Mechanism design of a small mobile robot for inspection of underground cables-in-pipe

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Abstract. With the rapid growth of urban power load, underground cables-in-pipe is increasingly used in urban power transmission. The operation status inspection of underground cables-in-pipe is very important to guarantee the safety of power transmission. At present, mostly, the inspection of the underground cables-in-pipe is implemented by workers after cutting the power supply. Cutting power supply will cause economic loss. In addition, the workers cannot step into the narrow pipes, which lead to low inspection efficiency and the high omission factor. In order to solve the above problems, this paper proposes a novel mechanism of a small mobile robot for underground cables-in-pipe inspection. In the pipes where cables have been laid, the remaining space is narrow and irregular. Through the unique compact design of the robot mechanism, we make the robot able to run smoothly in the pipes. In this paper, we firstly establish the remaining space model of the cable-laid pipes. Then design the mechanism model of each part of the robot. After that, we determine the specific structural parameters. Finally, we carry out the feasibility analysis of the whole robot mechanism. The results of the analysis indicate that, the designed robot mechanism can move smoothly in underground cable pipes.

1. Introduction
With the rapid growth of urban power load and the increasing requirements of the national economic life for power supply reliability, more and more cities adopt underground cable for electric power transmission. Pipe laying is widely used in underground cable installation by the reason of its low economic cost and strong protection capability against damage[1]. Obviously, it is of great difficulty to inspect the cables-in-pipe in the underground narrow environment. Thus at present, the manual inspection is mostly used. This inspection method is arduous for the workers with poor safety, low efficiency. Worse, power cut during the inspections will cause huge economic losses[2]. Small pipe robots can perform cables-in-pipe inspection instead of workers without power cut. In addition, it is safer, more reliable and efficient to use pipe robot than workers to do the inspection work.

The research on pipe robots started from PIG pipe cleaner in the 1950s. Later, with the improvement of computer technology and virtual mechanical design and manufacturing technology, the research upsurge of small pipe robots aroused[3]. In 2000, Bernhard Klaassen et al. in Germany developed a robot composed of six identical split modules---MAKRO. However, due to its complex structure, it is difficult to control and has poor stability[4]. In 2009, Korea Aerospace University developed a wireless micro-robot driven by piezoelectric materials, but the speed of piezoelectric drive is slow, and sensor installation is difficult due to the small size of the robot[5]. In 2012, Beijing
University of Posts and Telecommunications proposed a squirming pipe robot driven by flexible lead screws, which could only walk in ordinary circular pipes, with insufficient load capacity and low walking efficiency[6]. In 2016, Northeast Electric Power University designed a pneumatic micro-pipe robot with flexible transmission capability[7]. In 2019, Beijing University of Civil Engineering and Architecture proposed a snake-like pipe robot[8]. Nevertheless, the above machines cannot walk in the pipe with cable laid, and the design of driving mode and transmission mechanism is complicated, leading to poor practicability of the robots.

Aiming at the common defects of pipe robots mentioned above, this paper proposes a novel small pipe inspection robot. With its unique compact and adjustable mechanism, the robot is able to move smoothly and efficiently in narrow and irregular shaped spaces such as the pipes where the cables are laid.

2. Analysis of robot operating environment and design requirements

According to the actual robot operation environment (as shown in figure 1), to enable the robot to move smoothly in the pipe, through the shape closure and force closure[9], several questions are considered as follows:

The pipes are generally laid 0.7 meters underground, above the pipes are mostly reinforced concrete pouring. Due to the electromagnetic shielding, wireless communication in the pipe is difficult[10], thus the robot uses wire communication. In order to reduce the resistance to the robot, we use multi-functional wire to connect the robot and the handheld control device, and the wire is lubricated before use.

The material of the pipes are mostly CFRP or alkali-free glass reinforced plastic, the inner wall of the pipes are smooth and free of burrs[11], which makes it difficult for the robot to move without slipping. For this, the surface of the robot wheels is roughened to increase friction.

Figure 1. Robot operation environment

The inner diameter of the pipe studied in this paper is 180mm, the cable model is YJLV22-3*300, the outer diameter of the cable is 80mm. Based on the above data, the remaining space model in the cable-laid pipe is established (as shown in figure 2), the green part on the right is the operational space for the robot. It can be seen from Figure 2 that the remaining space in the pipe is narrow and irregular. In addition, the robot body should not contact with the cable in order not to damage the cable or get stuck in the gap between the cable and the pipe. Therefore, the robot mechanism needs to be designed small and simple.

Figure 2. Remaining space of the cable-laid pipe
When the robot moving in the pipe, due to the enclosed environment and the heat from the power cable, the temperature is high, roughly 70℃, therefore we need to consider high temperature resistance of all the robot components. Finally, the robot may encounter system failure or be trapped in the pipe. Thus, we need to set safety devices to handle these problems, such as safety ropes to pull out the robot in the above situations.

3. Mechanism design of the robot

3.1. Overall composition of the robot
Considering the design requirements of the robot in Chapter 2, the mechanism of the robot is designed as shown in figure 3. The designed robot mainly consists of robot frame, supporting mechanism, driving mechanism and mileage measurement mechanism. Each part cooperates with each other, so that the robot can move safely and smoothly in the pipe.

![Figure 3. 3D model of the pipe robot](image)

3.2. Supporting mechanism
As shown in figure 4, the supporting mechanism consists of four sliding pairs at the back of the robot, each of which has a small wheel called driven wheel at the end, and a big wheel in the front of the robot called guide wheel. The driven wheels contact with the inner wall of the pipe and the guide wheel contact with the cable. Totally, five contact points support the robot to keep it balance while moving in the pipe.

Springs are put into the sliding pairs, when the robot is put into the pipe, the springs are compressed to generate pressure between the driven wheels and the inner wall of the pipe. In addition, the adjustable setting make the robot adaptive to different radius pipe. The guide wheel is designed to have a surface of revolution, which ensure its sufficient contact area with the cable. Thus, the guide wheel can guide the robot to move along the cable.

3.3. Driving mechanism
Driving force of the robot is provided by a double outlet stepper motor. The motor has small size and big output torque to provide large traction force. At each end of the motor shaft, a driving wheel is installed. The driving wheel is designed to have trapezoidal EPDM surface which ensure sufficient friction between the wheel and the inner wall of the pipe, as shown in figure 5.
3.4. Robot frame and protective setting

The robot frame is made of 7075 aluminum alloy, which has high strength, high abrasive resistance, small density. All the other parts are fixed on the robot frame to compose a integral device. It consists of a main plate where the motor driver, controller, battery, sensors, are fixed, two metal bars to install the guide wheel, a fixing plate and a tortuous metal bar to fix the motor as shown in figure 6.
A protective shell is designed to fix outside the main plate, to protect the electronic elements from dust, water and so no. At the back of the frame, there is a connector to connect safety rope to the robot, in case of unexpected failure of the robot in operation.

3.5. Mileage measurement mechanism

The guide wheel is connected to an encoder through a gear pair, as shown in figure 7. While the robot is moving in the pipe, the guide wheel will rotate due to the friction force from the cable surface. The turning laps of the guide wheel can be measure through the encoder, and then to calculate the moving distance of the robot which is can be used for local positioning of the robot.

3.6. Robot mechanism parameters

According to the dimensions of the cable and the pipe, the robot mechanism is designed as shown in figure 8 and table 1. $l_1$, $l_2$ and $l_3$ are the length, width and height of the main plate. $l_4$ is the length of the motor. $l_5$, $l_6$ are the dimensions of the motor frame. $\Phi_1$ and $l_7$ are the diameter and width of the driving wheel. $\Phi_2$ and $l_8$ are the diameter and width of the driven wheel. $l_9$ is length of the upper part of the sliding pair. $l_{10}$ is the extension length of the lower part of the sliding pair. $l_{11}$ is the distance between the driving wheel and the motor. $\theta_1$ is the angle between the sliding pair and horizontal direction.

![Figure 7. Mileage measurement mechanism](image)

![Figure 8. Robot mechanism parameters (a) Front view (b) Side View](image)
Table 1. Specific parameters of the robot.

| Parameter | Value |
|-----------|-------|
| $l_1$/mm  | 350   |
| $l_2$/mm  | 75    |
| $l_3$/mm  | 10    |
| $l_4$/mm  | 60    |
| $l_5$/mm  | 57    |
| $l_6$/mm  | 57    |
| $l_7$/mm  | 15    |
| $l_8$/mm  | 12    |
| $l_9$/mm  | 40    |
| $l_{10}$/mm | 15-35 |
| $l_{11}$/mm | 20    |
| $\Phi_1$/mm | 50    |
| $\Phi_2$/mm | 20    |
| $\theta_1$/° | 45    |

4. Feasibility analysis

4.1. Driving capability analysis

Once we put the robot into the pipe, the force generated by the compressed spring in the sliding pairs is transmitted to the contact point between the driving wheel contact and the inner wall of the pipe. When we start the motor the torque from motor is transmitted to the driving wheel. As a result the reactive friction force between the driving wheel and the inner wall will push the robot to move forward.

![Figure 9. Forces on the robot when moving in the pipe](image)

Seen from figure 9, there are totally seven contact points between the robot and the environment. They are the contact points between the four driven wheels and the inner wall of the pipe, the contact points between the guide wheel and the cable, the contact points between the driving wheels and the inner wall of the pipe. Because the mechanism of the robot is designed to be symmetrical about the axis of the pipe, Y-directional forces on the robot is balanced, and obviously, X, Y, Z-directional moments are balanced. In X direction, there are eight force exerted on the robot, because most weight
of the robot distributed on the middle part namely the main plate of the robot, Y-directional moment on the robot is balanced.

Consider the X-directional force, we have

$$F_1 \sin \theta_1 + F_2 \sin \theta_1 + mg = F_3 \sin \theta_2 + F_4 \sin \theta_2 + F_5 \sin \theta_2 + F_6 \sin \theta_2 + F_7$$

(1)

As for Z-directional forces, the generation of overall Z-directional force namely the traction force on the robot is shown in figure 10.

Express the static friction coefficients between the driving wheels, driven wheels, guide wheel and the inner wall of the pipe as $\mu_1$, $\mu_2$, $\mu_3$, respectively. Express the friction force from the inner wall of the pipe to the driving wheel as $f_i$, we obtain

$$f_1 = F_1 \times \mu_1, \quad f_2 = F_2 \times \mu_1, \quad f_3 = F_3 \times \mu_2, \quad f_4 = F_4 \times \mu_2, \quad f_5 = F_5 \times \mu_2, \quad f_6 = F_6 \times \mu_2, \quad f_7 = F_7 \times \mu_3$$

(2)

Then, to move the robot move forward, the following inequation should be satisfied

$$f_1 > \sum_{i=2}^{7} f_i$$

(3)

Because the driven wheels and the guide wheel are all installed on ball bearings shafts, they need very small torque to rotate. Therefore, once there is sufficient normal pressure between the driving wheels and the inner wall of the pipe, the robot can move along the X direction. Thus, we select motor with large driving torque and springs with large elastic coefficient to move the robot.

4.2. Motion analysis

Based on the model of the robot and the pipe, we perform the motion analysis using Solidworks software, as shown in figure 11. The analysis result indicates that, the designed robot can move in the cable-laid pipe without collision.

![Figure 11. Motion analysis](image)
5. Conclusion
Aiming at the problem of inadaptable of the existing pipe robots to move in narrow and irregular space. This paper proposes a novel robot mechanism for underground cable-in-pipe inspection. Driving capability and motion analysis are performed, and the results indicate the robot can move smoothly in the cable-laid pipe. Although the design is based on specific pipe and cable, however, the dimensions of the designed mechanism are variable with adjustable supporting mechanism. Therefore, this study provides a reference for the development of the pipe robot design.

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