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An In-Pipe Inspection Robot with Permanent Magnets and Omnidirectional Wheels: Design and Implementation

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Abstract: This paper aims to present the design and prototype of an inspection robot that can perform both horizontal and vertical locomotion in ferromagnetic pipelines. The proposed robot applies to a range from 5-inch (127 mm) diameter pipes to flat plates. The train-like robot is mainly composed of three sealed modules with omnidirectional driving wheels for longitudinal and transverse movements. Permanent magnets were designed to provide sufficient magnetic adhesion between the robot and the ferromagnetic surface of the pipes. The internal condition of the pipe can be monitored visually through cameras and sensors. Specific experimental conditions have been carried out to validate the robot's capabilities, including maximum speed, payload capacity, and vertical climbing distance. The experimental results also show that the robot is capable of passing through a straight pipe and elbow fitting in both upward and downward directions.

Keywords: in-pipe robot; pipe inspection; magnetic robot; train-like robot

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1. Introduction

Ferromagnetic pipelines are the primary means of transporting gas, oil, and other liquids, especially in the industrial sector. Pipeline maintenance and inspection are necessary to ensure proper functioning conditions. The manual assessment of the internal conditions of small diameter pipes by workers and/or in hazardous conditions is unfeasible. To prevent the exposure of operators to these conditions, in-pipe inspection robots could potentially replace the human-conducted tasks.

In the literature, in-pipe inspection robots are categorized into five common systems based on robotic locomotion. First, wheeled robots [1–4] have simple structural designs. These systems typically have good maneuverability and can be controlled easily. Wheeled systems are also extensively combined with other locomotion types [5]. Second, inchworm-like robots [6–10] can perform both horizontal and vertical locomotion, but still have difficulties in traveling along a curved pipe. Third, wall-pressed robots [11–16] are the most popular system used for the application of in-pipe inspection robots [5]. These systems require a frictional force between the leg or wheel of the robot and the inner wall of the pipe to travel along the pipe. These robots have difficulties in passing through elbow and tee connectors. Due to the structure of the wall-pressed robots, the range of accessible pipe diameters is restricted. Fourth, snake-like or train-like robots [17–22] are modular

robots that have a strong adaptability to complex configurations of pipelines and fittings. However, due to the modular design, these robots may experience unreliable motion control problems. Fifth, magnetic systems [23–27] can be applied in vertical, horizontal, and curved ferromagnetic pipes. These systems are also applicable to a wide range of pipe sizes. Kawaguchi et al. [27] designed a robot to move in vertical pipes using 2 magnet wheels. The robot can move in both longitudinal and lateral directions by rotating the wheels, but it is difficult to control the robot to move steadily in the lateral direction.

From the literature review, our proposed in-pipe robot is inspirationally designed based on a combination of the easy-to-control characteristics of wheeled robots, the flexibility characteristics of snake-like or train-like robots, and the advantageous ability of a magnetic system that can be applied to the various sizes of ferromagnetic pipes. In this article, we present the design and implementation of an in-pipe inspection robot that is applicable to a wide range of ferromagnetic pipe sizes from 5-inch (127 mm) diameter pipes to flat plates. The proposed robot can travel in any direction and pass through 90-degree elbow fittings. The robot can also provide real-time visual feedback and operate in waterlogged conditions.

2. Design Principle

2.1. Mechanical Design and Materials

In order for the proposed in-pipe inspection robot to move inside the 5-inch (127 mm) diameter pipe, the robot was designed to be 110 mm wide, 99 mm tall, and 450 mm long. Figure 1 shows the 3D CAD model of the robot, which is mainly composed of three modules in the manner of a train with front, middle, and rear modules. The front and rear modules consist of motor-driven CCTV cameras, a flashlight for dark environments, and a powertrain system for forward–backward (longitudinal) motion. The middle module consists of electronic components and a powertrain system for transverse motions. The sealed modules provide the water-resistant ability of the robot. As shown in Figure 2, each module is connected by a passive linkage mechanism that allows the module to rotate freely. Moreover, the passive links ensure that the robot is flexible enough to move around curves and that all modules adhere to the surface all of the time. Rectangular magnets of 40 mm × 20 mm × 10 mm Neodymium (NdFeB)-N35 are used to provide the adhesive force for the robot. Four permanent magnets are located underneath the front and rear module and three magnets under the middle module.

According to the analysis in the literature, it is apparent that robots with magnetic adhesion mechanisms are competent in exploring pipelines of various sizes and configurations. However, these robots may experience difficulty in passing through curved pipes because the robots are unable to perform transverse movement around the pipeline's curve. To solve the problem of lateral maneuverability, omnidirectional wheels were introduced to assist the permanent magnets. The omnidirectional robot wheels allow longitudinal and lateral motions. In addition, the wheels improve the maneuverability of the robot by maintaining the optimal distance between the robot and the inner wall of the pipe to stabilize the adhesive force. The driving wheels and supporting wheels are attached to the front and rear modules. Two driving wheels are attached to the middle module for the purpose of transverse movement. In the proposed robot, the omnidirectional wheels are made from aluminum with a diameter of 60 mm. As presented in Figure 3, eighteen small rubber wheels (1.2 cm diameter) are plugged into each omnidirectional wheel. The rubber wheels are mounted perpendicularly to the rotational axis of the omnidirectional wheel.

Figure 1. The 3D CAD model of the proposed in-pipe inspection robot.

Figure 2. The side view of the robot configuration with the passive linkage mechanisms.

Figure 3. The 3D CAD design of the omnidirectional wheel.

2.2. Shim Plate

Figure 4a shows the size of the robot (110 mm wide and 99 mm tall) relative to the ferromagnetic pipes of different sizes (5 to 9-inch or 127 to 228 mm diameters). When the size of the pipe changes, the distance between the magnet and the inner wall of the pipe also changes. For the magnetic adhesive force to have the desired value for different pipe diameters, a shim plate with a specific thickness is required to be mounted on the front and rear modules, as shown in Figure 4b. The suitable thickness of the shim plate for the various pipe sizes can be calculated from Equations (1) and (2) based on the parameters shown in Figure 5.

$$w = r_t - \sqrt{r_t^2 - d_c^2} \quad (1)$$

$$c = w + u - h_m - g_h \quad (2)$$

where c is the thickness of the shim plate, r_t is the radius of the pipe, d_c is the distance between the center of the robot and the center of the wheel (45 mm), u is the distance between the base of the robot wheel and the lowest end of the robot body (17.4 mm), w is the distance between the base of the robot wheel and the inner wall of the pipe below the robot, h_m is the thickness of the permanent magnet (13.5 mm), and g_h is the distance between the lowest end of the magnet and the inner wall of the pipe below the robot.

Figure 4. (a) The size of the robot relative to the pipes of different sizes. (b) The shim plate installation.

Figure 5. The parameters for the shim plate thickness calculation.

After calculation, the suitable thickness of the shim plate for various pipe sizes is presented in Table 1. To keep the distance between the lowest end of the magnet and the inner wall of the pipe below the robot (g_h) equal to 4 mm (see Section 2.4), a 5-inch (127 mm) diameter pipe requires an 18-mm shim plate. Table 1 also shows that larger pipe diameters require thinner shim plates to satisfy the requirement of the adhesive force.

Table 1. The suitable thickness of the shim plate for various pipe sizes.

Pipe Diameter (in)	5	6	7	8	9	10	11	Flat Plate
Shim Plate Thickness (mm)	18	14	12	10	9	8	7	1

2.3. Magnetic Adhesive System

We used the adhesive force of the permanent magnets for the vertical movement of the robot. In this subsection, the adhesive force of the permanent magnets is detailed and analyzed statically. According to [28], the magnetic force depends on the magnetic flux density (B), where the flux density is based on the distance between the magnet and the ferromagnetic object, the area of the magnetic pole (A_g), and the magnetic permeability of air or of a vacuum (μ_0), which is equal to $4\pi \times 10^{-7}$ H/m as presented in Equation (3).

$$F_{\text{magnet}} = \frac{B^2 A_g}{2\mu_0} \quad (3)$$

Figure 6 shows the simulation results of the magnetic flux distribution using Finite Element Method Magnetics (FEMM4.2). At the same distance between the magnet and the ferromagnetic objects, the results reveal that a higher magnetic flux distribution when the magnet is inside the pipe (Figure 6a) compared to that in the flat plate (Figure 6b). Due to the curvature of the pipe surface, the maximum magnetic flux distribution occurs at the edge of the magnet.

Figure 6. The 2D simulation results of the magnetic flux distribution: (a) The magnet in the ferromagnetic pipe; (b) the magnet on the ferromagnetic flat plate.

For vertical movement, the force analysis to prevent the robot from slipping is presented in Figure 7. The frictional forces at the driving wheels (F_{fric1} , F_{fric2} , F_{fric3} , and F_{fric4}) are related to the normal forces (N_1 , N_2 , N_3 , and N_4) where the normal forces depend on the adhesive force of the permanent magnets (F_{mag1} , F_{mag2} , and F_{mag3}). The relationship can be expressed as:

$$N_1 = \frac{d_1}{l_1} F_{mag1} \quad (4)$$

$$N_4 = \frac{d_2}{l_1} F_{mag3} \quad (5)$$

$$N_2 = N_3 = \frac{F_{mag2}}{2} \quad (6)$$

where d_1 , l_1 , d_2 , and l_2 are presented in Figure 7.

Figure 7. The free body diagram and static force analysis of the in-pipe inspection robot.

In order to prevent the robot from slipping or falling from a vertical surface, the magnetic adhesive forces are calculated from the formula for frictional force given by $F = \mu_s N$, where μ_s is the coefficient of static friction between the robot's wheel and the ferromagnetic surface. The sufficient frictional force can be obtained as follows:

$$F_{fric1} = \mu_s \frac{d_1}{l_1} F_{mag1} \quad (7)$$

$$F_{fric2} = \mu_s \frac{d_2}{l_2} F_{mag3} \quad (8)$$

$$F_{fric3} = F_{fric4} = \mu_s \frac{F_{mag2}}{2} \quad (9)$$

When the robot is in vertical motion, it is loaded by the robot's weight (G_{robot}) and the increment in the length of the control cable (G_{cable}). The gravitational force due to the control cable's weight can be expressed as:

$$G_{cable} = 9.8(A_m l + m_{slipring+connector}) \quad (10)$$

where A_m is the ratio of the weight of the control cable per unit length, l is the length of the control cable from the robot to the ground, and $m_{slipring+connector}$ is the mass of the slip ring and connector. Hence, the frictional force needed to oppose slipping or sliding along the contact surface is required to be greater than the loads of the robot and the control cable, which can be expressed as follows:

$$\mu_s \frac{d_1}{l_1} F_{mag1} + \mu_s \frac{d_2}{l_2} F_{mag3} \geq (G_{robot} + G_{cable}) \sin \theta \quad (11)$$

$$\mu_s F_{mag2} \geq G_{robot} \cos \theta \quad (12)$$

2.4. Motor Power

The calculation for the motor power of this proposed robot is based on the vertical mobility of the robot because this is the stage that the robot requires its maximum load capacity. While the robot is in vertical motion, the required driving force (F_{req}) for the robot is presented in the following equations:

$$F_{req} = F_{fric} + (G_{robot} + G_{cable}) \sin \theta + (m_{robot} + m_{cable})a \quad (13)$$

$$F_{fric} = \mu_{rolling} \left(\frac{d_1}{l_1} F_{mag1} + \frac{d_2}{l_2} F_{mag3} \right) \quad (14)$$

where m_{robot} and m_{cable} are the mass of the robot and cable, respectively, a is their acceleration, and $\mu_{rolling}$ is the coefficient of rolling friction when the wheel rolls over a ferromagnetic surface. In this study, the viscous frictional force was assumed to be zero as the robot travels linearly along the pipe and its travel velocity is relatively slow, so the viscous frictional force is very small compared to all other forces. The required motor power (P_{req}) can be obtained from:

$$P_{req} = F_{req} v_{robot} \quad (15)$$

where v_{robot} is the robot's travel velocity in the vertical direction. The proposed robot is equipped with two driving motors for forward-backward motion. Each motor is assembled in the front and rear modules. In this study, however, the motor power calculation was considered in the case of the total weight of the robot and related device loads on a single motor. Since some energy losses were not included in the calculation, such as the losses from the mechanical and electronic devices, a factor of safety (S_{fs}) of two was selected. Then, the required motor power was given by:

$$P_{motor} = P_{req} S_{fs} \quad (16)$$

For finding the proper gear ratios, the equations of the motor angular velocity (ω_{motor}) and the motor torque (τ_{motor}) are presented as follows:

$$\omega_{motor} = rt_{motor} \times rt_{robot} \times \frac{60v_{robot}}{2\pi r_w} \quad (17)$$

$$\tau_{motor} = \frac{P_{motor}}{\omega_{motor}} \quad (18)$$

where rt_{motor} and rt_{robot} are the gear ratios of the robot and the motor, respectively, and r_w is the radius of the robot's wheel.

To determine the proper power of the motor, the effect of the distance (between the permanent magnet and the curved surface of the pipe) on the magnetic force was investigated in the experimental study presented in Figure 8. First, the gravitational force was set to zero by the tensile tester machine so that it was not added into the magnetic force. The results show that the increment in the distance results in the exponential decay of the magnetic force. To provide sufficient frictional force for the vertical movement of the robot, the proper distance between the magnet and the pipe's surface can be determined based on Equations (11) and (12). As a result, a distance of 4 mm for the front and rear modules provides a magnetic force of 92.4 N and a distance of 2.9 mm for the middle module provides a magnetic force of 71.6 N. Then, the power, speed, and torque requirements of the motor can be calculated from Equations (16)–(18) and the results are presented in Table 2. From these results, Maxon's EC16 brushless DC servo gearmotor with GP16A planetary gearhead was selected to satisfy the requirements of the motor.

Figure 8. (a) The experimental setup and (b) the results demonstrating the influence of distance on the magnetic force.

Table 2. The power, speed, and torque requirements of the motor.

	Power (W)	Speed (rpm)	Torque (Nm)
Calculated results of motor requirements	31	37,836	0.0078
Maxon's EC16 motor with GP16A gearhead specifications	30	38,100	0.0083

2.5. Kinematic Analysis

In the proposed robot, variable speed motors are used for the robot's motion control. Due to the advantageous characteristics of the omnidirectional wheels, the robot is able to travel in any direction along the pipe at all times.

The speed of the robot and the angular velocity of the wheels are presented in Figure 9, and their relationships are given by:

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \frac{1}{r_w} \begin{bmatrix} 1 & 0 \\ 0 & r_t \\ 0 & -r_t \\ 1 & 0 \end{bmatrix} \times \begin{bmatrix} \dot{x}_r \\ \dot{\theta}_r \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} \dot{x}_r \\ \dot{\theta}_r \end{bmatrix} = r_w \begin{bmatrix} 0.5 & 0 & 0 & 0.5 \\ 0 & \frac{1}{2r_t} & \frac{-1}{2r_t} & 0 \end{bmatrix} \times \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \quad (20)$$

where $\dot{x}_r$ is the speed of the robot along the x-axis, $\dot{\theta}_r$ is the angular velocity of the robot about the centerline of the pipe, r_t is the pipe's inner radius, r_w is the radius of the robot's wheel, $\dot{\theta}_1$ is the rotational speed of the driving motor on the front module, $\dot{\theta}_2$ and $\dot{\theta}_3$ are the rotational speeds of the driving motors on the middle module, and $\dot{\theta}_4$ is the rotational speed of the driving motor on the rear module.

Figure 9. A kinematic model of the in-pipe robot with (a) perspective view and (b) side view.

2.6. Electrical Systems

As presented in Figure 10, the electrical systems are divided into two parts: the side of the robot and the control station. The signal is transmitted between the side of the robot and the control station through an RS485 interface with Modbus RTU protocol using two control cables. A PLC (programmable logic controller) in the control station is configured as the master and the side of the robot as the slave. For electrical power, two sets of 48V DC power supplies are used to supply the robot and the control station. In addition, 8-core AWG24 cables are connected to the front and rear camera for data transmission.

Figure 10. The schematics of the robot's electrical diagram.

The side of the robot uses a microcontroller to receive control commands and to send the measurement data from the sensors, e.g., temperature and humidity, to the control station. The main tasks of the control station are to control the robot's movement, to display the measurement data and real-time feedback from the camera, and to supply the electrical power to the robot. As presented in Figures 11 and 12, the robot can be controlled via visual control panels that are divided into two parts: a camera display panel (Figure 11) and the robot's control panel (Figure 12). The camera display panel is equipped with two screens to display the real-time video and images from the robot's front and rear cameras. The images and videos can be recorded and saved to external hard drives via USB ports. The robot control panel is equipped with power switches, status indicator lights, a joystick to control the robot's motion, and a 7-inch Siemens SIMATIC HMI touch screen panel. The touch screen panel displays the internal temperature and humidity of each robot module and the robot's speed.

Figure 11. A diagram of the camera display panel.

Figure 12. A diagram of the robot's control panel.

3. Prototype and Experiments

Figure 13 presents the prototype of the developed robot with the camera display panel and control panel. The robot is mainly composed of three modules with omnidirectional wheels. The wheels can be classified into six driving wheels and four supporting wheels. The front camera and headlamp are mounted on the front module. The rear camera and control cable are attached to the rear module. The parameters of the robot are summarized in Table 3. As shown in the table, several experiments were conducted to evaluate the performance of the prototype, e.g., the maximum velocity, payload capacity, and vertical distance that the robot is capable of climbing without slipping. The robot is also able to pass through a straight pipe in both horizontal and vertical directions.

Figure 13. (a) The prototype of the developed in-pipe inspection robot; (b) the camera display panel and the robot's control panel.

Table 3. The specifications of the prototype of the developed robot.

Parameters	Value
Material	Aluminum, nylon, and PLA
Dimension	110 mm × 99 mm × 450 mm
Weight	3 kg
Magnet	Neodymium block 40 × 20 × 10 mm N35
Wheel diameter	10 cm
Power	220 V 50 Hz
Top speed	30 cm/s
Working space	In-steel pipe, from 5-inch (127 mm) diameter to flat plate
Payload	59 N
Vertical distance	10 m
Control cable length	50 m
Motor	Maxon EC16 30-watt brushless DC motor
Motor gear	GP16A ratio 104:1
Robot gear	Spur gear ratio 4:1
Analog camera	FOV 160° 1000TVL
Camera display	7 inches
Sensors	3 humidity sensors and 4 temperature sensors

To evaluate the robot's capability to pass through a curved pipe, two experiments were conducted in an 8-inch (203 mm) diameter pipe, as shown in Figure 14a,b: a curved up elbow (horizontal to vertical) and a curved down elbow (vertical to horizontal). The results demonstrated that the robot can stably move in the upward and downward directions for both curved up and curved down conditions. However, irregular welds or uneven weld beads may occasionally cause the wheels to slip. Furthermore, the robot can move on the ceiling of the pipe, as shown in Figure 14c, in order to avoid any liquid or slag in the pipe. Figure 15 shows the real-world visual inspection from when the robot was used in a horizontal oil drainpipe at a real site.

Figure 14. The experimental setup to evaluate the robot's capability to pass (a) through a curved up elbow, (b) through a curved down elbow, and (c) by attaching to the ceiling.

Figure 15. The internal surface of the pipe captured by the front camera: (a) a rusty surface; (b) slag ash.

4. Conclusions

In this article, a train-like inspection robot was proposed for the visual inspection of the inside of ferromagnetic pipes with a diameter of 5 inches (127 mm) or larger. The robot combined omnidirectional wheels and permanent magnets as the adhesion mechanism between the robot and the pipes. Two perpendicular sets of omnidirectional wheels provided two-directional movements (longitudinal and lateral) and ensured that the robot could travel longitudinally along the path of the pipe. The waterproof robot was designed for operation in waterlogged conditions. The visual control panels were used to control the robot's movement and to observe the inspection area in real-time through the front and rear cameras. The robot was also equipped with temperature and humidity sensors to provide the real-time monitoring of the pipe's internal conditions. The robot prototype was tested in several conditions in order to prove that the robot is capable of passing through straight and curved pipes in any direction. The developed robot can also be applied for the external inspection of ferromagnetic structures, such as ferrous storage tanks. Autonomous functionalities, such as surface examination and corrosion detection, are very interesting and will be the focus of our future investigation.

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