Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 3, No. 3, 2022

Research Status and Development Trend of Oil and Gas Pipeline Robot

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Abstract: The oil and gas pipeline will have defects such as wear, cracks, corrosion, aging and mechanical damage in the working process, which need to be detected and repaired in time. At present, there are various types of robots in the field of pipeline inspection, including wheeled robots, tracked robots, PIG robots, screw driven robots, walking robots, and inchworm robots. In this paper, the specifications, design and performance of different types of in pipe inspection robots are reviewed. Finally, a summary and prospect are made to provide a theoretical basis for the design and research of robots in this field.

Keywords: Oil and gas pipeline, Pipeline robot, Defect detection, Development trend.

1. Introduction

With the continuous progress of science and technology and increasing energy demand, pipeline transportation technology has made great progress and is widely used in the field of oil and natural gas. Pipeline transportation is one of the safest and most economical ways to transport oil, liquid, gas, chemicals and other fluids [1]. As the service time goes by, the pipeline will have problems such as wear, cracks, corrosion, aging and mechanical damage. As the liquid gas transported by the oil and gas pipeline is flammable and explosive, once the oil and gas pipeline fails, it is very easy to cause major safety accidents, seriously endanger the safety of local people's lives and property, and may cause catastrophic consequences to the local ecological environment. Therefore, it is of great practical significance to develop an efficient pipeline repair, cleaning and maintenance robot [2].

Most oil and gas pipelines are buried underground, and the detection environment is relatively complex, so it is impossible to directly detect the underground pipeline when conducting pipeline leakage detection. Limited by technology and detection methods, the detection and maintenance of oil and gas pipelines are difficult. In order to ensure the safety of oil and gas pipelines, the methods of manual excavation and patrol inspection were usually used in the past to complete the regular inspection or early scrapping of oil and gas pipelines. These methods will cause a lot of economic losses, and the rate of missing inspection is high, and the work efficiency is low. In the process of data acquisition, the pipeline robot is affected by the surrounding environment, and there is also a large noise interference. The superposition of many interference factors may lead to false alarm, missing alarm and other situations in pipeline leakage detection. Therefore, how to accurately identify and locate pipeline defects and timely repair them under complex working conditions and environments is the key point in this field.

The pipeline robot is mainly a special robot developed for inspection, spraying, interface welding, foreign matter cleaning and other maintenance operations of oil and gas pipelines. It integrates intelligent mobile carrier technology and pipeline defect nondestructive testing technology. The pipeline inspection robot must have high working efficiency, good mobility, stability and reliability, and be able to adapt to various pipeline sizes. This kind of pipeline inspection robot can reduce human intervention, avoid dangerous environments, and enter places that are usually impossible for humans to enter, making inspection easier and more economical [3]. This paper will consider the size and shape, adaptability, operability, types of inspection methods, loaded equipment and other parameters of the pipeline in the design process, classify the pipeline robots with different motion forms, discuss the advantages and limitations of the design concept of each pipeline inspection robot, and provide a theoretical basis for the design, selection and research of robots in this field.

2. Classification of Pipeline Inspection Robots

The oil and gas pipeline robot is a complex of advanced technologies such as detection technology, mechanical-electrical integration technology, intelligent mobile technology, etc. According to the working environment of pipeline, it can be divided into in pipe robot and out pipe robot; According to the motion mode, it can be divided into active motion mode and passive motion mode; According to the difference of mechanical structure and other characteristics, it can be divided into bionic type, vehicle type, support wheel type, crawler type, and screw driven type. Combining the motion mode and mechanical structure, the pipeline inspection robot can be further classified into: wheel driven robot, tracked robot, PIG robot, screw driven robot, walking robot, inchworm robot [4], as shown in Figure 1.

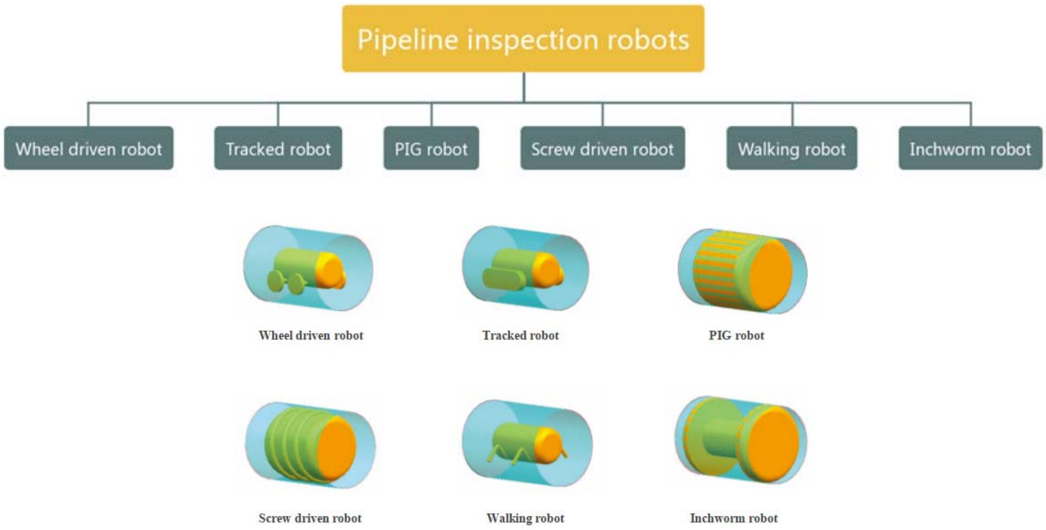

Figure 1. Classification of pipeline inspection robots

2.1. Wheel driven robot

The wheel driven robot is similar to a flat car, which is widely used in the pipeline inspection. Its working principle is to push the robot forward by driving motor. Most wheel driven robots have an environment adaptation mechanism, which enables their wheels to ensure continuous traction [5]. These robots are equipped with some detection sensors to enter the pipeline for detection. Simple type of wheel driven pipe robot, only used for horizontal movement. The wheeled robot has simple design, good mobility and high efficiency in operation, and is widely used in oil and gas pipeline inspection. Although a lot of research has been carried out on wheeled inspection robots, there are still great difficulties in moving in bent pipes or right angle pipes [6].

In order to effectively detect pipeline defects, Mohammed MN et al. [7],developed an autonomous mobile robot with ultrasonic sensors, and communicated through GSM and GPS. The robot integrates wireless functions to facilitate viewing of collected data and images. The robot's IP camera is also used for visual inspection, integrated with wireless functions, and easy to view the acquired data and images. The system can effectively observe, detect, quickly analyze and diagnose, and work reliably in a closed and dark environment.

Aras et al. [8], put forward a model of three pressure wall sprockets, used SolidWorks software for modeling, and carried out stress and strain analysis and other simulation. The robot adopts an adaptive diameter changing mechanism, which enables the robot to adapt to the change of pipe diameter. The experiment proves that the average speed of the robot in the pipeline is 0.0096 m/s, and the robot can accurately move in a straight line in the pipeline.

Atsushi Kakogawa et al. [9], developed a multi link articulated wheeled pipeline robot, as shown in Figure 2. The robot is composed of four links connecting their joints, and moves back and forth through the driving wheels on each joint axis. The torsion coil spring presses the wheel onto the inner wall of the pipe, making the robot move upward in the vertical pipe. When the robot enters the bend, the joint can be opened and closed according to the shape of the bend, so that the robot can easily pass through the bend pipe.

Figure 2. Multi link articulated wheeled pipeline robot

Hadi et al. [10], designed a small inspection robot that can move in inclined, vertical and curved pipes. The robot uses shape memory alloy spring as the actuator of the adaptive arm. The author establishes a CAD model on SolidWorks, carries out dynamic simulation on ADAMS, and carries out simulation in MATLAB Simulink software. The experimental results prove the adaptability of the robot to the environment and its ability to move in inclined, vertical and curved pipes.

Li et al. [11], developed a pipeline robot composed of six symmetrical supporting wheels, motors and advanced control systems, which is specially used for oil pipelines with diameters ranging from 1219 mm to 1440 mm, as shown in Figure 3. After several months of actual testing, the robot has achieved good results in traction, climbing ability, obstacle avoidance ability, running endurance, etc. The test results show that the inspection robot can meet the requirements of CNPC.

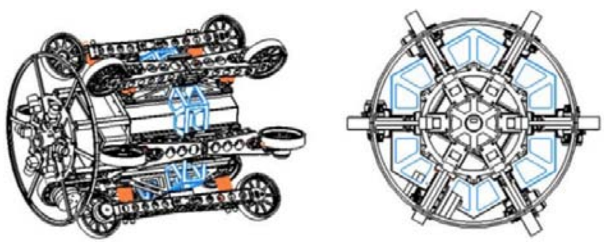

Figure 3. Multi link articulated wheeled pipeline robot

Aras et al. [12], developed a pipe inspection robot, which has an adaptive mechanism controlled by a microcontroller and can monitor and inspect pipes with diameters ranging from 215mm to 280mm. The performance evaluation results of the robot show that it can navigate accurately along the straight path in the pipeline.

2.2. Tracked robot

Tracked robot is evolved from wheeled pipeline robot. This kind of robot uses crawlers to drive instead of wheels.Crawler robot provides sufficient traction, good stability and obstacle surmounting ability. Crawler robot has complex structure, high power consumption and strong bearing capacity. It consists of three key components: center body, track and pantograph mechanism. However, robots also face some challenges, including poor mobility, slow speed and difficult driving [13].

Chang Sheng et al. [14], proposed a tracked robot that can adapt to different pipe diameters in view of corrosion, fracture, etc. of pipes and in combination with the pipe inner diameter adaptive problem of current market pipe robots. Through SolidWorks modeling and design analysis, the robot can perform tasks in pipes with diameters ranging from 300 mm to 350 mm, and has strong adaptability to pipes with different diameters and flexible diameter change.

Zhao et al. [15], proposed a tracked robot, which has three tracks, and the angle between tracks is 120 degrees, as shown in Figure 4. It can be adjusted independently by electric push rod to adapt to the radius of the track. The robot is equipped with a pressure sensor to check the traction; The encoder sensor obtains the actual speed of the robot, the laser radar sensor is installed in front of the robot to obtain information about changes in pipe diameter, irregular obstacles or joints, and the accelerometer tracks whether the attitude is balanced.

Figure 4. Multi link articulated wheeled pipeline robot

Kwon et al. [16], designed a caterpillar robot with three caterpillar chains for small pipes, which can adapt to diameters of 80mm to 100mm, as shown in Figure 5. The robot can steer by independently controlling the speed of each track wheel. The unique connection between the two robot modules is a spring for easy navigation. The robot uses two modules to control independently in order to turn the T-tube.

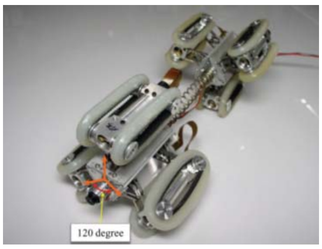

Figure 5. Small tracked robot

2.3. PIG robot

PIG is one of the commonly used inspection robots at present. It uses the flowing pressure of water to work to clean or monitor the pipeline. Use PIG transmitter to launch PIG into the pipe, and use the pressure of fluid in the pipe to convert it into the power of robot motion, which can accurately control its speed, and the robot can operate very stably [17]. However, because the pressure of fluid is used as the driving source, the motion of PIG robot is limited to the large diameter pipeline with sufficient pressure conditions. The problems of traditional PIG are mainly due to the lack of failure activity caused by the change of pipe diameter and sharp turns. The quick opening and closing of valves inevitably produce liquid hammer, which generates pressure in the pipeline and reduces the operation efficiency. The wireless communication remote control adjustable structure improves the flexibility and mobility of passing through bends and branches by changing the pipe diameter, and reduces the impact of the hydraulic hammer [18].

In order to improve the flexibility of PIG robot through bending pipes, Ramirez Martinez et al. [19], developed a geometrically adjusted PIG robot, which can improve the detection accuracy by carrying ultrasonic sensors through concave and convex pipes. The system reduces the risk of PIG robot being stuck in the pipeline, and has a joint drive system, which can reduce the energy consumption of the system.

The increase of the pressure in the pipe will lead to the increase of the robot's motion speed, which will cause wear to the pipe wall and damage to the robot itself. In this regard, Mishra et al. [20] proposed a pipeline inspection robot based on the kinematics model that predicts the position of the robot in the pipeline. The robot is equipped with a variety of sensors, which are used to cross the crude oil pipeline to achieve pipeline cleaning and leakage detection, as shown in Figure 6. The pipeline robot can keep the speed unchanged during operation, and has no damage to the pipe wall during operation.

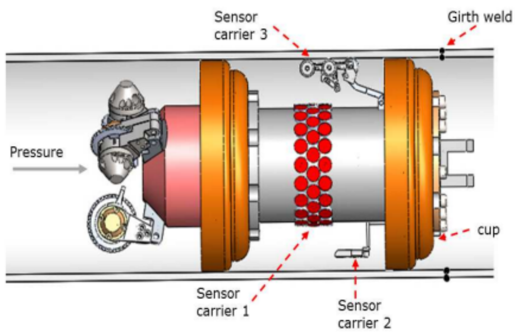

Figure 6. PIG robot

Pasha et al. [21], proposed a low-cost pipeline nondestructive testing robot based on magnetic flux leakage testing technology. The robot consists of a circular ceramic disk. This disc helps to produce and distribute magnetic flux uniformly throughout the pipe. The magnetic flux generated is determined by MAG3110 TMR sensor and HMC5380 AMR sensor. The experimental results show that AMR and TMR magnetometers combined with permanent magnets can detect defects in ferromagnetic pipes.

Tan et al.[22], designed a speed regulating PIG robot based on butterfly bypass valve, as shown in Figure 7. It consists of PIG main body, control unit, execution unit and speed acquisition unit. The valve structure includes a slider crank mechanism to drive the butterfly valve and regulate the flow and speed of the PIG robot. The butterfly valve bypass valve is composed of valve disc, push rod and bearing seat above the support valve disc. In addition, three odometer wheels are located at the rear of the robot, which provides the speed and position of PIG in the pipeline.

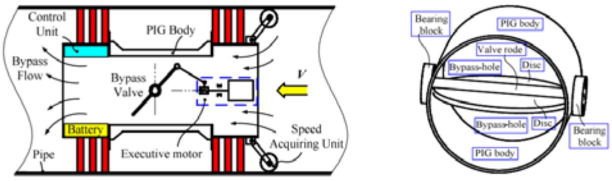

Figure 7. The structure of butterfly bypass valve speed regulating robot

Dacon Inspection Services Co., Ltd. has designed an in pipe inspection robot system that can inspect 90 degrees bends. SeeSnake, a flexible pipeline robot system developed by the company, is equipped with MFL sensors to detect and measure wax, scale and non-magnetic gaskets in the pipeline [23].

Many robots developed by Rosen Group are used for pipeline cleaning and inspection. In the pipeline, there are several wheels in front of and behind the robot, and the center is supported by a cup or disk. The robot system is developed for cleaning with brush magnet. The system is called Rocombo MFL-A/XT In Line service and is used to detect metal loss and abnormality in the pipeline. Rocombo MFL-A/XT, Rocombo MFL - c/XT and Rocombo MFL-A require a minimum turning radius or bending radius of 1.5 times the pipe diameter [24].

2.4. Screw driven robot

The front wheels of the screw driven pipe inspection robot incline at a certain angle to control the circular motion of the robot. Therefore, in the process of driving motion, the robot has both rotary motion and translational motion [25]. These robots use fewer actuators, which is conducive to reducing weight, power consumption, and production and maintenance costs. The screw driven robot is very flexible and can adapt to pipes of different diameters.

Kurata et al. [26], proposed a spiral rotating inspection robot for flexible pipes. The whole body of this type of robot is in spiral motion, and the body will not drag along the pipe wall, so it will not harm the pipe wall, and it will not hinder the flow of liquid. The spiral motion of the robot is realized by manipulating 4 pipe columns with 4 drivers.

The screw driven pipeline inspection robot is faced with the problems of passing through bends, branches and vertical pipelines. Li Peng et al. [27], designed a pipe detection robot, which can not only pass obstacles, but also turn in branches, and also adapt to changes in pipe structure, such as moving in circular and square pipes. Its motion mode is shown in Figure 8.

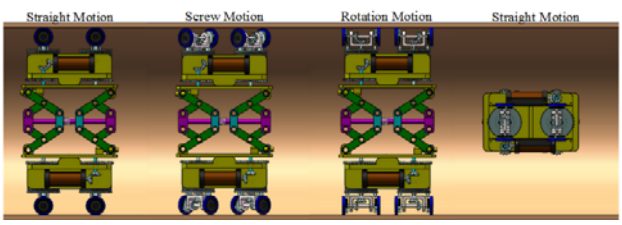

Figure 8 Multi motion mode of screw driven robot

Li Tao et al. [28], proposed a parametric simulation system based on ADAMS secondary development technology and a simple design strategy to solve the problem of rapid design of screw driven pipe robot. A simple design strategy is put forward, and the design application of 225 mm pipe is studied. The results show that the parameterized simulation system can quickly establish and test various spiral driven pipe robot models by inputting only some design parameters.

Shan Yanxia et al.[29] , proposed a dual drive pipeline robot suitable for medium pipelines based on the characteristics of the new 3-UPU parallel mechanism with strong load capacity and simple internal structure. The robot uses parallel mechanism as the supporting driving mechanism to realize the supporting motion mode, including turning motion and walking in non cylindrical pipes, and has good turning performance. The robot has high operation efficiency, compact structure and good stability when working, and can well meet the tasks of detection, obstacle crossing and turning.

Nishimura et al. [30], proposed a spiral adaptive robot, which is composed of only two motor drivers and has the ability of path selection. The robot has three motion modes, which can be easily navigated through elbows and branches. The robot is driven by a screw and has steering and rolling modes; It has good adaptability, can work in pipe diameters ranging from 109mm to 129mm, and can pass through various elbows and horizontal T-joints.

Nayak et al. [31], developed a wall pressure spiral robot, which includes three modules - rotor, stator and control unit. The rotor module has three wheels mounted on the periphery with a helix angle of 15 degrees. The wheel of the rotor moves longitudinally in the pipe along the spiral path on the inner surface of the pipe. The robot is applicable to the inspection of pipes with inner diameter between 127mm and 152mm, as shown in Fig. 9. It can pass through vertical and horizontal pipes, and can easily pass through the elbow of pipes.


Figure 9. Wall pressure spiral robot

2.5. Walking robot

Walking pipe robot is driven by walking legs with multiple degrees of freedom. It can crawl in the pipe and cross obstacles encountered in the process of movement. In order to enable the robot to detect in the pipe, it is necessary to design extremely complex mechanical structures and many drivers, which makes the system bulky and faces challenges such as manufacturing difficulties, trajectory generation, inverse kinematics, and system control [32].

Savin et al. [33], proposed a walking robot based on state observation of Riccati equation, as shown in Figure 10. This state observer helps to control the connection of the robot smoothly. The author shows how to generate motion trajectories for robots. The trajectory generation requires the position and direction of the robot. The author uses a heuristic method, that is, the direction vector, to get the direction of the robot. The trajectory generation requires multiple iterations, and it is not necessary to provide an accurate direction for the algorithm at the initial stage [34]. Subsequently, Savin et al. [35], studied the motion planning algorithm based on random search random tree, namely RRT algorithm. The algorithm represents the pipe as a point cloud. This representation is realized by using some distance detection sensors, namely, laser radar and stereo camera system.

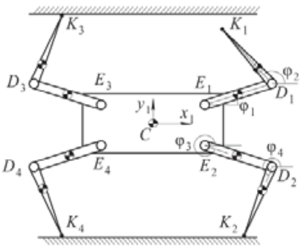

Figure 10. Walking robot based on state observation of Riccati equation

2.6. Inchworm robot

Inchworm robot is a kind of bionic robot. The robot pushes itself through repeated contraction and expansion. In the process of movement, the robot has less friction with the pipe wall and better obstacle surmounting ability. However, due to its limited traction capacity, slow moving speed and large energy loss, the robot is only suitable for small pipes and pipes with short distance [36]. The inchworm robot has effectively overcome the problem that the wheeled robot wears the pipe wall seriously, and has also surpassed the wheeled robot in obstacle surmounting, so it is widely used in small pipe diameter and short distance tasks.

Qiao J et al. [37], proposed an inchworm robot with self-locking mechanism to improve the traction ability of the pipeline robot and avoid its traditional limitations. The robot's traction ability is increased through the spiral link and spring link. The test results show that the static force measured by the robot is 15.2 N, which is 43 times higher than the traditional static force 0.35 N.

Chablat et al. [38], designed a bionic robot by imitating the movement of worms. The robot is composed of two parts: one is the movement part, and the other is the part with outriggers. Three legs with grooved follower are used to realize the movement of the track. At the same time, the author also discussed the static algorithm in the clamping process, and deduced the relationship between the contact force between the pipe and the leg by using the bending moment equation and Coulomb friction law. The prototype of the robot is shown in the Fig. 11 .

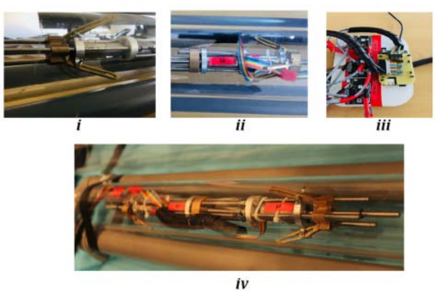

Figure 11. Prototype of Inchworm robot

Takagi et al. [39], studied and made a mobile inchworm robot prototype suitable for narrow spaces, as shown in Figure 12. The prototype uses double network hydrogel on the foot of inchworm robot to enhance the friction performance of the robot. By applying current to DN gel, the friction coefficient can be reduced from 0.04 - 0.07 to 0.02. The author discusses the physical principle of the inchworm search robot's walking motion and the actual mechanism of providing thrust for the walking motion. The model realizes a single step of 40 seconds and a travel distance of 28.4mm, so there is much room for improvement in driving speed and flexibility.

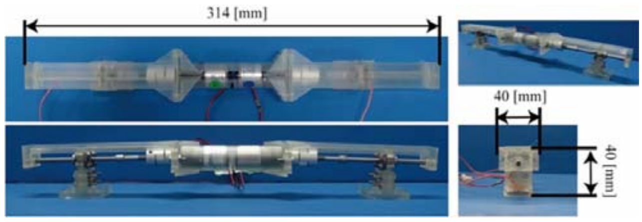

Figure 12. Inchworm robot

Xu Hongtao [40], considered the limitations of traditional robots that rely on media to work in pipelines, designed a peristaltic electromagnetic driven pipeline traction robot that can adapt to non fluid and unconventional fluid pipelines, and simulated the model in ADAMS software. The experimental results show that the robot can work normally in the pipeline, and can meet the special working conditions, at the same time, it has a certain obstacle avoidance ability, which provides a new solution for the inspection and maintenance of conventional or special oil and gas pipelines.

Hayashi et al. [41], studied and developed a walking robot with dual network friction control, as shown in Figure 13. The robot is equipped with an annular tube on the end node, and the clamping mechanism is improved, which can withstand a clamping force of 160N. The retaining mechanism has a structure similar to that of a car tire wheel, which can help reduce the volume size. The robot can turn in six directions by operating the EFPA unit. The robot is suitable for pipes with a diameter of 55mm~75mm. Experiments show that the inchworm walking robot can achieve high-speed pipeline detection by properly controlling the friction of DN gel.

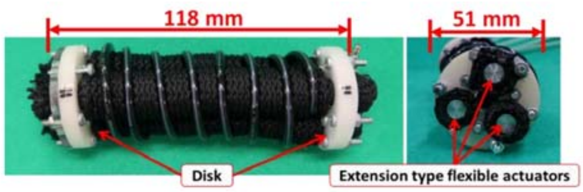

Figure 13. Flexible pneumatic robot

3. Results and Discussion

It can be seen from Table 1 that different types of pipeline inspection robots have their own advantages and disadvantages. The wheeled wall pressing robot can be used in most places. Most wheeled robots are equipped with four-bar linkage adaptive mechanisms, but the steering ability and driving ability need to be improved. Crawler type robots can be used in situations that require greater traction. They have greater stability and traction, strong obstacle surmounting ability, and can carry inspection tools. PIG robot is suitable for long-distance pipeline detection, but it is difficult to pass through pipes of different diameters, and it is also difficult to make sharp turns in pipes. The steering and backward driving ability of the screw driven pipeline inspection robot needs to be improved. The structure of walking pipeline inspection robot is complex and has great development space. The inchworm robot has weak traction ability and slow movement speed, which will cause certain wear on the inner wall of the pipe, but it can move flexibly in complex pipes.

Table 1. Performance comparison of Pipeline inspection robots

Motion mode	Driving speed	Obstacle surmounting	Active steering	Motion reliability	Pipe diameter adaptability	Robot structure
Wheel	Excellent	Average	Good	Good	Excellent	Excellent
Track	Good	Excellent	Average	Excellent	Excellent	Good
PIG	Average	Average	Average	Excellent	Poor	Good
Screw	Good	Average	Average	Good	Good	Good
Walking	Average	Good	Excellent	Good	Good	Poor
Inchworm	Poor	Average	Good	Average	Average	Good

4. Summary and Outlook

There are various types of robots in the field of pipeline inspection, including wheeled robots, caterpillar robots, PIG robots, screw driven robots, walking robots, and inchworm robots, which are reviewed in this paper. We analyze and prospect the specifications, design and performance of different types of in pipe inspection robots.With the development of science and technology and more and more researchers' attention to the oil and gas pipeline robot, the future research on the oil and gas pipeline robot will mainly focus on the following aspects.

Flexible and stable mechanical structure. The future oil and gas pipeline inspection robot will tend to be multifunctional and modular in structure, integrating functions such as cleaning, inspection, cutting, spraying and welding. At the same time, robots can still maintain good trafficability and adaptability in oil and gas pipelines with special forms such as downhole operations, curves and variable diameter pipelines.

Walk intelligently. The rapid development of artificial intelligence technology has promoted the rapid development of intelligent robots in defect detection. In the context of today's advanced intelligent control algorithms, the path planning and walking decisions of robots in pipelines in complex environments are constantly optimized, and the efficiency and quality of pipeline detection will also be continuously improved.

Intelligent detection. With the development of some intelligent technologies such as deep learning and artificial neural network, combined with intelligent image processing technology, the robot can quickly identify obstacles ahead and defects in the pipeline, and its defect detection capability and efficiency are further improved.

Energy optimization. When the robot works in a long distance, it generally adopts the form of streamer power supply, which has certain requirements on the load capacity of the robot. The cable free mode reduces the load constraint of the robot, but in some cases, the power supply performance will decline sharply, which restricts the inspection work and motion characteristics of the pipeline robot, and its motion distance is limited to a large extent. In the future, there may be few or no cables for energy optimization, so it will become a new trend to use the energy of fluid or differential pressure drive, electromagnetic drive and other off-site energy supply.

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