_3]^T$ denote the coefficient vectors, and $P_{1i}^1 = [x_{L_1}, y_{L_1}, 1]^T$ and $P_{2i}^2 = [x_{L_2}, y_{L_2}, 1]^T$ denote the point sets along the lines. Here, the superfix denotes the reference frame and the subfix denotes the line seen in Figs. 7 and 8. Rewriting (2) and (3) with respect to the global coordinate frame gives

$$a^T R_{\theta_i}^{-1} P_{0i}^1 = 0$$

$$b^T R_{\theta_i}^{-1} P_{0i}^2 = 0$$

These equations are satisfied at $P_1$ which is the sliding contact point between the pneumatic cylinder and the gripper link, and $P_2$ that between the gripper link and the finger.

Since the pneumatic cylinder only moves in the horizontal direction, the $y$ position of $P_1$ is constant. Then, if we assume that $\theta_1 = 0$ is the initial configuration, the initial $x$ position of the contact point is represented as $x_0 = S_{x_0}^{\theta_1}([a^T R_{\theta_1}^{-1} P_{0i}^1]$ from (4). Similarly, $\theta_1$ is computed from (4) as

$$\theta_1 = S_{\theta_1}([a^T R_{\theta_1}^{-1} P_{0i}^1](x_{i1} = x_0 + d)$$

where $d$ is the displacement of the pneumatic cylinder from $x_0$.

Representing $P_2$ that moves along the line $L_2$ in the global coordinate frame gives $P_{0i}^2 = R_{\theta_1} P_{1i}^1$, which should be located on the line represented in (5), which gives the $\theta_2$ as

$$\theta_2 = S_{\theta_2}(b^T R_{\theta_2}^{-1} R_{\theta_1} P_{2i}^2)(\theta_1)$$

where $\theta_1$ comes from (6). Fig. 9 shows the kinematic analysis result of the gripper. As the pneumatic piston moves the gripper link and finger angle rotate in the cw direction which is the gripping direction. Fig. 9(a) is the gripper link angle which is the same as the angle variation for the first version of the gripper. Fig. 9(b) is that of the proposed version. The gain of the gripper angle variation with respect to the cylinder displacement is improved by almost two times, which means the gripper
can cover a wider range of a pipe distortion and pipe diameter changes.

D. Force Analysis

In order to obtain the reaction force being exerted on a pipe, the contact point between the finger and the pipe, $P_3$ should be known. The trajectory of the inner circle $C_2$ is represented as $G_{C_2}([x_2, y_2, 1]^T) = (x_{C_2} + O_{C_2,x})^2 + (y_{C_2} + O_{C_2,y})^2 - r_{C_2}^2 = 0$ with respect to the $x_2 - y_2$ frame. The elliptic outer line of the pipe is represented as $G_{E_i}([x_0, y_0, 1]^T) = e_1^2 x_0^2 + e_2^2 (y_0 - c_1)^2 - e_1^2 e_2^2 = 0$, where $e_1$, $e_2$, and $c_1$ denotes the longest and the smallest diameter of the ellipse that represent the outline of the pipe, and the offset position of the pipe so that the gripper body is in contact with the pipe, respectively. Then, the following three equations should be satisfied at $P_3^0$:

$$G_{C_2}(P_3^0) = 0$$

(8)

$$G_{E_i}(P_3^0) = 0$$

(9)

$$\det J = 0$$

(10)

where

$$J = \frac{\partial G_{C_2}/\partial x \quad \partial G_{C_2}/\partial y}{\partial G_{E_i}/\partial x \quad \partial G_{E_i}/\partial y}$$

evaluated at $P_3^0$. The last equation comes from the inscription condition. From these equations, we can compute the $P_3^0$ and $\theta_1$. Rearranging (7) with respect to $\theta_1$ gives

$$\theta_1 = S_{\theta_1}(b^T R_{\theta_2}^{-1} R_{\theta_1} P_2^1)|_{(\theta_2)}$$

(11)

and (6) with respect to $x$ gives

$$x = S_{x}(a^T R_{\theta_2}^{-1} R_{\theta_1} P_1)|_{(y_0, \theta_1)}.$$  

(12)

The moment equilibrium condition at $O_1$ gives

$$\Sigma M_{O_1} = -P_1^1 \times F_p^1 + P_2^1 \times F_1^1 = 0$$

(13)

where

$$F_i^1 = |F_i| n^1 = |F_i| R_{\theta_1} R_{\theta_2} n^2$$

(14)

where $n^2 = [b_1, b_2]^T / \sqrt{b_1^2 + b_2^2}$, and $R_{\theta_j}$ denotes the rotation part of the transformation matrix. The moment equilibrium condition at $O_2$ gives

$$\Sigma M_{O_2} = -P_3^2 \times F_p^2 + P_2^1 \times F_1^2 = 0$$

(15)

where

$$F_2^2 = |F_g| n_2^0 \quad F_1^2 = |F_i| n^2$$

$$n_2^0 = \frac{[e_2^2 P_{d_1}^2, e_1^2 (P_{d_2}^0 - c_1)]^T}{\sqrt{e_1^2 P_{d_1}^2 + e_1^2 (P_{d_2}^0 - c_1)^2}}.$$  

Fig. 10 shows the contact point and the corresponding gripping force with respect to various pipe configurations. As the pipe diameter increases, the contact point moves in the right direction and the gripper can grab the pipe between 55 mm and up to the 75 mm as well as seen in Fig. 10(a). The corresponding force gain is shown in Fig. 10(b). As the pipe becomes an elliptical shape, the contact point moves in the right direction and if the shortest diameter is below 53 mm, two contact points occur, which is a bad condition for the robot. The corresponding force gain is shown in Fig. 10(d). As the pipe distortion level increases the contact points become weak. However, the gripping force increases, which compensates for this increased distortion.
III. AUTOMATIC PIPE TRACKING

A. Analysis of an Orientation Angle Measurement

Two cameras are attached at the bottom part of the robot’s body. One is for its forward movement and the other for its backward movement. Since its forward movement and backward movement are similar, only the forward movement is considered. If the robot is aligned well to the bending direction of the pipe the edge line of the pipe is aligned with the vertical line of the camera image. However, if the robot has an orientation error, the edge line has the same amount of an angle as the vertical line of the image. The orientation angle can be computed from an image processing algorithm.

In order to obtain an insight on how the surface image of the pipe is to be displayed in the camera image, a geometric analysis is performed, as shown in Fig. 11. Let us think about the cross section of a pipe cutting on angle of \( \beta \), which is assumed to be a circle \( C_1 \). This circle can be parametrized by using the pipe radius \( r_p \) and an angle \( \alpha \). Then, the points in the circle can be represented in the \( x_0 - y_0 \) coordinate as

\[
W_h = T_x \begin{bmatrix} r_p \cos \alpha & r_p \sin \alpha & 0 & 1 \end{bmatrix}^T \tag{16}
\]

where

\[
T_x = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \beta & -\sin \beta & -\rho(1 - \cos \beta) \\
0 & \sin \beta & \cos \beta & \rho \sin \beta \\
0 & 0 & 0 & 1
\end{bmatrix} \tag{17}
\]

A 3-D position of the circle can be projected on the camera image coordinate as

\[
C_h = PR_x^b R_z^b T_x W_h \tag{18}
\]

where \( T_x, R_x^b, R_z^b, \) and \( P \) denote the transformation matrices representing the camera translation, camera orientation in the \( x \)- and \( z \)-directions, and the projection caused by the pin-hole lenz model represented as a homogeneous transformation form. The circular shape of the cross section would be displayed as an elliptic shape in the camera image according to (18).

The edge lines of the pipe mapped into the camera are the inscription lines of the ellipse, the projection of the circle in the image coordinate. Let the ellipse for the \( i \)th cross-section circle be \( x_i(s) \ y_i(s) \) and that of the \( (i+1) \)th be \( x_{i+1}(t) \ y_{i+1}(t) \), where \( s \) and \( t \) are the parameters. The inscription line between these ellipses can be computed from the inscription condition of both ellipses as

\[
\Delta x_i(s)(y_i(s) - y_{i+1}(t)) - \Delta y_i(s)(x_i(s) - x_{i+1}(t)) = 0 \tag{19}
\]

\[
\Delta x_{i+1}(t)(y_i(s) - y_{i+1}(t)) - \Delta y_{i+1}(t)(x_i(s) - x_{i+1}(t)) = 0 \tag{20}
\]

The projected ellipses and the inscription lines are computed from (18) through (20), as shown in Fig. 12 for three cases of the orientation angle. The radius of the curvature of the bending and the diameter of the pipe are set to be 95.25 and 73.3 mm, respectively, which are typical values for a 2.5-in feeder pipe. The \( z \)-orientation of the camera is set to be 10.5° to adjust the estimated angle to be zero at an initial orientation of the robot. The orientation angle is computed by averaging the slope along the edge points from \( A \) to \( B \) [see Fig. 12(a)], which is the integration of the derivative of the edge line divided by its length on the horizontal axis, i.e., the slope of the line that connects the end points \( A \) and \( B \). Fig. 13 shows a comparison of the actual angle versus the estimated angle. The estimated angle
shows linear characteristics with a gain of 1.088 and a standard deviation of 1.67°, which can be easily compensated for by multiplying the reciprocal of the gain. After a compensation, the standard deviation of the linearity is 0.27°, which is sufficient enough for a feeder pipe inspection.

B. Image Processing Algorithm

Since the orientation angle measurement is based on the camera image, and the image is distorted caused by a lenz distortion and misalignment of the imaging device, the image needs calibration to obtain a more exact measurement result. A type of self-calibration method proposed by Zhang [22] is used for computing the calibration parameters. Then, the results are as follows: the focal length is \( \alpha, \beta = [419.72, 404.31] \), the principal point is \( [u_0, v_0] = [186.97, 92.48] \), and the distortion coefficient is \( [k_1, k_2] = [-0.57, 0.27] \). Fig. 14(a) shows the original camera image without the calibration procedure. The straight line becomes distorted to become a curved line, which results in a measurement error. However, after the calibration a corrected image can be obtained, as shown in Fig. 14(b).

An image processing algorithm is developed to extract the orientation angle of the pipe from the camera image. The procedure is as follows:

1) capture the source image;
2) convert it to a gray image;
3) undistort the image based on the camera calibration result;
4) smoothing and thresholding the image;
5) applying a dilation to remove the small holes;
6) extract the edge line using the Canny edge detection algorithm [23];
7) extract the slope of the edges based on the Hough transform [24];
8) compute the moving average value of the angle of the lines;
9) the result is the orientation angle.

Since there is a possibility that many of the lines are not the edges of a pipe, a type of filtering algorithm is required. Since the orientation angle is assumed to be smaller than 90°, and most of the pipe lines would almost be vertical lines. Therefore, the lines with the \( \theta \) value within \( \pm 10^\circ \) and \( 180 \pm 10^\circ \) are filtered out. After filtering out of the noise lines, eight candidate lines are used for the pipe edge computation. Based on these lines, a unique line that represents a pipe edge is computed by averaging the computed slope angle. A moving average method with 20 data points is used for the computation.

Fig. 15(a) and (b) shows the camera images and the line detection results, respectively, at the zero orientation angle. The edge line is similar to the analysis done in Section III-A. There are many lines in the resultant image from the Hough transformation that are mainly caused by the curved section of the pipe and the noise within the image. The averaging result of the sensing is almost zero where the normal deviation of the measurement is below 2.0°. Fig. 15(c) and (d) shows the camera images and the line detection results, respectively, when the orientation angle is 40°. The pipe is slanted and the orientation angle can be computed from the image by measuring the angle between the vertical axis and the edge lines. This orientation angle can be used to adjust the robot’s attitude so that it follows the exact outer circumference of a curved feeder pipe.

C. Automatic Tracking Control

An automatic pipe tracking control algorithm is developed based on the orientation angle obtained from Section III-B. Since the motion of the robot is discrete, i.e., the robot moves 6.25 mm and rotates 7.6° for one step. A repeated application of the movement and rotation commands determines the robot’s position. The possible commands of the robot are move forward and backward, rotate in the cw and ccw directions, and stop.

In the automatic tracking mode, the robot moves and rotates at a constant speed that is prescribed by the operator, and the amount of the rotation is automatically determined by the control algorithm. The algorithm is a simple switching controller with allowable error band, i.e., if the absolute value of the orientation error is within the error band, the control objective is considered to be accomplished. If the orientation error is larger than the upper limit of the error band, the translation movement is stopped, and the rotation actuator is driven in negative direction to reduce the error, and vice versa. If the error band is too small, the control algorithm stops the movement motion too frequently to adjust the orientation angle, which lowers the speed of the translation movement. If the value is too high, the steady state error of the orientation angle control becomes high. A tradeoff is required to determine a suitable value.
IV. EXPERIMENTAL SETUP

Fig. 16 shows a picture of a mobile robot attached to a curved pipe. Table I shows the specifications of the robot. The robot’s bodies are made of aluminium to reduce its weight, and the pistons and joints are made of steel to attain enough mechanical roughness. The piston diameters of the pneumatic actuators for the translation actuator and rotation actuator are 6 mm. That of the grippers are 8 mm to increase their gripping force. When the air pressure is 58.9 N/cm², the piston force within the gripper is 29.4 N. A flexible 3.2 mm pneumatic tube is used for connecting the controller and the robot. There are six pneumatic cylinders, two for each gripper and two for both the translation and rotation actuators.

A control system is developed, as shown in Fig. 17, and its block diagram is shown in Fig. 18. The two grippers and the translation actuator are controlled by three five port directional control valves each, and the rotation actuator is controlled by two five-port directional control valves. Therefore, five valves are used to control the robot. The valves are driven by using five MOSFETs. The switching sequence of the MOSFETs is controlled by using a DSP. Two small cameras are attached at the bottom side of the robot to measure the edge lines of the pipe. These images are transferred to the PC through an image capture board. After the orientation angle computation from the image processing algorithm, and control law computation, a control command like “Move,” “Rotate,” “Speed,” etc., is transferred to the DSP controller through the RS-232 communication port. This command data is decoded to generate a control sequence for each valve.

<table>
<thead>
<tr>
<th>Specifications of the Robot</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>350 g</td>
</tr>
<tr>
<td>Thickness of the robot</td>
<td>12 mm</td>
</tr>
<tr>
<td>Max. moving speed</td>
<td>14.2 mm/s</td>
</tr>
<tr>
<td>Max. rotating speed</td>
<td>13.8 deg/s</td>
</tr>
<tr>
<td>Moving resolution</td>
<td>6.25 mm/step</td>
</tr>
<tr>
<td>Rotating resolution</td>
<td>7.6 deg/step</td>
</tr>
<tr>
<td>Min. allowable pipe curvature</td>
<td>66 mm</td>
</tr>
</tbody>
</table>

V. RESULTS

The robot is installed with an initial orientation error of 40°. Then, the automatic tracking controller is activated to adjust the orientation angle while the robot is moving forward. The translation movement is controlled by a human operator. The experiment is performed for two error band values which are 5° and 2°. Fig. 19(a) shows the results of the offset orientation angle when the error band is 5° with a moving speed of 4.9 mm/s. After activating the controller, the robot rotates in the ccw (−1) direction because of the positive error of 40°, the corresponding rotation command is (−1) direction, as shown in Fig. 19(c). After 2.5 s, the rotation motion is stopped because the error is within the error band, and it moves forward. Note that zero rotation command means a forward movement of the robot. The initial error is reduced within 3 s. However, an average steady state error about −5° still exists, which is caused by the control scheme of the automatic tracking control. Once the orientation angle is within the error band, the controller assumes that the control objective is completed, and no control action is applied. Fig. 19(b) shows the standard deviation of the orientation angle measurement. While the robot is adjusting the orientation angle, the standard deviation increases which is caused by the vibration generated by the robot’s movement. Fig. 19(d) shows the
Fig. 19. Result of the offset orientation angle control when the error band is 5° indicating (a) the error of the angle control, (b) the standard deviation of angle measurement, (c) robot movement and rotation sequence at low speed (4.9 mm/s), (d) the error of the angle control, (e) the standard deviation of the angle measurement, and (f) robot movement and rotation sequence at high speed (12.4 mm/s).

results of the offset orientation angle when the moving speed is 12.4 mm/s. Since the speed is 2.5 times faster than the previous experiment. The settling time is reduced, but the amount is not exactly proportional to the speed because there are additional forward movement near 1.3 s, and there is a possibility of slip-page. Similar to the case of a low speed, an average offset error of about −5° still exists. While travelling along the pipe, the robot can slip that is caused by gravity and an impact-like motion generated by switching of the pneumatic forces. This creates an orientation error, which requires additional adjustments while the robot is travelling as observed at 3.7 s.

Fig. 20(a) shows the results of the offset orientation angle when the error band is 2° with a moving speed of 4.9 mm/s. The settling performance is similar to the case of the error band of 5°. However, the average offset error is reduced considerably. Due to the small error band, a switching between the cw (1) and ccw (−1) directions is repeated more frequently, as shown in Fig. 20(c), at the steady state, which means the orientation error is adjusted more frequently. A control action is only applied in the cw (1) direction, as shown in Fig. 20(c), which means that the offset angle is regulated near a lower bound of the error band. Fig. 20(d)–(e) shows the results of the offset orientation angle, standard deviation, and rotation command when the moving speed is 12.4 mm/s. The settling performance is improved while reducing the orientation error.

VI. CONCLUSION

This paper presented a mobile out-pipe inspection robot by using an inch-worm mechanism for a feeder pipe inspection in a PHWR. Design requirement of a feeder pipe inspection robot for a PHWR was provided. One of the major design requirements for the dimension of this robot was satisfied by using an inch-worm mechanism, and by embedding pneumatic actuators into the robot’s body frame. Detail working principles and mechanism descriptions were provided. A design and analysis method for a gripper actuator for a stable contact of the pipe and robot were presented, which are important for an inch-worm like mechanism. An automatic pipe tracking system by utilizing a machine vision technique was proposed to make the mobile robot follow the pipe automatically. A calibration technique for a sensor system to measure an orientation angle was investigated. The mechanism, the sensing system, and automatic pipe tracking algorithm were implemented and the applicability was verified. Although the developed robot is targeted for a feeder pipe inspection for a PHWR, it is directly applicable to other pipe inspection works.
REFERENCES


