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An In-pipe Robot with Multi-axial Differential Gear Mechanism

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Abstract— **This paper presents a mechanism for an in-pipe robot, called MRINSPECT VI (Multifunctional Robotic crawler for In-pipe inspection VI), which is under development for the inspection of gas pipelines with 150mm inside diameter. The mechanism is composed of multi-axial differential gear mechanism, wall pressing one, and driven by single motor. It is designed to adapt to the varying inside geometries of pipelines such as elbows by modulating the velocities of active wheels mechanically without any control effort. In this paper, the design features of the mechanism are detailed and its effectiveness is experimentally validated.**

I. Introduction

Pipelines are fundamental elements in industrial facilities used for transporting gas, oils and fluids. Since they are usually installed under the ground or inside buildings, it allows only limited access, though it is necessary to be periodically inspected and maintained to ensure their safety and integrity. Moreover, we need to localize the pipelines to detect defects or damages, and repair to reduce the expense for further maintenance activities. In general, inside the pipeline is very much narrow with complicated geometrical structures and thus, in-pipe robots with excellent three-dimensional mobility and high adaptability to the environmental conditions are required to enhance the accessibility to the pipelines.

Up to now, a number of in-pipe robots have been reported [1-11]. Among them, the combination of wheel and a wall-press method is proven to provide outstanding mobility of the robots. As a typical example, Yi et al. developed the robot has three active wheels and mechanical clutch system for rescue. It can adjust its height depending on the change of the pipelines along the radial direction [12-13]. Lim and Ohki developed a robot with two modules and an active joint [14]. It could generate adhesion force by using a DC motor. In addition, the active joint was controlled by RC servo motor. Choi et.al designed a mechanism for generating adhesion force based on magnetic forces [15].

MRINSPECT is the in-pipe robot series still under development in our group. MRINSPECT I~V can minimize the difference of the pressing force among the wheels due to the changes of the pipe diameter by employing spring-link mechanism. MRINSPECT II and III can select the direction of steering in a branch using steering module operated by the Double Active Universal Joint [16, 17]. MRINSPECT IV can steer and drive simultaneously by using three active differential driving modules [19-20]. It allows the independent control of each driving wheel. MRINSEPCT V has the mechanical structure similar to that of MRINSPECT IV, but contains improved steering system by introducing a clutch-based driving mechanism. MRINSPECT V can change its driving force flexibly according to the pipeline configurations such as horizontal, vertical pipelines [21-23].

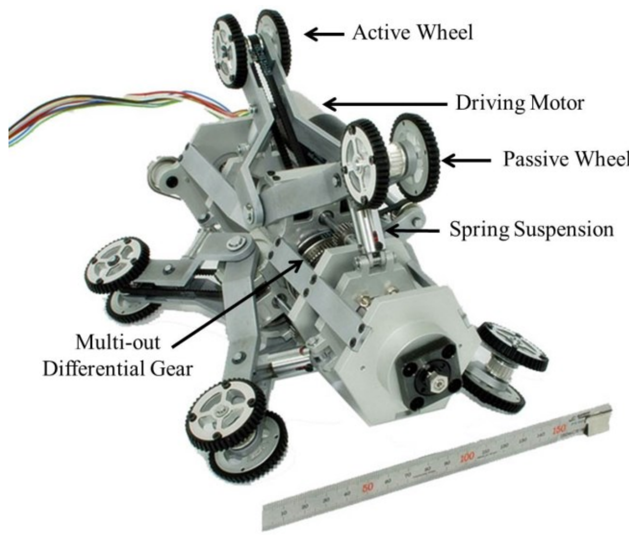

Figure 1. MRINSPECT VI

MRINSPECT VI presented in this paper is the sixth model of the MRINSPECT series, which is designed for 150mm gas pipeline inspection. The concept of speed modulation and mechanism including the power transmission are explained in details. In addition, the prototype of MRINSPECT VI is manufactured and its effectiveness is experimentally validated.

II. Overviews of MRINSPECT VI

MRINSPECT VI consists of three active wheels, three passive wheels, linkages and differential gear mechanism. As shown in Fig.1, the robot has a radially symmetric structure. Each passive and active wheel is surrounded by the robot body frame at 120 degree apart circumferentially. In addition, each wheel is connected to the spring-link mechanism to generate pressing forces to the pipeline wall. The initial position of the wheels can be adjusted simultaneously by using a ball-screw. Moreover, each wheel is able to move independently by using an individual spring attached to each wheel and ball-screw slider as depicted in Fig.2

Comparing with previous robots, the major improvement of MRINSPECT VI is that the robot can mechanically modulate the speeds of individual active wheels without any

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control effort. It is enabled by using a novel multi-axial differential gear mechanism, which allows each wheel to have different velocity automatically depending on the friction force acting on each wheel. In reality, if the speeds of the active wheels constrained by the wall are not accurately modulated, the robot tends to experience excessive forces due to frictions. It may consume unnecessary energy on traveling, or cause unrecoverable damage to the robot in the end. The modulation of the speeds of active wheels is an extremely important feature of in-pipe robots moving inside the pipelines with friction forces by pressing the wall, which is realized in MRINSPECT VI.

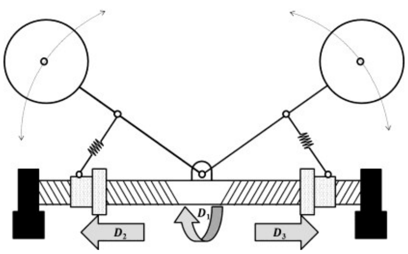


Figure 2. Ball-screw slider mechanism

III. Mechanism of MRINSPECT VI

The mechanism of the proposed robot consists of two major parts, that is, wall-pressing mechanism and multi axial differential gear mechanism.

A. Wall pressing mechanism

As illustrated in Fig.2, the wall pressing mechanism consists of a ball-screw, springs, and linkages. The spring-link mechanism is an independent suspension system attached to each wheel. The wall pressing mechanism adjusts initial position of front and rear wheels using ball-screw. Furthermore, each wheel can adapt to various pipeline conditions using the spring attached between each wheel and ball-screw sliders. The mechanism generates wall pressing force by controlling the compressed distance of the spring. The distance is controlled by using a ball screw and the link mechanism as shown in Fig.2. In this figure, the ball-screw provides the same compression distance through both-hands screw thread. The displacement of the left and right sliders that is, of D_2 and D_3 can be adjusted by rotating the ball screw to the direction of D_1. Each slide moves the same distance to the two opposite directions. Moreover, the input displacement is transported to the spring mechanism through the attached link mechanism. As shown Figs.3 and 4, the design is advantageous in overcoming the obstacle and steering in curved pipes.

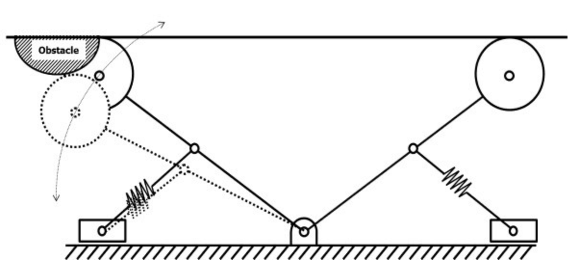


Figure 3. Wall pressing mechanism

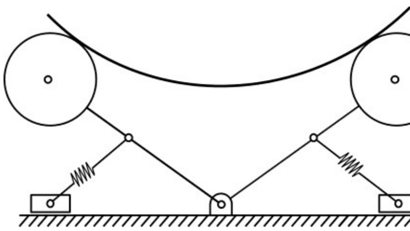


Figure 4.Wall pressing mechanism in curved pipeline

B. Multi Axial Differential Gear Mechanism

The multi axial differential gear mechanism is a novel feature of MRINSPECT VI. As depicted in Fig. 5, the input pulley from the motor spins the multi axial differential gear and the power is distributed to each drive wheel via output pinions, bevel gears and high torque timing belts.

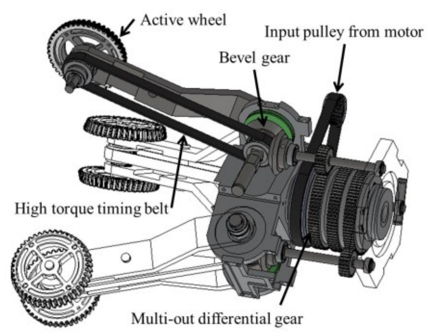


Figure 5. Power transmission of MRINSPECT VI

As shown in Fig.6, the multi axial differential gear mechanism is single input and multiple output transmission mechanism, that is, triple outputs in this paper. It can be considered as three dimensional version of the differential drive mechanism for automobiles [24]. Details of the first differential part and the second differential one are given in Figs. 7 and 8.

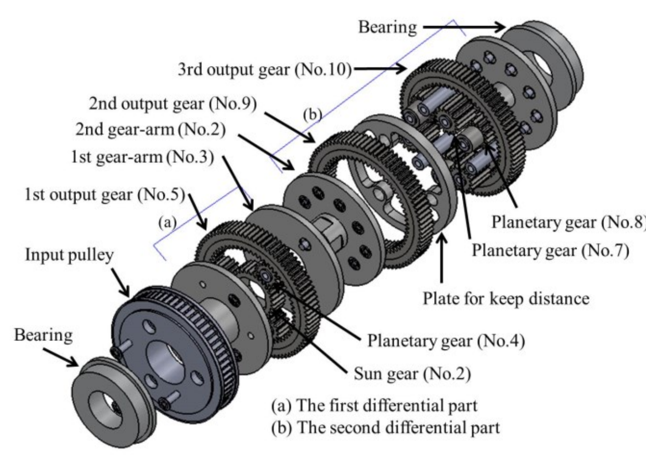


Figure 6. Exploded view of multi axial differential gear mechanism

As depicted in Figs.6, 7 and 8, the driving force generated from the driving motor is delivered to the multi-axial differential gear mechanism via the input pulley. The actuator spins the first gear arm because it is attached to the pulley and three small planetary gears are connected to the first gear arm. Each planetary gear is not fixed with respect to the gear arm and they are in between the sun gear and the output gears. In addition, the output gear is not fixed so that it can rotate freely.

Depending on the external load of the first output gear (No.5), the sun gear (No.2) and the first output gear has the function of differential. When the robot travels in straight pipelines, these two gears rotate in the same direction with exactly the same speed. Thus, for straight motion of the robot, there is no relative motion between the planetary gear (No.4) and the first output gear and the sun gear. The sun gear is attached the second gear arm which is the input axis to the second part as shown in Fig.8. The sun gear (No.2), the second gear arm and the third gear plate are mechanically connected and thus represented as No.2 in the paper. The second and the third output gear in the second part have the function of differential through the planetary gear though the active wheels may have different contact positions. Thus, all three output gears have the function of differential.

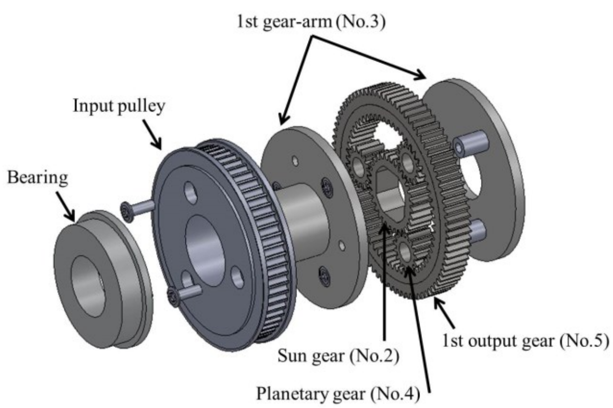


Figure 7. Details of the first differentail part

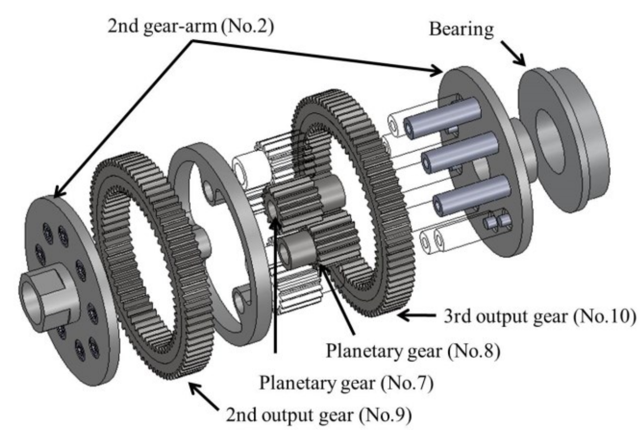


Figure 8. Details of the second differentail part

If the robot moves in straight pipelines, all three output gears will have the same directions and angular velocities such that the relative angular velocities of all gears are zero. On the other hand, in curved pipelines the wheel velocities need be different depending on the position of contact with the wall because they have different distances of travel. The proposed mechanism modulates all the gears with different relative angular velocities with inner motions and, all three outputs on the output gears can have corresponding angular velocities.

In order to verify the performance of the proposed mechanism, we derive the angular velocity relations by using the principle of superposition as follows.

$$\omega_5 = \omega_3 + \left(\frac{N_4}{N_5}\right)\left(-\frac{N_2}{N_4}\right)\omega_{\frac{2}{3}} \quad (1)$$

$$\omega_9 = \omega_2 + \left(\frac{N_7}{N_9}\right)\omega_{\frac{7}{2}} \quad (2)$$

$$\omega_{10} = \omega_2 + \left(\frac{N_8}{N_{10}}\right)\left(-\omega_{\frac{7}{2}}\right) \quad (3)$$

where, i represents the index of a gear, N_i is the number of tooth for the ith gear, respectively. ω_i denotes the angular velocity of the ith gear and gear arm. $\omega_{i/j}$ represents the angular velocity of the i gear relative to the jth one. To express the relative velocity of each inner gear, a matrix equation is built up as follows.

$$\begin{bmatrix}\omega_3\\ \omega_{2/3}\\ \omega_{7/2}\end{bmatrix} = \begin{bmatrix}1 & (N_4/N_5)(-N_2/N_4) & 0\\ 1 & 1 & (N_7/N_9)\\ 1 & 1 & -(N_8/N_{10})\end{bmatrix}^{-1}\begin{bmatrix}\omega_5\\ \omega_9\\ \omega_{10}\end{bmatrix} \quad (4)$$

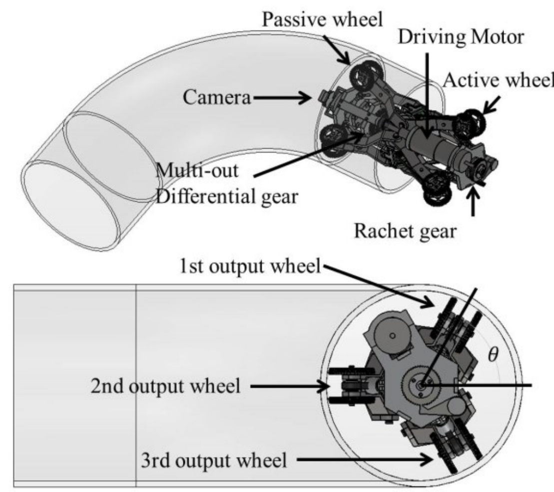


Figure 9. Assumption of experiment

Now, let us compute the velocity of the motor to realize the desired velocity of the robot, assuming that the robot enters the pipeline with the configuration shown in Fig.9. Here, θ is the rolling angle of the robot with respect to the center of the pipeline, C is the curvature of curved pipeline, D is the pipeline diameter, and v represents the velocity at the center of the robot. r denotes the radius of the active wheel. All the units of length are given in mm. Now, let us calculate the input angular velocity ω_3 of the motor to achieve the given robot velocity v by using Eqs.(5)~(9). In the first, the velocity of each wheel required for the robot velocity v is obtained as

$$v_{\text{wheel1}} = \frac{v\left(C + \frac{1}{2}D\cos\theta\right)}{C} = r\omega_5 \quad (5)$$

$$v_{\text{wheel2}} = \frac{v\left(C + \frac{1}{2}D\cos\left(\theta + \frac{2}{3}\pi\right)\right)}{C} = r\omega_9 \quad (6)$$

$$v_{\text{wheel3}} = \frac{v\left(C + D\cos\left(\theta + \frac{4}{3}\pi\right)\right)}{C} = r\omega_{10} \tag{7}$$

From Eqs.(1)~(3), we can have

$$\left(\frac{N_8N_9 + N_7N_{10}}{N_9N_{10}}\right)\omega_5 + \left(\frac{N_8N_2}{N_{10}N_5}\right)\omega_9 + \left(\frac{N_7N_2}{N_9N_5}\right)\omega_{10}$$

$$= \left(1 + \frac{N_2}{N_5}\right)\left(\frac{N_8N_9 + N_7N_{10}}{N_9N_{10}}\right)\omega_3 \tag{8}$$

Also, from Eqs.(5)~(8), we define correlation between ω_3 and v as follows.

$$\omega_3 = \frac{v}{rC}\frac{\left(\delta\alpha + \frac{N_8N_2}{N_{10}N_5}\beta + \frac{N_7N_2}{N_9N_5}\gamma\right)}{\left(1 + \frac{N_2}{N_5}\right)\delta} \tag{9}$$

where

$$\alpha = C + \frac{1}{2}D\cos\theta,\ \beta = C + \frac{1}{2}D\cos\left(\theta + \frac{2}{3}\pi\right),$$

$$\gamma = C + \frac{1}{2}D\cos\left(\theta + \frac{4}{3}\pi\right),\ \delta = \frac{N_8N_9 + N_7N_{10}}{N_9N_{10}}.$$

Assuming that the robot moves in the pipeline with three wheels apart 120 degrees circumferentially, all three wheels have different angular velocities. Under these computations, if θ equals zero, the first output wheel should rotate faster than the others. If θ equals to 180 degrees, the first output wheel should rotates slower than the others. For an example, we assume that the velocity of the robot is 5cm/s, and the velocities of the output gears and inner ones are computed by using MATLAB. As shown in Fig.10, we can find that the input velocity ω_3 should be changed corresponding to the velocities of inside gears. In addition, we can observe that the robot performs the differential drive successfully while θ changes.

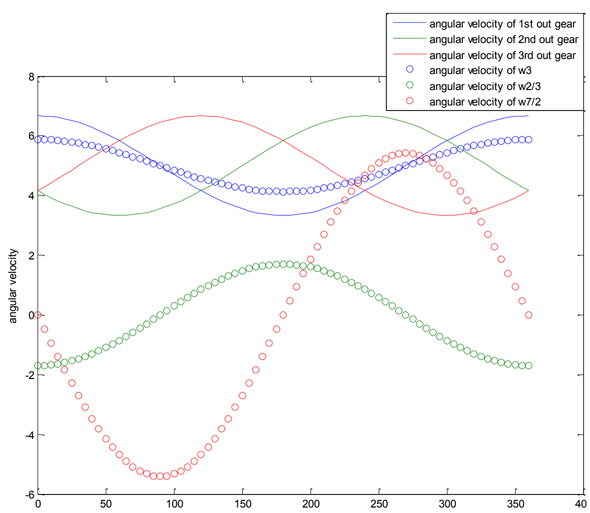


Figure 10. Each gear's angular velocity according to θ

IV. Experiments

To validate the performance of the robot, we manufactured a prototype of MRINSPECT VI and built up an indoor environment for testing with transparent pipelines of 150mm diameter. The environment includes a vertical pipe, horizontal pipes, and curved pipes. The curved pipe consists of a vertical elbow and a horizontal elbow. The curvature of each curved pipe is 225mm.

A. Outline of MRINSPECT VI

MRINSPECT VI is driven by a BLDC motor (MAXON EC- MAX) and its configuration is as explained in Fig.11. The robot is controlled by a main computer, which is located in the outside of the pipe. The external power and control signal is transmitted though the cables. The robot has a micro controller to control the BLDC motor. It is connected to main computer through CAN communication for transmission of the control signal and the sensor signal. In addition, the current velocity of each wheel and the velocity of the BLDC motor are sensed using incremental encoder. Each encoder data is transmitted to the main controller.

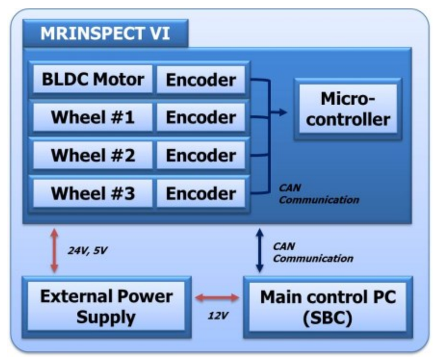


Figure 11. System configuration of MRINSPECT VI

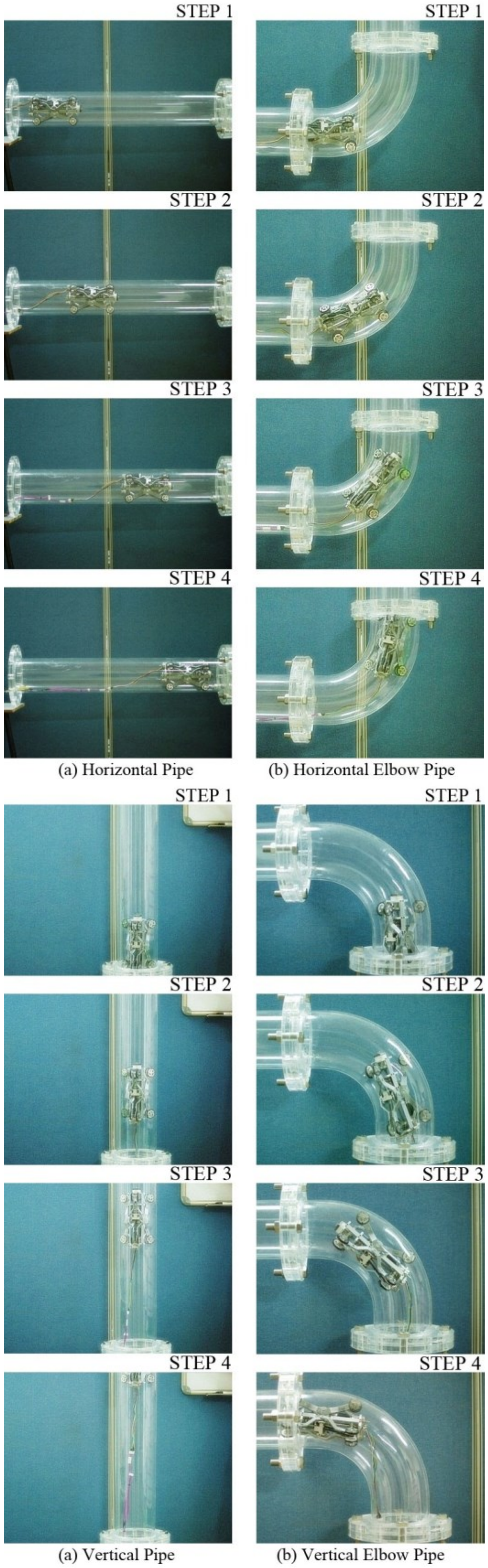
B. Experiments

Figs. 12(a) to (d) show the experimental procedures in actual pipelines. In the first, the robot moved in a horizontal pipe, as shown in Fig. 12(a). In the next, it entered into a horizontal elbow pipe as shown in Fig. 12(b). In the third, Fig. 12(c) shows the robot moved up a vertical pipeline. Finally, it entered into a vertical elbow pipe in Fig. 12(d).

The angular velocity of each active wheel is described to confirm performance of the multi-axial differential gear system as in Figs.13 and 14. As shown in these figures, the robot could automatically change the velocity of each wheel in the curved pipe and straight pipes for steering of the robot. When the robot traveled in the straight pipe, the velocity of each active wheel was similar to the other wheel as in Fig.13. Each active wheel had different friction force and different moving path in curved pipeline. In these reason, the velocity of each active wheel was different as shown in Fig.14.

V. Conclusions

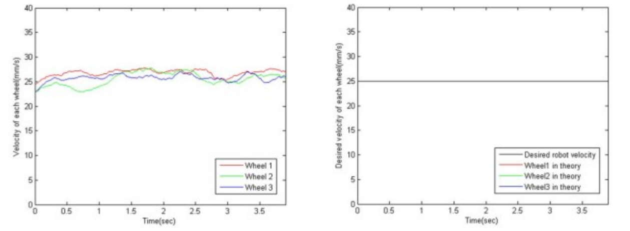
In this study, we proposed a robot, named MRINSPECT VI for in-pipe inspection using a multi-axial differential gear mechanism. The proposed robot has the ability to travel curved pipelines without any additional control effort. In addition, an actual test in various pipe elements confirmed the effectiveness the proposed robot. As shown in the experiment results, the proposed differential driving system has high adaptability to curved pipelines. Furthermore, the robot is able to adapt to the arbitrarily curved pipelines.



(a) Horizontal Pipe (b) Horizontal Elbow Pipe

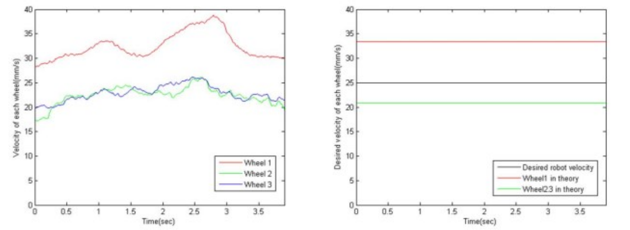
(a) Vertical Pipe (b) Vertical Elbow Pipe

Figure 12. Experiments of the proposed in-pipe robot



(a) Velocity of each wheel (b) Theoretical velocity of each wheel

Figure 13. Velocity of each wheel in straight pipe



(a) Velocity of each wheel (b) Theoretical velocity of each wheel

Figure 14. Velocity of each wheel in curved pipe

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