Comprehensive Analysis on Structural Design and Application of Supporting In-Pipe Robot

Zhangfengyi Xiao[1, *]

[1] College of Mechanical and Transportation Engineering, China University of Petroleum-Beijing , Beijing, 100000, China

* 2020010940@student.cup.edu.cn

Abstract. Due to the rapid development and maturity of pipeline transportation systems in the oil and gas industry, in-pipe robots have become an important means of daily pipeline inspection and maintenance. Under the requirements of special transportation media and extremely serious accident consequences, the importance of in-pipe robots continues to increase. The current research goal is to use structures with minimal volume and strong adaptability to meet the requirements of daily operations. This article provides a comprehensive overview and analysis of the structural design and application status of supported in-pipe robots, focusing on three types of supported pipeline robots: wheeled, tracked, and walking. By systematically elaborating on the current research status of supported in-pipe robots and combining with the main motion modes, this article explores the three major issues of motion control, real-time positioning, and energy supply of supported in-pipe robots. Moreover, the future research direction for development are analyzed.

Keywords: supporting in-pipe robot, structural design, intelligent robot

1 Introduction

In the current oil and gas industry, pipeline transportation is the most important and largest transportation method [1]. With the increasing demand for oil and gas resources, higher requirements have been put forward for the safety and performance of pipelines after long-term operation [2].

Due to the inherent characteristics of the transportation medium of oil and gas pipelines, if the defects or cracks generated by long-term operation of the pipeline further develop into pipeline perforation, it will face very serious consequences [3, 4]. First is that it will bring serious economic losses. Second is that due to the flammable and explosive characteristics of the transportation medium itself, if an explosion occurs, it will bring huge damage, not only endangering personal safety, but also seriously damaging pipeline facilities, affecting the normal operation of the entire pipeline system [5]. Third is that it will have a negative impact on the surrounding natural environment. When oil and gas products enter soil, rivers, or underground

B. H. Ahmad (ed.), *Proceedings of the 2023 International Conference on Data Science, Advanced Algorithm and Intelligent Computing (DAI 2023)*, Advances in Intelligent Systems Research 180,
https://doi.org/10.2991/978-94-6463-370-2_11

aquifers, they will seriously pollute the soil and water medium, and bring toxic substances into the food chain, which may even cause species extinction [6].

In the past, manual inspection was mainly used to detect defects such as cracks, corrosion, or indentations in pipelines [7, 8]. This method not only has low detection efficiency and many blind spots, but also poses hidden dangers to the personal safety of inspectors [9]. When major accident hazards are discovered and need to be repaired, the entire pipeline is usually required to be shut down and excavation operations are carried out on the surface to complete the task. While time-consuming and laborious, some defects inside the pipeline are still difficult to repair, and the overall efficiency of maintenance process is very low [10].

By means of in-pipe robots for inspection and maintenance, we can save a lot of manpower and resources, and eliminate the necessity of large-scale engineering such as manual excavation [11]. Supporting in-pipe robots are one of the important directions. Supported in-pipe robot refers to the in-pipe robot whose motion is achieved through the transmission of a supporting structure, with independent motion mechanisms and transmission mechanisms [12]. Although there are currently various types of supported in-pipe robots and their development is not yet mature, many research institutions and scholars have turned their attention to supported in-pipe robots [13].

This article aims to provide a comprehensive overview and analysis of the structural design and application status of supported in-pipe robots. By introducing the current mainstream supported in-pipe robots, this article clarifies the innovation direction and analyzes some technical difficulties.

2 Robot structure design

2.1 Wheeled structure

This structure is mainly balanced by the support system and wheels, with a simple and efficient structure and principle, and low cost, which has been widely used. Overall, it can be summarized as three types of motion mechanisms: diameter changing mechanism, transmission mechanism, and module deflection mechanism. The diameter changing mechanism is driven by an electric motor or other forms of energy supply, and with the cooperation of the transmission mechanism, the robot legs or movable rods are changed to achieve diameter changing and provide power. At the same time, when crossing the bend pipe, the module deflection mechanism will adjust the robot's rotation angle and adapt to the inner diameter of the bend pipe with the support of the diameter changing mechanism and transmission mechanism [14].

There are two main energy supply methods in traditional wheeled structures. First is a fluid-driven robot, with no driving device installed within the entire structure, and all power comes from the driving force provided by the fluid inside the pipeline. But the problem with this type of structure is that there is no stable source of power, the speed of robot motion cannot be controlled, which has a significant impact on the accuracy of robot motion positioning. Second is a motor-driven robot, which is responsible for supplying energy by installing motors within the overall structure.

Although the instability of motion positioning has been resolved through the installation of motors, the endurance of long-distance detection operations has become a major challenge. Taking China as an example, the current distance between stations in oil and gas transportation pipeline systems is generally over 30km, Installing a battery with sufficient battery capacity on the robot to meet its range not only greatly increases the cost of each robot, but also poses risks to the safety of pipeline operation. At the same time, when the pipeline is in a high flow operation state, the friction between the wheels and the pipe wall will be greatly limited, and the robot will encounter difficulties in movement.

In subsequent research, many scholars have made structural improvements to motion stability. The main improvement points are the diameter changing structure and transmission structure. Guo et al. designed a supported mechanical differential wheeled in-pipe robot with a simpler and more compact transmission system that can adjust its rotational speed according to the distance traveled by each driving wheel. This robot can not only adjust the speed of the driving wheel in real-time to avoid slipping, but also crawl in pipelines with smaller inner diameters. Its driving wheel achieves a differential function during cornering, avoiding slipping between the driving wheel and the inner wall of the pipeline, and improving the motion stability of the in-pipe robot [15].

The adaptive pipe diameter full drive in-pipe robots designed and developed by Zheng et al. is a six-wheel pipeline robot that independently adapts to the diameter of the pipeline without the need for an electric motor to drive. The robot utilizes flexible springs and parallel support rod hinges to achieve adaptability to different pipe diameters. The independent diameter reduction achieved through flexible springs makes additional driving power no longer a necessity. At the same time, the combination of the entire rigid support and flexible spring avoids the phenomenon of wheel slipping or jamming when passing through the bend, greatly improving the stability of the entire pipeline robot [16].

The active helical drive in-pipe robot designed and developed by Liu et al. improves the transmission efficiency of the entire mechanism by changing the target of torque and directly applying torque to the driving wheels through the planetary gear system instead of the wheel frame. Meanwhile, due to the fact that the diameter of the driving wheel is much smaller than the diameter of the pipeline, the requirement for motor speed is reduced, thereby reducing the volume of the robot and improving its flexibility [2].

The axiomatic wheeled pipeline robot designed and developed by Shang et al. adopts magnetic wheels as the walking mechanism, reducing the impact of gravity on the robot's operation and making the robot have good adaptability in vertical pipelines. The structure of the robot consists of three independent transmission structures and a central motion structure. The central motion structure consists of a rotating motor and some gear transmission structures. Through coupling design, the acceleration of the robot can be adjusted with the driving force and friction force to achieve the optimal motion state, thus adapting to different pipe diameters and pipeline conditions [17].

Shan et al. proposed a dual drive pipeline robot based on a new 3-UPU parallel mechanism, which achieves support driving mode through a parallel mechanism and spiral driving mode through a four leaf spiral mechanism. This robot has the advantages of strong bearing capacity of parallel mechanisms and fast crawling speed driven by screws. At the same time, the timely conversion of the two driving modes improves the robot's pipeline adaptability and better meets the requirements of walking, turning, detecting, and obstacle crossing in the most common medium-sized pipelines [18].

2.2 Tracked structure

The overall structure of tracked pipeline robots is similar to traditional wheeled structures, with the main difference being that the motion mechanism has changed from wheels to tracks. This change greatly enhances the adaptability of the robot to different internal environments and media properties of pipelines. Whether it is finished oil or high viscosity and high wax crude oil, the tracked pipeline robot can operate stably. Although there has been some improvement in the performance of motion, the existing issues of range and positioning accuracy have not been resolved. The problem of roll often occurs in practical operations.

In order to improve the motion performance of tracked pipeline robots, improvements are usually made in terms of materials and structure. The greater the friction between the track and the pipe wall, the greater the load on the robot [19]. Due to the fact that the contact area between the motion structure of the tracked pipeline robot and the pipeline is much larger than that of other forms of pipeline robots, the material of the contact surface will greatly affect the performance of the robot. Usually, the variable diameter mechanism and transmission mechanism of tracked pipeline robots are composed of a scalable diameter changing system and a gear transmission structure [20]. However, how to make the robot better adapt to the complex environment inside the pipeline is currently the research direction of many scholars.

The new diameter changing tracked pipeline robot designed and developed by Liu et al. used rubber as the material of the track, and adopts a coaxial and different direction gear transmission structure to drive the connecting rod structure to achieve variable diameter. Not only can it adapt to complex horizontal pipeline movements, but it can also meet the operational requirements of vertical pipelines. The tracked walking mechanism is not directly connected to the robot body, but indirectly connected to the body through the fixed structure of the track. Its overall structure can achieve coaxial rotation in different directions, with flexible design and space saving to a certain extent, reducing the manufacturing cost of the robot. The modified tracked walking mechanism takes into account the diameter changing and walking functions of pipeline robots, while the rubber type tracks can increase the contact area with oil and gas pipes, increase friction, and improve driving and load capacity [20].

Liu et al. designed an active anti-roll device to address the problem of unstable motion and easy roll of dual wheel tracked in-pipe robots in pipelines. Although this device is used for tracked pipeline robot for operations in water pipelines, its design concept has significant reference value for oil and gas pipelines [21]. The device mainly consists of a driving motor, gears, racks, horizontal guide rails, anti-roll bars, and adjustable supports. Adjustable supports are used to fix the anti-roll bar on both sides of the robot body device through double end pin shafts. The driving motor is connected to the gear, which meshes with the gear rack, thereby driving the horizontal movement of the guide rail. There is a sliding groove on the upper part of the anti-roll bar, which is fixed to the horizontal guide rail through a pin shaft. Therefore, when the horizontal guide rail moves, it will drive the anti-roll bar to retract inside and outside to adapt to the working environment of different pipe diameters. At the same time, a level gauge and a resistance strain gauge sensor are also used to achieve real-time monitoring of its posture and force information. Through the Zigbee wireless transceiver module and servo motor control, automatic deviation correction and roll prevention of the robot are achieved, greatly improving the stability of the pipeline robot.

2.3 Walking structure

The main structure of walking in-pipe robots differs significantly from wheeled and tracked pipeline robots. Usually, crawling movements are carried out in a structure similar to the legs or feet of animals. This type of in-pipe robot can complete many complex movements and adapt to more diverse and chaotic work environments. However, due to the complex and precise mechanical structure and a large number of drivers required to achieve the walking of pipeline robots, their manufacturing and control difficulties are extremely high, resulting in extremely high costs, so they are rarely used in practical applications. The use of walking in-pipe robots is only considered for a few special job requirements, so this article will not elaborate further.

3 Challenges and research prospects

3.1 Technical problems

3.1.1 Motion control. During the operation process, the speed and smoothness of in-pipe robots, as well as their ability to turn and overcome obstacles, are directly related to the quality of the operation effect [22]. The motion performance of the robot is also affected by obstacles in the pipeline, output errors of the robot's executing mechanism, and changes in the robot's own load. Even if the issue of motion performance is resolved, it is still a challenge to accurately determine the direction of the pipeline robot through the tee or cross and ensure smooth operation in the vertical pipeline [23]. Therefore, the motion control problem of pipeline robots has become one of the research focuses and difficulties in the field of pipeline robots.

At the same time, due to the special working environment inside the pipeline, there are requirements for the volume and complexity of the robot. Because it is unrealistic to simply increase the volume of equipment or components to improve robot performance, it is also a practical direction to try to make the entire robot structure more compact and efficient while controlling the volume of individual components.

3.1.2 Robot positioning. In the positioning problem of pipeline robots, the indicators peoples need are composed of accuracy, complexity, reliability, and cost. The current mainstream positioning methods have different tendencies in these indicators. Sensing positioning has good accuracy and a simple structure, but it is prone to external interference and reduces the stability of its positioning; Algorithm-based positioning methods also have good accuracy, but the cost is too high; The GPS satellite positioning method has high positioning accuracy, but due to the influence of the internal environment of the pipeline, the problem of signal shielding is significant, resulting in poor performance in complex multipath pipelines and significant delay issues. Currently, most robots use odometer wheel positioning, which essentially records the number of turns the odometer wheel has made to obtain the current position. Due to the transportation of medium in the pipeline, wax deposition and other conditions may form inside the pipe wall, and the positioning wheel may slip when running on the waxed pipe wall. At the same time, defects in the pipeline can cause the robot to experience bumps. Slipping, bumps, and other external influences can cause errors in the position data recorded by the positioning wheel. Especially in long-distance pipeline detection, the error of the mileage wheel continues to accumulate, which will exceed the allowable range of error.

3.1.3 Remote control. At present, in-pipe robots mainly adopt control methods of cable control and wireless communication remote control. Due to the increasing scope of cable control, the control ability will gradually weaken, greatly increasing the difficulty of system operation. Subsequently, scholars adopted optical fibers to replace traditional cables for signal transmission, but when operating in oil and gas pipelines, robots often work at distances of tens of kilometers, making it difficult for even optical fibers to meet the requirements. So some research institutions have conducted research on remote wireless signal transmission of robots, and some have proposed communication methods based on radio waves and radio frequencies [24]. However, due to the signal blocking effect of the pipeline itself, the maximum operating radius of this type of technology can only reach 500m.

3.1.4 Energy supply. The current commonly used streamer power supply method cannot meet the needs of long-distance operations, and the use of battery power supply is limited by existing energy storage technology, making it difficult to achieve a longer moving distance. At present, most pipeline robots still use motor driven methods, but due to the high requirements for energy supply equipment in the narrow space inside the pipeline, the integration of various components not only increases the load of the entire robot, but also affects the stability and reliability of the robot's motion [25].

3.2 Research Direction

3.2.1 Mechanical structure. The future oil and gas in-pipe robots should have a multifunctional structure, modularizing various functions and integrating cleaning, detection, cutting, spraying, welding, and other functions on one robot [26]. At the same time, robots can still maintain good trafficability in underground operations and special forms of oil and gas pipelines with bends.

Dividing the various modules of the robot into sections is also a way to improve performance. The first section mainly installs sensing devices and drag reduction structures, the second and third sections install motion, transmission, and deflection structures, and finally install energy supply and positioning structures according to the robot's operational requirements. By horizontally expanding the pipeline robot, it can avoid the problem of excessive volume while ensuring good performance in all aspects. Of course, cost issues also have to be considered.

3.2.2 Real-time stable control system. It is very difficult to ensure the stability and real-time performance of the robot control system in long-distance and large-diameter pipelines. To achieve reliable control in complex and ever-changing pipeline environments, communication and positioning capabilities also need to be improved simultaneously. Combining infrared and radio waves may be a feasible direction. On the premise of ensuring the quality and stability of long-distance communication, it is also necessary to extend the operating range as much as possible.

3.2.3 Energy supply. How to develop new energy supply technology products for oil and gas pipeline robots is a major challenge for future research. From the perspective of existing technology, utilizing the pressure difference of the medium transported in oil and gas pipelines to achieve energy supply for robots would be a good solution, but this solution has not yet formed a publicly available and reliable theoretical model [27]. To achieve stable and reliable control of fluid-driven pipeline robots, it is necessary to establish a theoretical model and conduct motion dynamic analysis.

4 Conclusion

Although the existing structural types of supported in-pipe robots can complete some pipeline detection and obstacle removal work, their practical applications are still severely limited due to equipment and distance limitations. Although the current oil and gas in-pipe robots are not satisfactory in some aspects, the application of oil and gas in-pipe robots has to some extent improved the detection accuracy, accuracy, and efficiency of oil and gas pipelines. The quality of oil and gas pipelines directly affects the efficiency of oil and gas transportation, so the research on in-pipe robots, especially supported in-pipe robots, is of greater importance. Starting from the structure, continuously improving and solving problems in motion, control, positioning, and energy supply are the keys to the current development of supported in-pipe robots.

References

1. Cheng, Qinglin, et al. "Studies on energy consumption of crude oil pipeline transportation process based on the unavoidable exergy loss rate." Case studies in thermal engineering 12 (2018): 8-15.
2. Liu Q., Li Y., Ren T., et al. "Active Spiral Driven Pipeline Robot. " Robotics, ,36.6 (2014): 711-718.

3. Cosham, Andrew, and Phil Hopkins. "The effect of dents in pipelines—guidance in the pipeline defect assessment manual." International journal of pressure vessels and piping 81.2 (2004): 127-139.
4. Colvalkar, Aniket, Sachin S. Pawar, and Bhumeshwar K. Patle. "In-pipe inspection robotic system for defect detection and identification using image processing." Materials Today: Proceedings 72 (2023): 1735-1742.
5. Zhang, Jie, et al. "Pipe inspection using guided acoustic wave sensors integrated with mobile robots." NDT & E International (2023): 102929.
6. Bhadoriya, Apoorv Vikram Singh, Vijay Kumar Gupta, and Sujoy Mukherjee. "Development of in-pipe inspection robot." Materials Today: Proceedings 5.9 (2018): 20769-20776.
7. Tang, Yang, et al. "A framework for identification of maintenance significant items in reliability centered maintenance." Energy 118 (2017): 1295-1303.
8. CHEN, Xiao, et al. "Passing property design of adaptive support pipeline detection robot." Journal of Central South University (Science and Technology) 49.12 (2018): 2953-2962.
9. Yeh, Chao-Yung, Chen-Ya Chen, and Jia-Yang Juang. "Soft hopping and crawling robot for in-pipe traveling." Extreme Mechanics Letters 39 (2020): 100854.
10. Wang, Zhongwei, et al. "Development of an autonomous in - pipe robot for offshore pipeline maintenance." Industrial Robot: An International Journal 37.2 (2010): 177-184.
11. Kang, Lae-Hyong, and Dae-Hyun Han. "Robotic-based terahertz imaging for nondestructive testing of a PVC pipe cap." NDT & E International 123 (2021): 102500.
12. Ab Rashid, Mohd Zamzuri, et al. "Modeling of the in-pipe inspection robot: A comprehensive review." Ocean Engineering 203 (2020): 107206.
13. Qing-you, Liu. "Research Status and Development Tendency of the Oil and Gas In-Pipe Robot [J]." Journal of Xihua University (Natural Science Edition) 35.1 (2016): 1-5.
14. Yangcaixia, Li Jianjun, xuxiaodong "Traction design and Simulation of supporting oil and gas pipeline robot." China Equipment Engineering 7 (2020): 83-85.
15. Guozhongfeng, Xu Bowen "Motion characteristics and simulation analysis of mechanical differential pipeline robot." Journal of Shenyang University of technology 3 (2022): 295-300.
16. Zhenglikang, fengyongli, lizhanxian, et al. "Structural design and analysis of adaptive diameter all drive pipeline robot." mechanical transmission 47.5 (2023): 67-73.
17. Qiao, Jinwei, and Jianzhong Shang. "Application of axiomatic design method in in-pipe robot design." Robotics and Computer-Integrated Manufacturing 29.4 (2013): 49-57.
18. Shan Yanxia, Fu Bingshuang, Li Ruosong, et al. "Design and research of dual drive pipeline robots based on parallel mechanisms." Mechanical Design 37.6 (2020): 17-23.
19. Cui Xianggui, Zhang Jizhong, Jiang Jinhua "Simulation analysis and optimization design of the variable diameter mechanism of tracked pipeline robots." Journal of Qingdao University (Natural Science Edition) 36.2 (2023): 79-83.
20. Chang Sheng, Liu Yuliang, Wang Zhongchao "Design of a new type of variable diameter pipeline robot." Mechanical Engineer 11 (2021): 64-68.
21. Liu Zenghui, Ma Zhengkuo, Peng Lei "Research on the anti roll mechanism of a dual wheel tracked pipeline robot " Mechanical Manufacturing and Automation 49.5 (2020): 142-145.
22. Tang, Chao, et al. "A pipeline inspection robot for navigating tubular environments in the sub-centimeter scale." Science Robotics 7.66 (2022): 8597.

23. Lee, Dongwoo, et al. "Novel mechanisms and simple locomotion strategies for an in-pipe robot that can inspect various pipe types." Mechanism and Machine Theory 56 (2012): 52-68.
24. Kazeminasab, Saber, et al. "Localization techniques for in-pipe robots in water distribution systems." 2020 8th International Conference on Control, Mechatronics and Automation (ICCMA). IEEE, 2020.
25. Fang D., et al. " Axiomatic design of fully hydraulic driven pipeline robot." Journal of National University of Defense Technology/Guofang Keji Daxue Xuebao 41.6 (2019).
26. Liu, Yan, et al. "A novel offline programming approach of robot welding for multi-pipe intersection structures based on NSGA-Ⅱ and measured 3D point-clouds." Robotics and Computer-Integrated Manufacturing 83 (2023): 102549.
27. Jiang, X. D., Q. H. Sun, and X. Y. Teng. "Dynamic characteristics analysis for an in-pipe robot driven by pressure difference based on CEL approach." Journal of Vibration and Shock 38.23 (2019): 259-264.