

Structure Design and Analysis of in-Pipe Robot Adaptable to Pipe Diameter

Quanyu Long^{1,*}, Bo Tang¹, Zhongxian Tan¹, Yangrui Zhang¹, Miao Wang¹

Yunya Wang²

¹ School of Engineering, Southwest Petroleum University, Nanchong 637001, China

² School of Information, Southwest Petroleum University, Nanchong 637001, China

Abstract

The structure of the in-pipe robot has a huge impact on its normal detection and dredging inside the pipeline. The blockage inside the pipeline and the structure and size of the pipeline have brought challenges to the design of the in-pipe robot. This paper proposes a pipeline dredging robot with pipe diameter adaptation. Through the analysis of the rocker slider mechanism, an adaptive mechanism based on the change of pipe diameter within a certain range is designed. Through the analysis of the robot's stability and power consumption, a two-stage belt drive transmission mode is designed, so that the drive motor is located at the center of the fuselage, which enhances the stability of the in-pipe robot. A physical prototype was made on the basis of theoretical analysis, and the feasibility of the design was verified through simulation and experimental tests, and the effect of adapting to the dredging of the pipe diameter was achieved.

Keywords

In-Pipe Robot, Adaptive Mechanism, Structure Design, Travelling Mechanism.

1. Introduction

With the development of urbanization and the increase of urban water consumption, more and more domestic and kitchen waste has been produced. These wastes are directly discharged without treatment. After a long period of accumulation, the pipes are aging, corroded, narrowed and even blocked. The increase of rainy season and water consumption has a great challenge on the smoothness and sealing of the pipeline [1]. In recent years, pipelines of various styles and sizes are widely used in various urban scenes, but most of the drainage pipelines in the city are deeply buried underground, forming a complex network, which brings difficulties to the dredging work. Traditional dredging methods often need manual cleaning. Although manual cleaning can dredge the pipeline accurately, the internal working conditions of the pipeline are complex, the operation space is limited, the manual cleaning efficiency is low, and the safety hazards are large. With the development of robot technology, it is of great significance to develop a pipeline adaptive robot that is controlled by a computer, can walk automatically in various pipelines, and complete the dredging work autonomously [2, 3].

At present, the pipe diameter adaptive mechanism is mainly divided into peristaltic type, crawler type, supporting wheel type and six independent driving wheel rod type [4]. The peristaltic adaptive mechanism structure can easily move forward, backward, obstacle crossing and turning, and can adapt to small pipelines. However, according to its multi degree of freedom structure, it moves in a peristaltic way with slow movement speed and poor flexibility [5]. The crawler type traveling mechanism has a large driving force, and the crawlers on both sides form a certain included angle, which can be adjusted to adapt to different pipelines [6]. The

disadvantage is that it can not be adjusted in real time according to the changes of pipelines in work [7, 8]. At the same time, the crawler type structure is complex and can only adapt to large-diameter pipelines [9]. The support wheeled in-pipe robot adopts a spatial support method to close the robot to the inner wall of the pipeline to improve its stability. It has the characteristics of strong maneuverability, flexibility, and simple structure. It can also adapt to pipelines of different diameters and can effectively pass through 90° bends and T-shaped pipes. However, due to the small size and light weight of the robot, it is only suitable for pipes with small pipe diameters, and the maximum traction is low. It cannot be equipped with heavy sensors, which is limited in function. The active wheel rod type is driven by a motor, with a large driving force, and through an adjustable mechanism, it can automatically adapt to pipes of different pipe diameters during operation[10].

From the current research status at home and abroad, we can see that the current research on the pipeline adaptive structure and dredging mechanism has achieved certain results, but most of the pipe diameters are low in feasibility, they have a small adaptation range, and high power consumption and cost. And the adaptive mechanism occupies a large space, resulting in inconvenient layout of the operating mechanism[11]. In response to the above problems, this paper proposes a pipe diameter adaptation mechanism based on a rocker slider mechanism. The rocker is driven to swing by a screw drive, and the wheel rod of the mechanism contacting the pipe wall is used as a slider to realize the pipe diameter adaptation function[12]. The rest of this paper is organized as follows: Section 2 designs the structure of in-pipe robot; Section 3 presents the experimental results; and Section 4 concludes the paper.

2. Structural Design and Analysis of In-pipe Robot

In order to enable the in-pipe robot to adapt to different pipe diameters and complete the dredging operation efficiently and stably, combining the working conditions of the household sewer pipes and the existing problems of the in-pipe robots, we design a robot travelling mechanism that can adapt to 200mm~250mm pipe diameter.

2.1. Design and Analysis of Pipe Diameter Adaptation Mechanism

According to the mechanism synthesis, in order to realize the pipe diameter adaptation, the slider rocker mechanism is used to design the pipe diameter adaptation mechanism. The schematic diagram of the mechanism is shown in Figure 1. It is mainly composed of the following parts: connecting rod, support rod, ball screw, axial moving slider, front support plate, rear support plate, etc. The end of the rocker is equipped with a driving wheel, the slider is matched with the nut of the ball screw, and the motor drives the screw to rotate, thereby driving the slider to move axially, and finally makes the rocker swing and change the end radius.

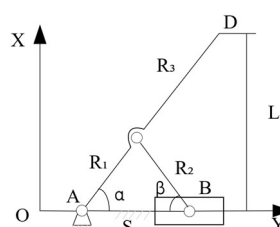


Figure 1. Two or more references

In order to facilitate the analysis, the coordinate system XOY is established in Figure 1, where point A is the hinge point of the front support plate, which is the fixed point. Point B is the hinge point of the axially moving slider, which is the moving point. The distance between points A and B from the center of the ball screw axis is 40mm. Point D is the axis center of the drive wheel

mounting hole of the end rod. The radius of the drive wheel is 20mm. The distance between point D and the frame is L. S is the horizontal distance between the two hinge points A and B, and the change in length is the stroke distance of the ball screw. The angle between the rocker and the frame in the horizontal direction is the support angle α , and the angle between the connecting rod and the frame in the horizontal direction is the transmission angle β . The distance between supporting hinge points A and C is R_1 , the distance between supporting hinge points C and D is R_3 , and the connecting rod length is R_2 . It can be known from the geometric relationship:

$$L=(R_1+R_3)\sin\alpha \quad (1)$$

$$\alpha=\arcsin\frac{L}{R_1+R_3} \quad (2)$$

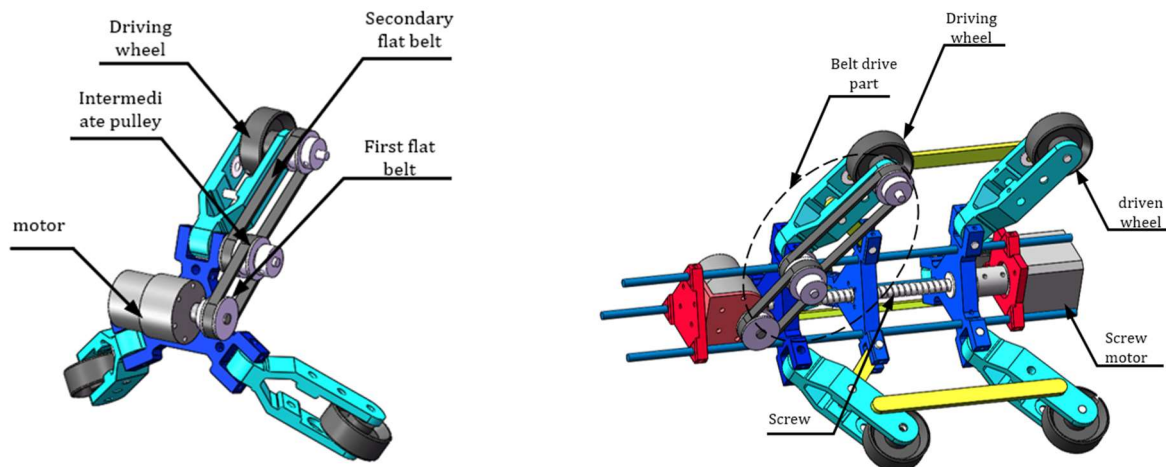
$$S=R_1\cos\alpha+R_2\cos\beta \quad (3)$$

In order to make the robot structure compact, the rods are interchangeable, and the connection is reliable, the hinge point C is the midpoint of the rocker, and the length of the connecting rod is equal to the distance between the hinge points A and C. That is, $R_1=R_2=R_3$, so now only need to determine the total length of the rocker, you can determine the size of the remaining sections. According to the adaptation range of the robot pipe diameter, the change range of L is 40mm~65mm. It can be known from statics that when the pipe diameter is the maximum pipe diameter of 250mm, if the support angle α is large at this time, the moment arm of the driving force of the driving wheel will be shortened, and the driving torque of the driving wheel must be increased correspondingly to overcome the resistance. This will make it difficult for the robot to drive, making it impossible to move forward. Therefore, when the pipe diameter is the maximum pipe diameter, the supporting angle α must be at an appropriate angle. It is determined that when the robot is in the extreme position, the support angle α is 55° , and the transmission effect is the best at this time, and the robot can work normally. Substituting the support angle $\alpha=55^\circ$ and the distance $L=65\text{mm}$ into equations (1)~(3), the final solution is that the rocker length is 80mm, the connecting rod length is 40mm, and the support angle α is 30° when it is the smallest pipe diameter. Therefore, the support angle α varies from 30° to 55° , and the horizontal distance S varies from 46.96mm to 69.28mm, so the ball screw stroke is 22.32mm.

2.2. Structure Design of Travelling Mechanism

In order to make the robot motion stable, the drive motor of the drive wheel at the end of the pipe diameter should be arranged in the center of the body as much as possible. Therefore, a two-stage belt drive is used as the power device of the walking mechanism. The drive motor drives the drive pulley to rotate. The rotation of the wheel drives the driven pulley to rotate, thereby driving the driving wheel to rotate and drive the robot to move forward, as shown in Figure 2(a). In order to realize the robot walking in the pipeline, this article adopts a three-support wheel walking method, that is, three sets of wheeled mechanisms are evenly distributed along the circumferential direction at 120° intervals, as shown in Figure 2(b). The supporting wheel mechanism is a variant of the wheeled robot. The mechanism can provide sufficient traction for the robot. Due to its symmetrical structure, the central axis of the robot can be kept consistent with the axis of the pipeline, resulting in better stability. Considering the robot walking driving power and motor installation requirements comprehensively, the JGB37-

520 DC geared motor that does not need to add an encoder and has a smaller volume, a larger torque and a higher speed is selected.



(a) Power part of travelling mechanism

(b) Integral part of traveling mechanism

Figure 2. Schematic diagram of travelling mechanism

3. Robot Simulation and Experimental Analysis

3.1. Simulation Analysis

3.1.1. Simulation Analysis of Pipe Diameter Adaptation Mechanism

Import the established robot 3D model into the simulation software, add a drive to a single pipe diameter adaptation mechanism and simulate, measure the axis center of the mounting hole at the end of the rocker, and study the vertical coordinate changes during the simulation process. The range of change is the adaptation range of the robot's pipe diameter, and the simulation results are shown in Figure 3.

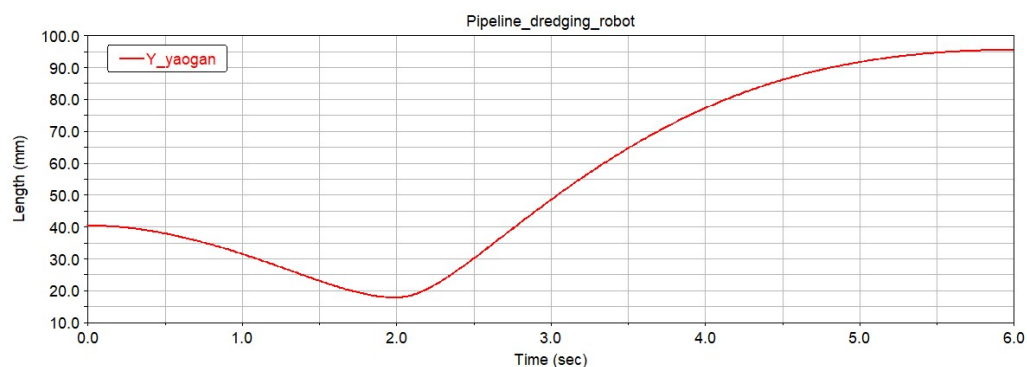


Figure 3. Applicable range of pipe diameter

From the simulation curve in Figure. 3, it can be seen that the range of the length L from the end of the rocker to the frame is 18mm~95mm. Combined with the analysis of the Section 2, it can be known that theoretically the design requirement is within the range of 40mm~65mm, that is, the designed pipe diameter adaptation mechanism can adapt to pipe diameters of 200~250mm.

3.1.2. Simulation Analysis of Travelling Mechanism

In order to facilitate the analysis of the robot's movement process in the pipeline, the height change of the center of the rear wheel of the robot along the vertical direction can be analyzed.

The simulation analysis is shown in Figure 4. It can be seen from the figure that the center positions of the three rear wheels of the robot are relatively displaced due to gravity during 0~2s, and then tend to stabilize. In 2~18s, the robot runs in a pipeline with a diameter of 250mm, and the rear wheels have no large fluctuations, and the fluctuation range is less than 5mm. Among them, the Z-direction coordinate of the rear wheel 3 is stable at about 100mm. In the period of 18~53s, the robot runs in the transition section of the pipeline. Because the diameter of the transition section is constantly changing, the three rear wheels fluctuate slightly, but the amplitude of the fluctuations all show linear changes. In 53~70s, the robot passes through the transition section and enters the pipeline with a diameter of 200mm. The operation process is basically stable. The coordinate of the rear wheel 3 in the Z direction is stabilized at about 75mm, and the rear wheel changes 250mm in the vertical direction. This height corresponds exactly to the pipe diameter difference.

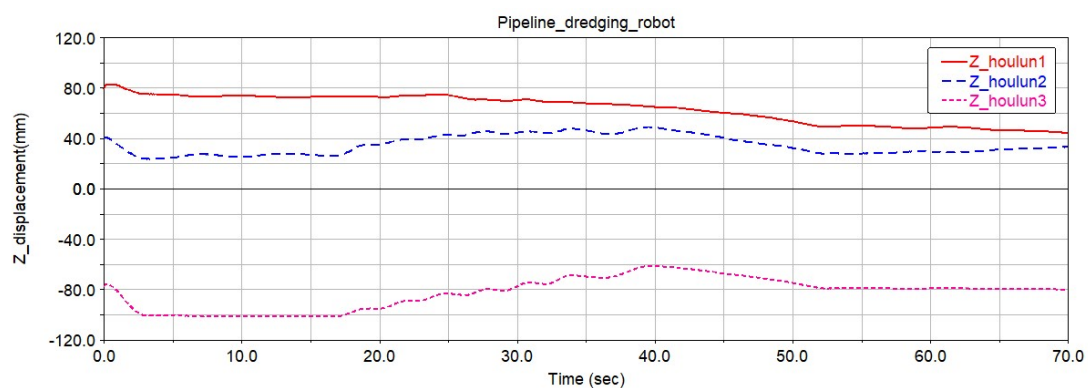


Figure 4. Displacement change of rear wheel center along z direction

3.2. Prototype Experiment Analysis

3.2.1. Robot Prototype Production

In order to make the robot prototype quickly, most parts of the robot are made by 3D printing, and the other parts are made of standard parts. The whole device is connected and combined by carbon rods. After the walking mechanism and the dredging device are made, they are installed together according to the assembly drawing to complete the assembly of the entire robot. The robot prototype is shown in Figure 5.

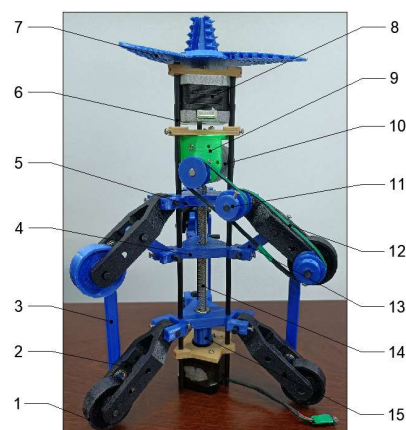
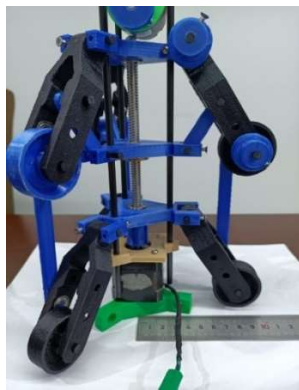


Figure 5. In-pipe robot prototype

In the picture: 1-wheel, 2-support leg, 3-auxiliary rod, 4-support slider, 5-leg support, 6-support carbon rod, 7-tool, 8-step motor, 9-motor bracket, 10-DC motor, 11-pulley, 12-flat belt, 13-connecting rod, 14-ball screw, 15-coupling.

3.2.2. Experimental Analysis of Pipe Diameter Adaptation Mechanism

After the assembly of the robot prototype is completed, the robot is connected to the electrical system, and the drive motor checks the reliability of the rotation of the drive wheel, the rotation of the lead screw and the movement of adaptation mechanism of the pipe diameter. In order to verify the adaptable range of the pipeline diameter of the travelling mechanism, the robot travelling mechanism is placed on the ground, and the end motor is driven to rotate the lead screw to measure the outermost range of the robot wheel, as shown in Figure 6. It can be seen from the figure that the minimum pipe diameter of the travelling mechanism is about 200 mm, and the maximum pipe diameter is about 250 mm, which meets the design requirements.



(a) Minimum pipe diameter



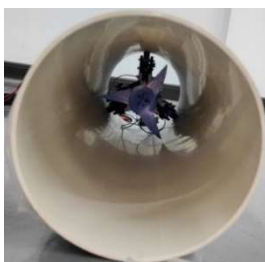
(b) Maximum pipe diameter

Figure 6. Pipe diameter adaptation range measurement

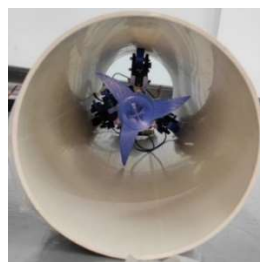
3.2.3. Robot Motion Experiment Analysis

In order to test the movement performance of the robot in the pipeline, the robot was placed in the pipe diameters of 200mm and 250mm to carry out the movement experiments, as shown in Figure 7 and Figure 8. After the screw motor is driven to rotate, the support slide moves smoothly, driving the parallelogram mechanism to deform, making the wheel close to the tube wall. Among them, Figure 7 (a) shows the minimum pipe diameter that the robot can adapt. It can be seen from the figure that the distance between the outermost position of the wheel and the center of the ball screw axis is 100mm, so the designed robot can adapt to the pipe with a diameter of 200mm. Figure 8(a) shows the maximum pipe diameter that the robot can adapt to. In the figure, it can be seen that the outermost wheel of the wheel can reach a distance of 125mm from the central axis, so the robot can adapt to a pipe with a diameter of 250mm. To sum up, the in-pipe robot designed in this article can realize the self-adaptation of 200mm to 250mm pipeline, which meets the design requirements.

As shown in Figure 8 and Figure 9, the walking experiments in the pipes with diameters of 200mm and 250mm were carried out respectively. From the experimental results, it can be seen that the six wheels can be close to the inner wall of the pipe, the robot runs smoothly, and the structure design of the walking mechanism is reasonable.



(a) Initial position



(b) Run to the middle



(c) Run to the end

Figure 7. Walk within 200mm pipe diameter

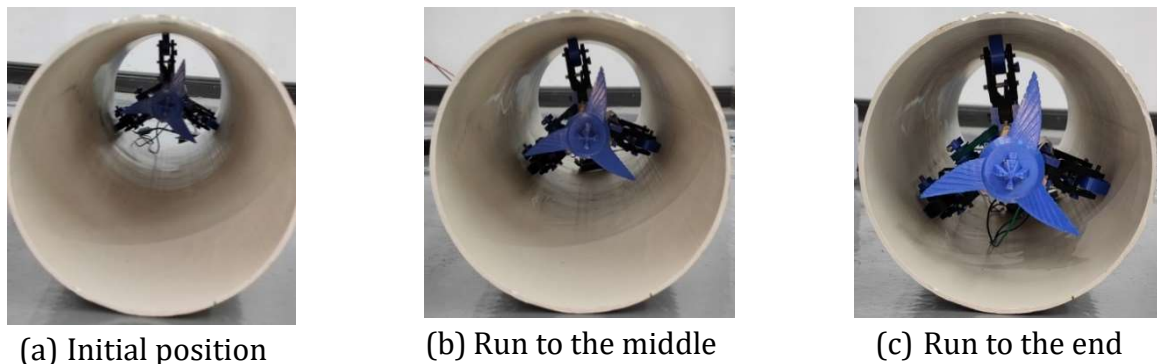


Figure 8. Walk within 250mm pipe diameter

4. Conclusion

Aiming at the problem of in-pipe robot adaptation to different pipes, this paper designs an adaptive pipe diameter in-pipe dredging robot. The robot is mainly composed of a pipe diameter adaptation mechanism and a travelling mechanism. The movement of the robot is driven by a two-stage belt drive. Through the cooperation of the two parts, the adaptation to the pipe diameter within a certain range is completed, and the difficulties encountered in the cleaning of the complicated urban sewer pipe working conditions and the processing of various pipe blockages of different pipe diameters have been solved, and it can be completed independently the pipeline cleaning work and the adaptive change of the airframe, have certain development prospects and application value.

Acknowledgments

This work was supported by the Nanchong City-Southwest Petroleum University City-School Science and Technology Strategic Cooperation Special Fund Project (Grant No. SXQHJH027 and SXQHJH034), Southwest petroleum university key project of extracurricular experiment in 2021 (Grant No. NKSZ21006), Southwest Petroleum University 2021 Provincial College Student Innovation and Entrepreneurship Training Program Project: Design of Pipeline dredging Robot and Design of Software Crawling Robot.

References

- [1] Z.W. Zhang, J.N. Wang: Crane Design Manual (China Railway Press, China 1998), p.683-685. (In Chinese).
- [2] C. Li, W.Q. Yin, and X.B. Feng.:Brushless DC motor stepless speed regulation system based on fuzzy adaptive PI controller, Journal of Mechanical & Electrical Engineering, vol. 29 (2012), p. 49-52.
- [3] China National Standardization Management Committee. Specifications of Crane Design (China Standardization Press, China 2008), p. 16-19.
- [4] J. Liu, E.L. Chen and Z.T. He: Journal of Shi Jia Zhuang Railway Institute (Natural Science), Vol. 22 (2009) No. 4, p. 40-42.
- [5] Do.Lee, Jungwan Park, Dongjun Hyun, GyungHwan Yook, Hyun-seok Yang: Novel mechanisms and simple locomotion strategies for an in-pipe robot that can inspect various pipe types, Mechanism and Machine Theory, Vol. 56(2012), P. 52-68.
- [6] Sabir Ghauri, Hassan Nouri: Progresses in Study of Pipeline Robot. 4th International Conference on Modelling, Identification and Control(ICMIC 2012)(Wuhan, China, June 24, 2012), Vol. 1, p.1-6.
- [7] Ying Qu, Petar Durdevic, Zhenyu Yang: Smart-Spider: Autonomous Self-driven In-line Robot for Versatile Pipeline Inspection, IFAC-PapersOnLine, Vol. 51(2018)No. 8, p. 251-256.

- [8] Mohd Zamzuri Ab Rashid, Mohd Fitri Mohd Yakub, Sheikh Ahmad Zaki bin Shaikh Salim, Normaisharah Mamat, Sharifah Munawwarah Syed Mohd Putra, Shairatul Akma Roslan: Modeling of the in-pipe inspection robot: A comprehensive review, *Ocean Engineering*, Vol 203(2020), No. 107206, p.1-22.
- [9] Nur Shahida Roslin, Adzly Anuar, Muhammad Fairuz Abdul Jalal, Khairul Salleh Mohamed Sahari: A Review: Hybrid Locomotion of In-pipe Inspection Robot, *Procedia Engineering*, Vol. 41(2012), P. 1456-1462.
- [10] Z. Q. Li et al : Structural and Passability Analysis of Pipeline Robot, *Journal of Mechanical Transmission*, Vol. 45 (2021) No.6, p. 146-152.
- [11] Ankit Nayak, S.K. Pradhan: Design of a New In-Pipe Inspection Robot, *Procedia Engineering*, Vol. 97(2014), P. 2081-2091.
- [12] S.Y. Liu: Optimization Design and Dynamic Characteristics Research of Dredging Device of Pipeline Robot(MS., Shenyang Jianzhu University, China 2019), p.18.