A Multi-link In-pipe Inspection Robot Composed of Active and Passive Compliant Joints

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Abstract— AIRo-5.1 an in-pipe inspection robot comprised of two passive compliant joints and a single active compliant joint that is driven by a series elastic actuator (SEA) is presented in the course of this study. As an aid in pipeline maintenance, AIRo-5.1 controls joint angles and the torque of middle joints, to enable them to adapt to bend, branch, vertical pipes, and slippery surfaces. To sense the joint torques, an improved durable polyurethane rubber spring was installed. To smoothly pass through T-branches, the angle trajectory of middle joints was calculated based on the pipe geometry and thus, was interpolated using a cosine curve. Experiments to verify robot performance in bent and T-branch pipes, its joint angle and torque control was conducted.

I. INTRODUCTION

In most developed cities, pipeline maintenance poses one of the major critical issues faced by humans. The identification of the aging pipes, their replacement, it's cost and timeconsuming implications when constructed underground or placed in high buildings, contribute significantly to the challenges in pipeline maintenance. Although industrial cameras have been applied in such inaccessible narrow areas, there are still limitations in the use of these cameras in pipelines located at corners of buildings. Hence, there is a need for robotic in-pipe inspection that addresses these challenges in manual task collection.

Existing reports have shown that a multi-link-articulated structure (snake-like body) as the best choice considered for addressing bend and branch pipes [1]–[9], a major critical challenge in the use of robotics in pipeline inspections, can drastically reduce the robot size without losing the in-pipe mobility. In most existing works, there is almost no detailed report regarding the branch pipe adaptability, particularly in vertical T-branch of in-pipe robots.

In our previous work [10], AIRo, an in-pipe inspection robot with a snake-like body was proposed, which can rotate around the pipe axis using spherical wheels comprised of two heads and a tail [11]. Although composed only of passive elastic joints using torsional spring, AIRo-2.2 can pass through a T-branch in cases where there is a wall ahead of the robot and the pathway branches upward and downward against the travel direction. However, it was impossible in case there is no wall in front of the robot and the pathway branches upward directions.



Fig. 1. Overview of an in-pipe inspection robot: AIRo-5.1.

TABLE I SPECIFICATIONS OF AIRO-5.1

A denting along inner diameters	4 5 in alt
Adaptive pipe inner diameter	4-5 inch
Total length (when extended)	0.51 m
Total weight (without cable)	2.37 kg
Max. moving speed	0.08 m/s
Max. continuous traction force	202 N (20.6 kgf)
Peak traction force	808 N (82.4 kgf)
Max. continuous joint torque	3.76 Nm
Peak joint torque	15 Nm
Joint angular speed	13.6 rpm (1.43 rad/s)
Nominal voltage	DC 24 V
Communication	Controller Area Network (CAN)

Therefore, we propose an in-pipe inspection robot with two passive compliant joints and only a single active compliant middle joint (AIRo-5.1) to pass through bend, T-branch, and vertical pipes.

Our developed in-pipe inspection robot called AIRo-5.1 is shown in Fig. 1 and its specifications are listed in Table I. Although there are reported studies on the adaptation of inpipe robots to vertical T-branches [12]–[14], our proposed robot is superior in size (4-inch inner diameter), has the ability to revolve around the pipe axis, adapts to diameter changes and can increase the traction force in slippery pipes using joint torque control. This active clamping function enables a constant 202 N (20.6 kgf) traction force in pipes. Furthermore, in most existing studies on the adaptation to vertical T-branches, the inner corner of the T-branch is rounded like an edge fillet, which decreases difficulty.

In this paper, to smoothly pass through T-branches with sharp inner corners, a joint angle trajectory was calculated based on the pipe geometry. Experiments were then conducted in vertical bend and T-branch to verify the performance of AIRo-5.1 and its joint angle and torque controls.

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Fig. 2. CAD model of the in-pipe inspection robot AIRo-5.1.

II. DESIGN OF THE IN-PIPE INSPECTION ROBOT

The design of the AIRo-5.1 is based on our previous work [15], [16], where head and tail rolling units were added by joining them with torsional springs. However compact design with all-electric circuit boards embedded inside the robot's body was achieved and the total length was shorter. AIRo-5.1 has two major features as follows.

- Although AIRo-5.1 has fewer actuators than that of conventional in-pipe robots with branch pipe adaptability, almost the same adaptability to T-branches as that they have is achieved.
- 2) Instead of normal steel spring, a durable polyurethane rubber spring in shear direction is adopted to achieve a large working range against the deformation.

A. Mechanical design

Figure 2 shows the CAD model of AIRo-5.1, composed of four links, one active compliant middle joint, two passive compliant joints, three pairs of the drive wheel (Omniwheel), and two pairs of roll wheel (hemi-spherical wheel). Omni-wheel with Nitrile butadiene rubber (NBR) is specially designed to achieve durability and high friction. One of the easiest ways to enhance the robot's adaptability to branch pipes is by providing an active degree of freedom at each joint. However, this leads to an increase in size and weight and a complicated system. Thus, our idea is that the minimum number of an active joint for branch adaptations can only be one if other joint compliance and passivity are utilized.

Compared to AIRo-2.3, with a more traction force at the expense of the moving speed, the speed of motors used for the drive wheels is decreased by a ratio of 378:1, by combining the gear head and the spur gear reducer. However, the torque of the active middle joint is decreased by a ratio of 693:1 of the gear chain.

A 50 rubber spring polyurethane shore was installed at the middle joint for a series elastic actuation [17]–[23]. Although the shore stiffness of the rubber spring used in AIRo-5.1 is



Fig. 3. Measured torque vs angular displacement of the polyurethane Shore A 50 rubber spring.



Fig. 4. Polyurethane rubber spring used for AIRo-5.1 (ϕ 36 mm diameter and 10 mm thickness): (a) conventional polyurethane rubber spring, (b) destruction of the conventional polyurethane, (c) new polyurethane rubber spring using POLYMETAC technic.

the same as that of AIRo-2.3 [16], it is; however, stiffer because of its shortened axial length. From a simple test rig used in the previous work [16], a value of k = 0.431 Nm/deg was obtained, and as for the passive compliant joints, a metal torsional spring with 0.014 Nm/deg of stiffness was installed. Figure 3 plots the measured torque vs angular displacement of the polyurethane Shore A 50 rubber spring. Although the hysteresis was not negligible, the torque error was within 10 % in the range of ± 20 deg of the angular displacement.

Polyurethane is a widely known material with superior mechanical properties, however, has poor adhesion properties when in contact with metals. Therefore, in our study, a new technic called POLYMETAC that Mitsui Chemicals Co. Ltd., Tokyo, Japan possess was adopted, to allow for strong adhesion and bonding with various metals and resins that was not possible with other conventional methods. Figure 4 (a) depicts the conventional polyurethane rubber spring and its breakage is shown in Fig. 4 (b), and a new polyurethane rubber spring using POLYMETAC technic is shown in Fig. 4 (c).

As in AIRo-2.3, a potentiometer RDC506018A (Alps Electric Co. Ltd., Tokyo, Japan) was installed between the input motor and rubber spring to measure the input angle (potentiometer 1). Another potentiometer (RDC506018A) was also mounted to measure the angular displacement of the rubber spring (potentiometer 2). The joint torque was measured by multiplying the angular displacement obtained from the potentiometer 2 and the angular stiffness of the



Fig. 5. Control system of AIRo-5.1.

polyurethane rubber spring. To increase the torque resolution, the angular displacement of the rubber spring was increased 2.5 times at the shaft of the potentiometer 2 by using spur gears. The 32-bit microcontroller used for the robot has an A/D converter of 12-bit resolution (4096 steps), and the measurement range of the potentiometer RDC506018A was 320 deg (approximately 5.58 rad). Therefore, in theory, 0.03125 deg (approximately 0.00054 rad) can be measured at the minimum. The linearity error of the potentiometer is $\pm 2\%$ at maximum. However, this corresponds to 0.000625 deg, which is negligible.

B. Control system

The control system used for the AIRo-5.1 is illustrated in Fig. 5. Three kinds of our designed printed circuit board are used for the drive wheels, the active joint, and the roll wheels. The ARM 32-bit microcontroller (Cortex-M4) is used for motor control and communication with a computer, while the CAN-BUS protocol (Controller Area Network) was adopted to send a command and to get a signal from the robot. The target signals (moving forward and backward, rolling around the pipe axis, stop, joint angle, and joint torque) are sent through a computer and a signal and power source converter box (from the USB serial to CAN-BUS). This box has an AC/DC converter of the power source and an EMO (Emergency Off) button.

The speed of the drive wheels and the roll wheels can be changed by adjusting the duty ratio of PWM (Pulse-Width Modulation), and to change the rotational direction of the motors, and to amplify the voltage of the motors, BD6232HFP-TR (ROHM Co. Ltd., Kyoto, Japan) is used. The maximum output current of each circuit board is 2.0 A



Fig. 6. Kinematic model of the robot and the parameters used to calculate the joint angle trajectory

despite the small size.

The microcontroller reads signals of two potentiometers at the same time through a voltage divider (from 5 V to 3.3 V). This is because the nominal voltage of the potentiometer RDC506018A is 5 V but the VDD of the microcontroller (IC power-supply voltage) is 3.3 V. The angle and torque of the middle joint were both controlled by general PID-control law as mentioned in our previous work [16].

III. JOINT ANGLE CONTROL TO PASS THROUGH A T-BRANCH

The proposed in-pipe inspection robots have the ability to pass through even winding pipelines with only joint torque control if its pathway is continuous. This is due to the wheels in contact with the inner wall of the pipe, and in other words, the rotational direction of the middle joint can always be in the direction. However, in a branch section, the robot needs to change the bending direction of the middle joint to detach the wheels from the inner wall. Here, the trajectory of the middle joint is derived based on the geometry of the robot and the T-branch.

A. Middle joint angle obtained from the geometry of a Tbranch

Figure 6 shows the kinematic model of the robot (AIRo-5.1) in a xy-coordinate system. As we have already discussed in [10], the model resembles to that of a robot manipulator except for the floating base. L_i is each link length (constant). θ_i and ϕ_i mean the relative and absolute angles of each joint, respectively. p_i denote the position vector of each joint, which can be defined by

$$\boldsymbol{p_i} = \left[\begin{array}{cc} x_i & y_i \end{array} \right]^{\mathrm{T}} \tag{1}$$

The in-pipe robot is constrained by a T-branch as illustrated in Fig. 7. $D_{\rm p}$, W, $R_{\rm d}$, $R_{\rm r}$, $H_{\rm w}$, $H_{\rm j}$, and S denote the inner pipe diameter, the width between a pair of the drive wheels, the radius of the drive wheel, the radius of the hemispherical wheel, the space where the drive wheels can move



Fig. 7. Kinematic constraints of the robot while passing through a T-branch

within, the space where the drive shaft can move within, and the space where the drive wheels cannot enter, respectively. From the geometrical relationship, H_w , H_j , and S can be derived by

$$H_{\rm w} = \sqrt{D_{\rm p}^2 - W^2} \tag{2}$$

$$H_{\rm j} = H_{\rm w} - 2R_{\rm d} \tag{3}$$

$$S = \frac{D_{\rm p} - H_{\rm w}}{2} \tag{4}$$

 α and β denote an inner angle between the lines p_4p_3 and p_4p_5 and an inner angle between the lines p_3p_5 and p_3p_4 , respectively. The robot posture during the movement in a T-branch can be calculated using general inverse kinematics under constraints. From the law of cosines, α and β can be derived by

$$\alpha = \arccos \frac{L_3^2 + L_4^2 - (x_5 - x_3)^2 - (y_5 - y_3)^2}{2L_3L_4}$$
 (5)

$$\beta = \arccos \frac{L_3^2 - L_4^2 + (x_5 - x_3)^2 + (y_5 - y_3)^2}{2L_3\sqrt{(x_5 - x_3)^2 + (y_5 - y_3)^2}} \quad (6)$$

Therefore, θ_4 , ϕ_3 and ϕ_4 can be determined by

$$\theta_4 = \pi - \alpha \tag{7}$$

$$\phi_3 = \arctan \frac{y_5 - y_3}{x_5 - x_3} - \beta \tag{8}$$

$$\phi_4 = \phi_3 + \theta_4 \tag{9}$$

Subsequently, the angle of the middle joint can be obtained by

$$\phi_2 = \arctan \frac{y_3 - y_2}{\sqrt{L_3^2 - (y_3 - y_2)^2}} \tag{10}$$

$$\theta_3 = \phi_3 - \phi_2 \tag{11}$$

B. The division into phases of the movement in a T-branch

To define the trajectory of the middle joint, an ideal movement in a T-branch is assumed as shown in Fig. 8. At the end of phase 3, the robot posture becomes symmetric against the line which is 45 degrees angle from the pipe and passes through the corner of the T-branch, without necessarily calculating the middle joint angle after phase 3, and thus, the angle can be retrieved by reversing the phases



Fig. 8. The transition of the robot posture: (a) phase 1, (b) phase 2, (c) phase 3, and (d) symmetricity of the robot in a T-branch

backward (from phase 3 to phase 1). More detail about each phase of the movement is explained as follows.

1) Phase 1 ($x_{3ini} \le x_3 \le 0$ and $x_4 \le s + H_w - R_d$): In phase 1, it is assumed that p_3 moves only horizontally at a constant speed and p_5 moves only vertically at the same speed of the p_1 . The input is given to be the angular speed of the middle joint wheel at constant speed ($\dot{\psi}_{x3}$). The xcoordinate of the middle joint and y-coordinate of the head roll wheel can be obtained from the following equation,

$$x_3 = x_{3\text{ini}} + d_3$$
 (12)

$$y_5 = y_{5ini} + d_3$$
 (13)

$$d_3 = R_{\rm d}\psi_{x3}t\tag{14}$$

where d_3 , x_{3ini} , x_{5ini} , ψ_{x3} , and t denote the moving distance of the wheel 3, the initial x-coordinate of the middle joint, the initial y-coordinate of the head roll wheel, the rotational angle of the middle joint wheel, and time, respectively.

Both of the drive wheel (p_3) and the roll wheel (p_5) keep contact with the inner wall of the pipe, thus, y_3 and x_5 are constrained by

$$y_3 = -S - R_d \tag{15}$$

$$x_5 = R_{\rm r} \tag{16}$$

2) Phase 2 ($0 \le x_3 \le S$): In a similar way as phase 1, in phase 2, it is assumed that p_3 moves only horizontally at a constant speed and p_4 and p_5 moves only vertically. The drive wheel (p_3) and the roll wheel (p_5) also keep contact with the inner wall of the pipe. However, unlike the phase 1, the drive wheel (p_4) keep contact with the inner wall and the speed of p_4 and p_5 are not constant. Therefore, y_3 and x_5 maintain the constraints as in (15) and (16). In addition to them, x_4 is constrained by

$$x_4 = S + H_w - R_d \tag{17}$$

3) Phase 3 $(0 \le \psi_{x3} \le \pi/4)$: In phase 3, except that p_3 traces an arc around the inner edge of the T-branch

TABLE II Simulation parameters



Fig. 9. The simulated trajectory of the middle joint angle (θ_3) relative to the moving distance of the wheel 3 (d_3)

 $(\begin{bmatrix} S & -S \end{bmatrix}^{T})$, p_4 and p_5 moves only vertically in the same manner as phase 2. Hence, the input is given by

$$x_3 = S + R_d \sin \psi_{x3} t \tag{18}$$

$$y_3 = -S - R_d \cos \psi_{x3} t \tag{19}$$

C. Simulation

The simulation runs from the robot posture that the wheel 4 (p_4) starts to float, and the middle joint also starts to rotate. Therefore, x_{3ini} and x_{5ini} can be given by

$$x_{\rm 3ini} = -\sqrt{L_3^2 - H_j^2}$$
(20)

$$y_{5\text{ini}} = \sqrt{L_4^2 - R_r^2 - D_p + S + R_d}$$
 (21)

Table II lists the parameters used in the simulation. These values are obtained from the real robot and pipe dimensions. Since most general pipelines are standardized, dimensions are easily predicted.

Figure 9 plots the simulation results of θ_3 relative to the moving distance of the wheel 3 ($d_3 = R_d \dot{\psi}_{x3} t$). The middle joint angle is given by the angular speed of the drive wheel. However, calculating the aforementioned kinematics in real-time is time-consuming and not realistic for implementation. Therefore, the cosine interpolation is adopted to define the trajectory function of the middle joint angle, which can be defined by

$$\theta_3 = -A\cos\frac{2\pi d_3}{d_{3\text{total}}} + B \tag{22}$$

where A, B, $d_{3\text{total}}$ denote amplitude and vertical shift of the cosine function, and the total moving distance of the wheel 3 during the movement in the T-branch, respectively. They can be given by

$$A = \frac{\theta_{3\text{max.}} - \theta_{3\text{min.}}}{2} \tag{23}$$

$$B = A + \theta_{3\min}.$$
 (24)

where $\theta_{3\text{max.}}$, $\theta_{3\text{min.}}$ denote the maximum and minimum values of θ_3 , respectively. From the simulation results, $\theta_{3\text{max.}} = 62.165 \text{ deg and } \theta_{3\text{min.}} = -18.406 \text{ deg}$, A = 40.2855 deg, B = 21.8795 deg, and $d_{3\text{total}} = 0.2737 \text{ m}$ are obtained.

IV. EXPERIMENT

To replicate the most severe situation, the adaptabilities in vertical bend and vertical T-branch were tested. Straight transparent 4-inch vinyl chloride, bend pipes, and opaque 4-inch vinyl chloride T-branch were used. There are two patterns of T-branches depending on the posture of the branch pipe. One is the posture where there is a wall ahead of the robot and the pathway branches are upward and downward against the travel direction (case 1). Another is the one where there is no wall in front of the robot and the pathway branches are in upward and forward directions (case 2). Case 2 is considered one of the hardest situations faced by engineers.

A. Experimental setup

1) Actual joint angle calculation: For the middle joint, its rotation is completely constrained by a pipe, and thus, the rubber spring may deform depending on the joint torque. The motor can, therefore, rotate further even after the robot touches the inner wall of the pipes. The actual middle joint can, therefore, be measured by the margin between the input joint angle and the deformation angle of the rubber spring.

$$\theta_3 = \theta_{\rm p1} - \theta_{\rm p2} \tag{25}$$

where θ_{p1} and θ_{p2} denote the middle joint angle of the input side and the deformation angle of the rubber spring, respectively. This structure corresponds to a differential elastic actuator [24], [25].

2) Actual cosine trajectory of the middle joint to pass through T-branches: From equation (22), angular frequency of the cosine function (ω) is given as

$$\omega = \frac{2\pi R_{\rm d} \dot{\psi}_{x3}}{d_{\rm 3total}} \tag{26}$$

From Table I, $R_d \dot{\psi}_{x3} = 0.08$ m/s, thus, $\omega = 0.91$ rad/s is obtained. The target angle of the cosine function in equation (22) was given by this angular frequency and time.

B. Experimental results

1) Vertical bend pipe (verification of the designed active compliant joint): Figure 10 shows the experimental results in a vertical bend pipe. As the robot moves up the horizontal straight pipe through the vertical bend, it returns to the original vertical straight pipe through the same pathway. During this movement, slippage happened sometimes if the joint torque (τ) is < 1 Nm. Therefore, τ was controlled to keep the constant middle joint torque to be equal to 1 Nm ($\tau = 1$ Nm). If the joint torque is not implemented, there is a need for the operator to change the joint angle manually. However, in our case, the joint angle is automatically adjusted according to the bend pipe shape as long as the joint torque control is



Fig. 10. Video cutouts of the experiment in a vertical bend pipe (from a horizontal straight pipe to a vertical straight pipe via a bend)



Fig. 11. Measured middle joint angle (θ_3) and middle joint torque (τ) with respect to time (t) while the robot moves up the horizontal straight pipe through the vertical bend and returns to the original vertical straight pipe through the same pathway.

working. This can be considered as a constant load spring pressing the drive wheels against the pipe wall.

Figure 11 plots the measured middle joint angle θ_3 and joint torque τ with respect to the time when the robot passes through the vertical bend pipe. According to the simulation result, $\theta_{3\min} = -18.406$ deg when the robot is in a straight pipe. However, the real middle joint angle became approximately -20 deg because of slight mechanical errors and tiny deformation of the Omni-wheels.

From the measured results, it was confirmed that the joint torque was controlled constantly in the straight section. When the robot encounters the bend section, the torque value increased instantaneously since the joint is bent by the external force from the pipe wall. On the other hand, the torque decreased when the robot moves out from the bend section, and it was also observed that the joint angle varied automatically according to the pipe shape.

2) Vertical T-branch (verification of the performance of our proposed in-pipe robot): Figures 12 and 13 depict the experimental results in vertical T-branches (both of cases 1 and 2). In both cases, the robot successfully travels through vertical T-branches.

In case 1, the robot was found to have fallen after its front half enters the vertical straight pipe, and in case 2, it was found idling for a while after its front had entered the vertical



Fig. 12. Video cutouts of the experiment in a vertical T-branch (case 1)



Fig. 13. Video cutouts of the experiment in a vertical T-branch (case 2)

straight pipe, due to the inability of the middle drive wheel to touch the inner wall of the pipe. These phenomena imply that the real movement was faster than expected since the front passive compliant joint pushed the whole body forward. However, since the cosine algorithm catches up gradually, the wheel touched the wall and the robot moved upward without slippage.

Figure 14 plots the measured middle joint angle θ_3 with respect to the time when the robot passes through the vertical T-branch (case 1). It was observed that the joint angle traced the simulated cosine curve although it had small errors. AIRo-5.1 could pass through both T-branches in cases 1 and 2 using only one middle active joint with cosine trajectory and other passive spring compliant joints.

V. CONCLUSIONS AND FUTURE WORK

In this study, we developed a multi-link in-pipe inspection robot combining active and passive compliant joints. Grip performance of the Omni-wheels, communication system, total size, and durability of the polyurethane rubber spring



Fig. 14. Measured middle joint angle (θ_3) with respect to time (t) while the robot passes through a vertical T-branch section (case 1)

are all improved compared to our previous work [16]. Traveling through vertical bend pipes without manual joint angle control was achieved due to the joint torque control. Furthermore, an ideal trajectory of the middle joint angle was simulated based on the geometry of the T-branch pipe, this trajectory was interpolated using cosine curves to make the target command easy. Although timing that starts to give the target trajectory has not been defined yet, the vertical T-branch adaptation was achieved. The joint torque can be also limited to avoid the breakage of the robot during the travel in T-branches. AIRo-5.1 is aimed at a completed adaptation to the vertical T-branch that previous studies are yet to record success on.

We are still facing some challenges that have not been solved. First, in the area of pipelines, where there are critical barriers that AIRo-5.1 cannot negotiate. For example, a threedimensionally winded bend pipe is the most difficult, where two bend pipes are connected without a straight section and its pathway is not on a single plane. This can be seen in gas and water pipelines sometimes. Second, due to difficulty in planning replacement task of pipes without the location information even if the operator finds a problem through the use of head camera, an identification of the robot position in pipelines is necessary. Third, experiments in longer pipeline environments should be conducted. A number of the bend and branch and total distance that the robot can complete is not clarified yet. We will examine those challenges under collaboration with cooperative companies in the future.

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