

A Review of the Literature on Pipeline Robot Technology Research

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Abstract: As a key technology to ensure the safety of energy transmission and fluid transmission, its development is of great significance to improving the reliability of pipeline systems and promoting industrial intelligence. This paper systematically reviews the research progress and challenges of pipeline robots in the fields of mechanism design, driving methods, motion control, and detection technology. The mechanism design shows a diversified trend: wheeled drive is efficient but not adaptable to complex environments. The Tracked drive has strong barrier-over ability and high energy consumption. Spiral drive is suitable for large pipe diameters but is susceptible to media viscosity. Peristaltic damage is small but has limited speed. Foot type is good and has complex control. Soft-bodied actuation has outstanding flexibility but weak load-bearing capacity. Motion control technology is developing towards intelligence. Traditional proportional-integral-derivative (PID) control is combined with intelligent algorithms (such as neural networks and reinforcement learning) to improve positioning accuracy through multi-sensor fusion, but real-time and complex fluid-solid coupling modeling are still difficult. The detection technology combines multi-source sensing, such as magnetic leakage, ultrasound, eddy current, and vision, and combines deep learning to achieve intelligent defect recognition, but it cannot detect and predict the lifespan of micro defects. Application scenarios extend from oil and gas, drainage pipelines, to special environments such as seabed and electricity, and face adaptability challenges such as high-pressure sealing and grain subsidence. Future research needs to focus on rigid-flexible coupled driving structure, data-model hybrid control framework, multi-physics collaborative detection system, and deepen the adaptability of special working conditions and multi-equipment collaboration mechanisms to break through the limits of pipe diameter adaptation, improve independent operation capabilities, and engineering application level.

Keywords: pipeline robot, mechanism design, motion control, detection technology

1. INTRODUCTION

As an important infrastructure for energy transmission and fluid transmission in modern society, the safe operation of pipelines is directly related to industrial production, energy supply, and social stability. With the continuous expansion of pipeline application scope and the increase in service life, the demand for internal defect detection, maintenance, and repair of pipelines is becoming increasingly urgent. Traditional manual inspection and maintenance methods face many challenges, such as inefficiency, poor safety, and high cost. Pipeline robots have become the key technical means to solve these problems with their advantages, such as automation, intelligence, and repeatability. Research on pipeline robot technology can not only improve the operating reliability of pipeline systems, but also provide important support for the intelligent development of industrial industries, and has significant academic value and engineering application significance.

This review mainly focuses on key issues such as the mechanism design, driving method, motion control, detection

technology, and its performance in different application scenarios. Through the review of related research in the field of pipeline robots in recent years, we aim to reveal the technological development context, existing achievements, and existing shortcomings in this field, and provide direction and guidance for subsequent research. In terms of cutting-edge theory, it involves the cross-fusion of multiple disciplines such as robotics, fluid mechanics, sensor technology, and intelligent control, especially the introduction of software robot technology, bionic driving principles, and intelligent detection algorithms, providing new ideas for the innovative development of pipeline robots.

2. DESIGN AND DRIVING MODE

The mechanism design and driving method of pipeline robots directly determine their ability to pass, adaptability, and operating efficiency in the pipeline. Judging from literature research, domestic and foreign scholars have carried out a lot of research

in this regard and formed a variety of representative technical solutions. According to statistics, among the 97 documents collected, about 35 specifically discuss the mechanism design and driving methods of pipeline robots, involving wheel type, crawler type, spiral type, peristaltic type, foot type, and soft-bodied actuation type.

Wheel-driven pipe robots have the characteristics of a simple structure and high motion efficiency, and are widely used in straight pipe segment inspection. Li Zhiqiang et al. ^[1] designed a new type of variable-movement pipeline robot, which adopts a passive support mechanism combined with the main and secondary springs and a drive mechanism with adjustable inclination. Through theoretical analysis and experimental verification, it is proved that the robot can successfully pass the pipe bending environment with a curvature radius $R \geq 1.5D$. However, wheeled drives have poor adaptability in complex pipelines (such as variable diameters, curves, and obstacle pipelines), and are prone to slipping and stuck problems. Yan Hongwei et al. ^[2] conducted a simulation analysis of the bending process of the wheeled pipe robot through Adams software and found that the relative distance between the center of mass and the pipeline midline of the robot during the bend will significantly affect the movement speed and contact force of the driving wheel. The speed ratio of the outer driving wheel and the inner driving wheel fluctuates significantly during the in-bending and out-bending stages, which shows that the movement stability of wheeled driving in complex pipelines needs to be improved.

The track-driven pipe robot provides greater driving force and friction through the contact between the track and the pipe wall, with better obstacle crossing ability and terrain adaptability. Cui Xianggui et al. ^[3] designed a crawler-type pipe robot with adaptive and active adaptation functions, using a combination of screw nut sub-diameter transformer and disc spring as the diameter transformer mechanism. Dynamic simulation shows that the robot's force transmission performance has been improved by 22.3%, which can overcome larger obstacles. Zhang Jizhong et al. ^[3] further studied the disc spring adaptive mechanism of crawler pipe robots. By establishing mechanical models and dynamic simulation, the rationality of the disc spring

providing positive pressure during the obstacle crossing process was verified. When crossing a 2.5 mm obstacle, the positive pressure of the adaptive mechanism to the pipe wall can reach 223.43 N(newtons). However, track-type driving also has the disadvantages of complex structure, large friction resistance, and high energy consumption, especially in small-diameter pipelines.

The spiral-driven pipeline robot uses the interaction between the spiral blades and the inner wall of the pipeline to generate propulsion force, which has the advantages of high driving efficiency and large adaptability to the pipe diameter range. Lee et al. ^[4] developed a capsule Ondol pipeline detection robot that uses the spiral drive principle to verify its mobility and image reception quality in curvature pipelines through laboratory testing. Jin Hangjia ^[5] conducted a systematic study of the spiral-driven granary robot, established a mechanical model and kinematic model between the spiral wheel and the grain surface. Through discrete element-multibody dynamic coupling simulation, the fastest straight-travel speed of the developed type II robot in a three-dimensional complex grain surface environment reaches 0.99 m/s, and the climbing speed is 0.56 m/s. However, spiral drives are prone to slipping in viscous media or pipes with large amounts of sediment, and wear of spiral blades can affect the durability of driving performance.

The peristaltic pipeline robot imitates the movement of worms and advances through the expansion and anchoring of the body. It has the characteristics of smooth movement and little damage to the inner wall of the pipeline. Song Maozheng et al. ^[6] designed a worm-imitating pneumatic soft pipe robot, consisting of a radial expansion driver, an axial telescopic driver, and an omnidirectional bending driver. Experiments show that the robot can reach a fastest speed of 5.05 mm/s in the pipe diameter range of 50-60 mm, and the maximum load-bearing ratio is 10:1. Liu Hongbin et al. ^[7] developed a hydraulically driven peristaltic crawling pipeline detection robot, which verified its operating stability and driving ability under complex operating conditions through multi-body dynamics simulation and physical prototype testing. However, the movement speed of the peristaltic drive is relatively slow, making it

difficult to meet the needs of rapid detection of long-distance pipelines.

Foot pipe robots have good obstacle-over-blocking ability and terrain adaptability, and can move flexibly in complex pipeline environments. Li Peng et al. studied the kinematics and gait planning of the four-legged wall-climbing robot in the inner wall of the pipeline, and used the improved Newton iterative method to solve the problem of problem of body positive kinematics. Through Adams' simulation and experiments, the robot's all-around wall-climbing ability in horizontal and vertical pipelines was verified. Zhang Tie et al.^[8] further planned the circumferential motion posture of the four-legged pipeline wall-climbing robot and designed a circumferential motion mode including foot posture adjustment, fuselage rotation, and fuselage translation. The experimental results verified the correctness of the pose planning. However, the control complexity of foot drive is high, requiring precise coordination of the movement of each foot, and it is difficult to arrange a sufficient number of feet in small diameter pipes.

As an emerging driving method, software-driven pipe robots have good flexibility and adaptability and can pass through narrow and curved pipes. Li Xingwang et al. ^[9]proposed a pneumatic soft four-legged robot based on bistable drivers. The driver uses spring energy storage and can quickly jump between two stable states, driven by compressed air. The terminal output force is 2-4 times that of the software driver under the same driving conditions. The average crawling speed of the robot is 158.62 mm/s and can carry a load of 400 g. Qi et al.^[10]developed a pneumatic soft serpentine robot that uses traveling wave motion to move in constrained environments, and verified its motion feasibility through simulation and experiments. The disadvantage of software drivers is that the load-bearing capacity is relatively weak, and the driving control accuracy needs to be improved.

3. MOTION CONTROL TECHNOLOGY

Motion control is the core technology for pipeline robots to achieve independent operations, which directly affects the robot's motion accuracy, stability, and adaptability. With the development of intelligent control theory and sensor technology, the motion

control technology of pipeline robots has been constantly innovating, and a variety of advanced control methods and strategies have emerged. Among the collected literature, there are about 25 studies on motion control technology of pipeline robots, including traditional control methods, intelligent control algorithms, and multi-sensor fusion technology.

Traditional control methods are still widely used in pipeline robot motion control, among which, PID control is widely used because of its simple structure and ease of implementation. Shi Tao et al. ^[11]designed a fluid-driven pipeline robot and proposed a speed control scheme based on PID control. By detecting friction resistance in real time, the robot can control its speed of the robot in the pipeline. Cui Xianggui^[12] used the PID algorithm to adjust the motor speed in the control of the tracked pipeline detection robot, and verified the effectiveness of the control algorithm through experiments. However, traditional PID control is poorly adaptable in complex nonlinear systems and is difficult to cope with parameter changes and external interferences during the movement of pipeline robots.

The introduction of intelligent control algorithms provides new solutions for motion control of pipeline robots, among which methods such as fuzzy control, neural network control, and reinforcement learning have been widely studied. Zhang Xing et al. ^[13]established a multi-body dynamic model of a tandem pipeline robot and a two-way flow-solid coupling joint simulation model of Adams and Matlab/Simulink, and optimized the robot structural parameters with neural network algorithms and genetic algorithms. The optimized robot axial, vertical, and pitch acceleration extreme values were reduced by 74.7%, 38.1%, and 37.27%, respectively. Yang Shuangye et al.^[14] discussed the application of AI technology in drilling operations and equipment, pointing out the huge potential of intelligent control algorithms in motion control of pipeline robots. Gao et al.^[15] proposed a quadruped robot motor skills learning method based on an environmental feedback mechanism, introducing expected state reward guidance based on the soft actor-critic algorithm (SAC), which improves the bionic gait learning

effect and training efficiency of quadruped robots. Experiments show that improved algorithms are better than simple SAC algorithms. The advantage of intelligent control algorithms is that they can handle complex nonlinear problems and uncertainties, but often require a large amount of training data and high computing resources.

Multi-sensor fusion technology plays an important role in the motion control of pipeline robots. By fusing multiple sensor information, the robot can improve the robot's perception ability and positioning accuracy of the environment. The modular synchronous autonomous diameter gas pipeline robot designed by Zheng Jie et al. ^[16] is equipped with a CMOS image sensor and an infrared reflection sensor, which can detect and record the defect locations of various defects such as rupture, corrosion, and misalignment in the pipe. Zhang Siyuan et al. (2024) studied the positioning algorithm of a serpentine pipeline robot based on strap-inertial navigation, used a nine-axis inertial measurement unit (IMU) fusion Kalman filtering algorithm to compensate the positioning system, and used the quaternary method to construct the attitude matrix of the strap-inertial navigation system. Experiments show that the maximum positioning error of this algorithm is no more than 4.7%. Wanfu et al. ^[17] proposed a method to optimize the fatigue life prediction of continuous oil pipes based on online detection data, emphasizing the importance of sensor data in robot status monitoring and control. The key to multi-sensor fusion technology lies in how to effectively deal with the time synchronization and spatial registration issues of different sensor data, and how to extract useful information from massive data.

The path planning algorithm is an important part of the motion control of pipeline robots and aims to plan a safe and optimal operating trajectory. Li Gang et al. ^[18] systematically analyzed and sorted out various path planning methods during the inspection process of inspection robots, explained the application of algorithms in different scenarios such as substations and transmission lines, and summarized the current research status and improvement methods of various path planning algorithms. Liu Zeming^[19] conducted gait planning research on multipedal pipeline robots and proposed

two diagonal gait schemes. Through simulation analysis, the movement speed and stability of different gaits were compared. The results show that the independent diagonal gait scheme is more suitable for the work needs of multipedal pipeline robots. Path planning algorithms need to consider the complexity of the pipeline environment, the kinematic and dynamic constraints of the robot, and the requirements of the work tasks. How to quickly generate the optimal path in complex environments is still a problem to be solved.

Fluid-solid coupling control is of special importance in fluid-driven pipe robots, and the interaction between fluid dynamics and robot motion needs to be considered. Teng Xiaoyan et al.^[20] constructed a flow-solid coupling dynamic model of a flexible multi-body system of a differential pressure pipeline robot based on the coupling Euler-Lagrange (CEL) method, and analyzed the influence of factors such as the number of cabins and inner diameter on the robot's dynamic response. The results show that the speed stability of the 5 cabins and the 3 cabins and the 3 cabins and sealing cup is greater, and the adaptability is worse. Jiang Xudong et al. ^[21] further used the CEL method to analyze the power characteristics of the pressure differential-driven pipeline robot and found that the initial driving pressure difference of the pipeline robot entered the pipeline, and the sealed leather bowl produced peak equivalent stress when it was located in the curve of the small curvature radius. As the inner diameter of the pipeline decreases and the length of the cabin increases, the equivalent stress, average friction, and average driving pressure difference of the sealed leather bowl increase. The difficulty of fluid-solid coupling control lies in establishing an accurate fluid-solid coupling model and solving complex fluid mechanics equations in real time.

4. APPLICATION SCENARIOS

One of the core functions of pipeline robots is to realize the detection and evaluate internal defects of pipelines. The advanced nature of detection technology directly determines the robot's operating capabilities and application scope. With the development of sensor technology and signal processing algorithms, the detection technology of pipeline robots has been continuously innovated, forming a variety of efficient and accurate detection

methods. Among the collected literature, about 30 studies involving pipeline robot detection technology and its application in different application scenarios, including magnetic leakage detection, ultrasonic detection, eddy current detection, visual detection, and other technical means.

Magnetic leakage detection technology is one of the most widely used technologies in pipeline defect detection. It can detect defects such as corrosion, cracks, and other defects in the inner wall of the pipeline based on the principle of magnetic permeability change of ferromagnetic materials. Xin Jiaying et al. [22] reviewed the cutting-edge progress in research on detection technology in oil and gas pipelines, pointing out that the leakage magnetic detection technology has the advantages of fast detection speed and high detection accuracy, and can be used to detect metal loss defects in the inner wall of the pipeline. Jian Yurui [23] studied the magnetic leakage detection and control circuit of the inner wall of a small-diameter pipeline. Through finite element magnetic field simulation, the impact of the magnetization device structure and defect size on the leakage magnetic field was analyzed, and a leakage detection exciter structure was designed, and an experimental testing system was built. The experiments showed that this method can effectively detect defects in the inner wall of a small-diameter pipeline. However, magnetic leakage detection does not apply to non-ferromagnetic material pipelines, and the detection results are greatly affected by the lift-off value.

Ultrasonic detection technology utilizes the propagation characteristics of ultrasonic waves in the medium to achieve accurate measurement of pipeline wall thickness, defect location, and size. Hu Chunyang [24] summarized the current status of external detection technology for subsea pipelines and pointed out that ultrasonic detection methods, such as ultrasonic waveguide detection and electromagnetic ultrasonic detection, have important application value in external detection of subsea pipelines. Yu Bin et al. [25] discussed the application prospects of ultrasonic detection technology in robot structure health monitoring in the study of key technologies for hydraulic drive of foot robots. The advantages of ultrasonic detection are high detection accuracy and quantitative analysis of defects, but

they have high requirements for detection conditions, require good coupling media, and have relatively slow detection speed.

Eddy current detection technology is based on the principle of electromagnetic induction and can be used to detect surface and near-surface defects of conductive material pipes. Zhou Zhaoming et al. [26] proposed an eddy current detection method, designed to use a differential curved surface probe to detect defects of duplex stainless steel continuous tubes [26] The array probe can fully cover 360° to detect continuous tubes with a diameter of less than 50.8 mm. This method can detect longitudinal and axial defects, overcoming the limitation that magnetic leakage detection can only detect unidirectional defects in carbon steel. The advantage of eddy current detection is that it does not require coupling media, has a fast detection speed, but has limited detection depth and weak detection ability for deep defects.

Visual detection technology uses cameras to collect internal images of the pipeline and combines image processing algorithms to achieve defect recognition, which is intuitive and real-time. Jack et al. (2018) developed a deep learning-based automatic detection method for sewer pipeline defects, using the Faster R-CNN model to train and detect CCTV images. Experiments show that the method has high detection accuracy, and mAP reaches 83%. Dong Qingqing [27] designed the mechanical structure and control system of a pipeline crack detection robot, developed a pipeline crack image processing system based on OpenCV, and proposed a crack detection method including median filtering, morphological gradient algorithm, Otsu threshold segmentation, Hough transformation, and other steps. The feasibility of this method was verified in experiments. The disadvantage of visual detection is that it is greatly affected by lighting conditions and cannot detect small defects.

Multi-sensor fusion detection technology integrates multiple detection sensors to achieve a comprehensive and accurate assessment of pipeline defects. Sun Jing et al. [28] studied a new comprehensive method of parallel mechanisms equivalent to the motion of the series-parallel mechanism, providing new ideas for the structural design of multi-sensor fusion detection robots. The

four-legged wall-climbing robot designed by Li Lin et al. [29] is equipped with a variety of sensors, which can achieve comprehensive detection of internal defects of GIS pipelines. Multi-sensor fusion detection technology can give full play to the advantages of each sensor and make up for the shortcomings of a single sensor, but it is necessary to solve key problems such as sensor data fusion algorithms and system integration.

In terms of application scenarios, pipeline robots have been widely used in various fields such as oil and gas pipelines, drainage pipelines, subsea pipelines, and power pipelines. In the field of oil and gas pipelines, Zhang Jun et al. [30] designed a WLAN-based spiral pipeline detection robot remote measurement and control system, realizing the detection of coating defects of 100–120 mm diameter pipelines, with a coating thickness detection

5. SUMMARY AND PROSPECT

To sum up, the research on pipeline robot technology shows a trend of multi-dimensional innovation. In terms of mechanism design and driving methods, traditional wheeled and crawler vehicles improve adaptability through structural optimization. New technologies such as spiral drive, peristaltic drive, and software drive break through the pipe diameter limitations. Software-driven has become a research hotspot, and bionics provides new ideas. Motion control is intelligent, and PID and neural network algorithms are combined to improve accuracy by integrating multiple sensors. Detection technology is integrated with multiple technologies, and the complementary magnetic leakage, ultrasound, vision, etc., are complementary, and deep learning promotes defect recognition. Application scenarios have now expanded to special areas such as the seabed and the granary. However, there are still many limitations in current technology. The pipe diameter adaptation range of the mechanism design is limited; the soft robot has weak load bearing, spiral drive is easy to slip, and the steering and diameter reduction mechanisms in complex pipelines are insufficient. The real-time performance of algorithms in motion control is poor, and multi-sensor fusion needs to be improved. The detection technology has a high detection rate of micro defects, but lacks longevity. In application scenarios, the waterproofing and

deviation of less than $\pm 3.2\%$. In the field of drainage pipelines, Ju Ming [31] studied the structure of the rolled pipe laying system of the submarine pipeline, providing a reference for the application of submarine pipeline inspection and maintenance robots. In the field of power pipelines, Li Gang et al. [18] reviewed the path planning methods of power inspection robots and pointed out the important application prospects of pipeline robots in power pipeline inspection. Different application scenarios have different performance requirements for pipeline robots, such as subsea pipeline robots need to be waterproof and pressure-resistant, and oil and gas pipeline robots need to be corrosion and explosion-proof, which has also promoted the targeted development of pipeline robot technology.

energy of the seabed robot and the anti-subsidence technologies of granary robots need to be broken through, and the research on the coordination mechanism is insufficient.

This article believes that breakthrough research on pipeline robot technology can be carried out from four aspects. The mechanism design can implement a "hard-flexible coupling" driving structure, fusing shape memory alloys and silicone materials, imitating the muscle structure of the octopus tentacles to achieve adaptive deformation, and introducing piezoelectric ceramics to optimize the dynamic response of the variable diameter mechanism. Motion control can introduce the "data-driven + model guidance" framework, using transfer learning to shorten the on-site training cycle of reinforcement learning, combine the physics engine and fiber grating sensing to achieve synchronous fusion of trajectory planning and multi-sensors, and improve the prediction accuracy of flow-solid coupling through physical information neural network (PINN). The detection technology focuses on the development of a "multi-physics collaboration" system, integrates terahertz imaging and distributed fiber sensing, and builds a defect feature database to achieve accurate identification and life evaluation. Application scenarios can target the development of a subsea robot fuel cell-wave energy hybrid power supply system and a granary

robot particle mechanics drive model, establish a modular collaborative operation platform, and promote the integration of standardization and industrial Internet.

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