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Machine Vision-Based Oil and Gas Pipeline Inspection Robot

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ABSTRACT

Pipeline transportation is currently the main method for large-scale, long-distance transport of oil and natural gas. As the service life increases, the risk of pipeline leaks also gradually rises. Oil and gas pipeline inspection, as a key link in pipeline integrity, can provide a scientific basis for the prevention and maintenance of pipeline accidents. Pipeline robots play an important role in pipeline inspection, as they can enter complex pipeline environments to carry out tasks such as inspection, cleaning, and maintenance. At the same time, with the development of artificial intelligence, machine vision technology is widely applied in pipeline inspection. This paper provides a comprehensive review of pipeline inspection robots based on machine vision, including mechanical structures and visual inspection methods, and analyzes and compares their performance characteristics. It summarizes the factors limiting their development and proposes solutions, providing a reference for the further development of machine vision-based oil and gas pipeline inspection robots.

KEYWORDS

Petroleum and natural gas; Pipelines; Robots; Machine vision

1. INTRODUCTION

In recent years, with the rapid development of world technology and the accelerated process of national industrialization, the demand for oil and natural gas, as important strategic resources, has been continuously increasing. As key infrastructure for energy transportation, the safety and reliability of oil and gas pipelines are directly related to national energy security and economic development. Pipeline transportation, due to its large capacity, convenience, speed, and low cost, has been widely used in the oil and gas sector. However, since oil and gas pipelines are often laid in complex and variable geographic environments, such as mountainous areas, deserts, and oceans, and are subjected to long-term operation and external factors, they are prone to defects such as corrosion, cracks, and deformation [1]. If these defects are not detected and repaired in time, they may lead to serious accidents like leaks or explosions, causing significant casualties and property damage. Therefore, pipelines need to be regularly inspected to ensure that affected sections can be repaired or replaced before a failure occurs. Typically, suitable pipeline robots are selected for inspection based on the pipeline's length and size. Pipeline inspection robots are specialized robots that can move freely inside pipelines, equipped with one or more sensors and operational mechanical devices. They can enter complex pipeline environments to carry out tasks such as defect detection, anti-corrosion coating application, debris removal, and processing within the pipeline. The data collected by the robots is transmitted to operators, who can identify the types of defects present in the pipeline walls, such as cracking, corrosion, and wear, and take necessary actions when required [2].

Figure 1. Pipeline Status Diagram

Traditional methods for detecting oil and gas pipelines mainly use two common inspection technologies: Magnetic Flux Leakage (MFL) and Ultrasonic Testing (UT), because they offer high accuracy. However, these technologies are very expensive and localized. With technological advancements and the development of intelligent systems, using machine vision technology for oil and gas pipeline inspection has become a new research direction [3]. Inspection technology integrated with machine vision has become an important part of pipeline inspection, such as the underwater inspection robot based on machine vision designed by Fangrui Yin and others [4], A 360° visual pipeline inspection robot designed by Karthik C H and others [5]. The pipeline leak detection method proposed by C Lyu and others [6], The pipeline internal inspection system proposed by Piciarelli C and others [7], These research results all demonstrate the tremendous potential and broad prospects of machine vision technology in the field of oil and gas pipeline inspection, indicating that machine vision has been successfully applied to oil and gas pipeline detection and evaluation. It can greatly reduce labor workload, improve the accuracy of pipeline fault identification, and help achieve intelligent inspection where parts of the pipeline can be safely monitored [8].

This article aims to review the current research status, technical challenges, and future development trends of oil and gas pipeline inspection robots based on machine vision. By examining relevant literature and research results both domestically and internationally, it analyzes the application and existing issues of machine vision technology in oil and gas pipeline inspection, and explores future development directions and potential value.

2. RESEARCH PROGRESS ON OIL AND GAS PIPELINE ROBOTS

Research on pipeline robots began in the 1950s, and it wasn't until the 1970s that relatively systematic studies were reported [9]. The internationally recognized French scholar J. Vertut is a pioneer in this field, having developed in-pipe mobile mechanisms that laid the foundation for the subsequent development of pipeline robots [10].

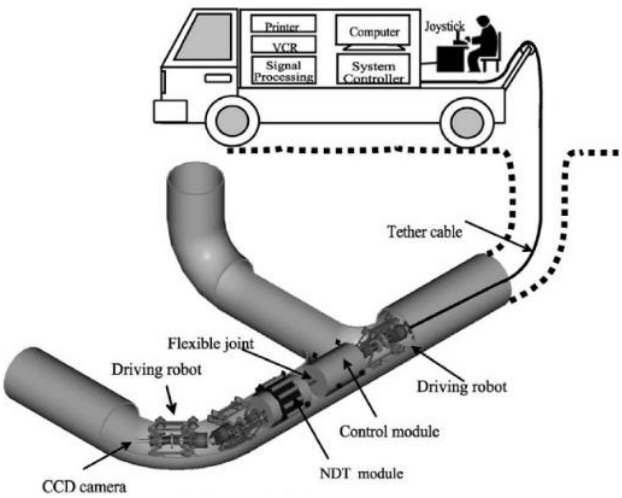


Figure 2. Schematic Diagram of Pipeline Inspection Robot

Pipeline robots can be classified according to their drive methods into cable-driven, wireless, and fluid-driven types, according to their modes of movement, they can be divided into active and passive types [11], based on differences in mechanical structure and other characteristics, they can be classified as wheeled, tracked, screw-type, and biomimetic [12]. Focusing on the structure and performance of the above types of pipeline robots, domestic and international pipeline robots can be divided into the following categories.

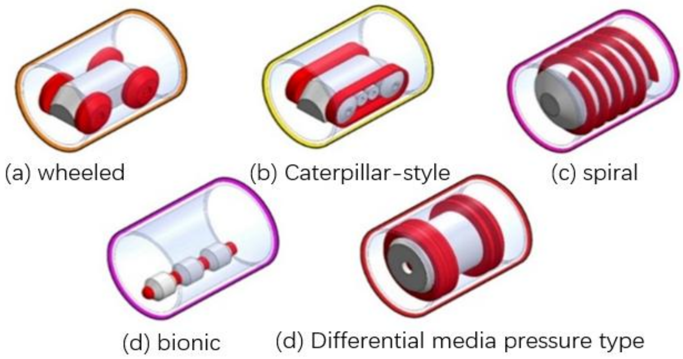


Figure 3. Pipe Robot Classification

2.1. Wheeled Pipeline Robot

Wheeled pipe robots move by driving wheels and are mainly divided into two types: wheel-type and support-wheel type. The support wheel presses against the inner wall of the pipe, allowing the robot to move along the pipe's axis with good stability. Wheel-type pipeline robots use wheels on both sides of the body to travel inside the pipe. They have a simple structure, flexible movement, rely on gravity to provide friction, have no clamping force, and relatively weak traction. The wheel mechanism is the most common and simplest propulsion system in pipeline robots [13]. Wheeled robots are widely used in oil and gas pipeline inspection due to their simple structure, good mobility, and high operational efficiency [14]. Although wheeled pipeline robots have been extensively studied, they still face significant difficulties in moving through bent or right-angle pipes [15]. D. Waleed and others designed a pipeline leak detection robot [16], as shown in Figure 4. This robot integrates multiple sensors, and its six rollers maintain contact with the inner surface of the pipeline to ensure smooth movement. It uses a neural network-based system to improve the robustness of leak detection by analyzing their identification of leaks, suitable for 203.0 mm pipelines.

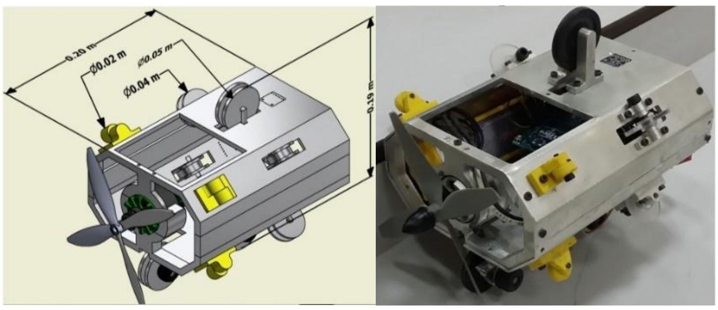


Figure 4. Pipe Leak Detection Robot

Li H and others developed a pipeline robot composed of six symmetrically supporting wheels, a motor, and an advanced control system, specifically designed for oil pipelines with diameters ranging from 1219 mm to 1440 mm, as shown in Figure 5 below. After several months of field testing, the robot performed well in terms of traction, climbing ability, obstacle avoidance, and endurance.

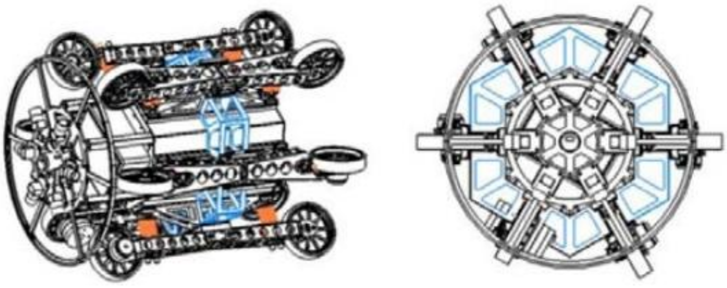


Figure 5. Multi-link Joint Wheeled Pipeline Robot

2.2. Tracked Pipeline Robot

Tracked pipeline robots rely on motors to drive their tracks for movement and can provide relatively high traction. This type of robot is mostly used in pipelines with more complex conditions. Because they can deliver strong traction, they can operate smoothly in harsh environments. However, tracked pipeline robots have a relatively complex structure, occupy more space, have poor maneuverability, and limited ability to pass curves, leading to higher energy consumption when operating inside pipelines [17].

To address various issues of existing pipeline robots, such as poor obstacle-crossing ability, complex mechanical structure, inconvenient control operation, and limited adaptability to pipe diameters, Fei Zhenjia and others designed a tracked pipeline robot with active adaptation features [18], as shown in Figure 6, for visual inspection of the inside of pipelines. This robot can adapt to pipelines with diameters ranging from 200 to 300 mm and has a weight of approximately 8 kg.

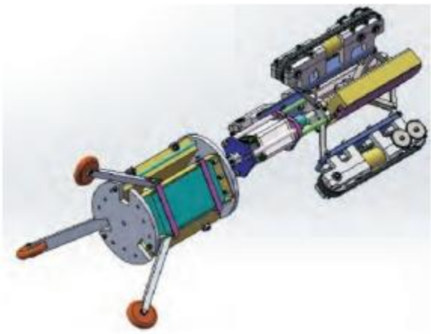


Figure 6. Active Adaptive Tracked Pipeline Robot

A tracked wall-pressing pipeline robot designed by Kim Y. G and others from South Korea is shown in Figure 7 below[19]. It features a scissor beam support, with cylinders controlling the scissor beam, allowing the robot to drive the tracks to adapt to different pipe diameters, with a diameter range of 600mm to 800mm and a load capacity of 20kg.

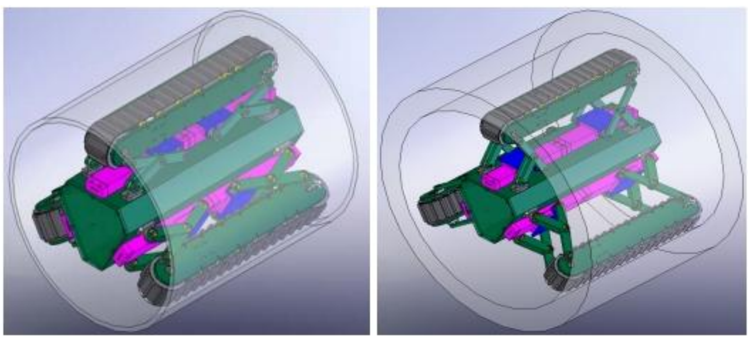


Figure 7. Tracked Pipeline Robot

2.3. Spiral Pipeline Robot

The spiral pipe robot is designed so that the axis of the drive wheel forms a certain angle with the axis of the pipe, allowing the drive wheel to move along a spiral path on the pipe wall, with the rotational movement along the spiral track enabling forward and backward motion [20]. The spiral pipe robot has a simple and flexible movement structure, making it suitable for pipes of different diameters. Although many countries have conducted extensive research, it has not yet been widely commercialized [21].

In response to the technical requirements for inspecting complex pipelines, Yabe S from Kanagawa University in Japan developed a screw-driven pipeline robot, as shown in Figure 8. This robot can connect multiple robot bodies, with the connection unit consisting of three servo motors [22]. The robot is suitable for pipelines with diameters ranging from 180mm to 220mm, demonstrating strong adaptability to complex pipelines. The dual-motor helical pipeline robot designed by the Atsushi Kakogawa team [23], as shown in Figure 9, has a length of 175.8 mm, is suitable for pipe diameters ranging from 109 mm to 129 mm, has drive wheels with a diameter of 28 mm, a helix angle of 10° on the drive wheels, a total weight of 0.7 kg, and a designed maximum travel speed of 500 cm/s.

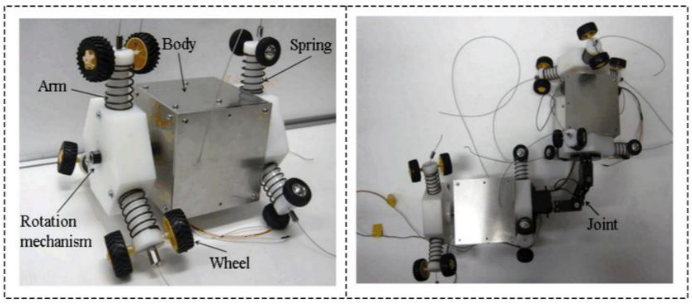


Figure 8. Japanese screw-driven pipeline robot

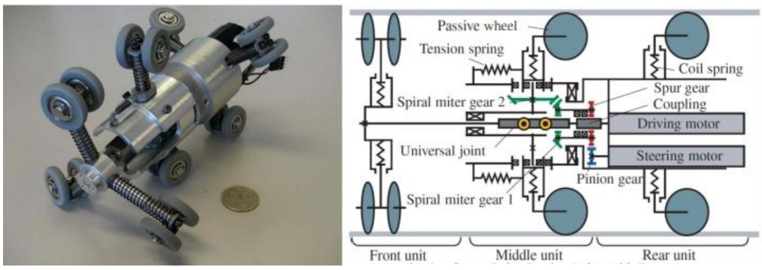


Figure 9. Dual-motor screw-type pipeline robot

2.4. Bionic Pipeline Robot

A bionic pipeline robot is a type of robot inspired by biology, designed based on the movement principles of creatures like spiders and snakes, and developed with a motion structure capable of overcoming obstacles and traveling [24]. This type of robot moves by extending and contracting itself, focusing more on mimicking the movement of living organisms, with a certain degree of flexibility and adaptability [25]. However, this drive method has low energy conversion efficiency and cannot provide significant traction. In addition, its structure is complex, it moves slowly, and its load capacity is relatively poor, mostly designed for tiny pipelines. In certain specific situations, bionic pipeline robots may offer better flexibility and adaptability, but they have certain limitations in traction and load capacity [26].

Paulo Debenest and others in Germany developed the PipeTron snake-like robot for pipelines [27], as shown in Figure 10. Each part of the robot has an active wheel pressed against the inner wall of the pipe by an elastic element. The parts are connected by steering joints, allowing it to move inside the pipe and carry out pipeline inspection.

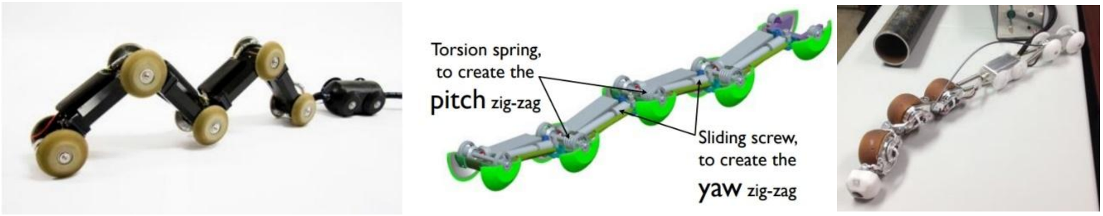


Figure 10. German Pipeline Robot—PipeTron

To address the issue of insufficient traction, Hadi Fekrmandi's team designed a modular biomimetic robot, as shown in Figure 11, which uses worm gear motion and modularizes its various functions to adapt to pipelines inclined from 0 to 180 degrees. This robot is used for pipeline diameter variations ranging from 101 mm to 127 mm [28]. The Bemhard team independently developed the MAKRO peristaltic pipeline robot, as shown in Figure 12. The robot weighs about 400N, has a body length of about 2 meters, and is capable of wireless information transmission and control [29]. This pipeline robot is used in cylindrical pipelines with diameters ranging from 300mm to 600mm.

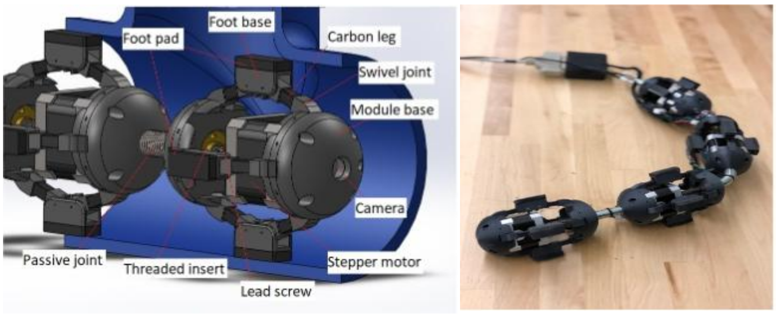


Figure 11. Multi-module peristaltic robot

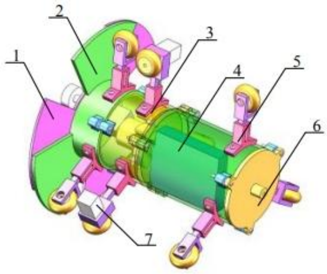
Figure 12. Multi-joint worm-like pipeline robot

2.5. Medium Differential Pressure Pipeline Robot

The differential pressure pipeline robot uses the power generated from the pressure and flow velocity of the fluid inside the pipe to drive the robot forward. It does not require cable connections or carrying excessive batteries, nor does it need to drain the fluid in the pipe, allowing it to operate over long distances inside the pipeline [30].

Scholars from the Massachusetts Institute of Technology in the United States and Chen J and other scholars from the University of Cambridge in the UK jointly developed a high-speed fluid pipeline robot [31], as shown in Figure 13. The robot's main body is designed with flexible materials, and its external structure is streamlined, allowing it to maintain flexible contact with the pipe wall while minimizing resistance from the fluid inside the pipe. However, its drawback is that it does not have a modular design, making maintenance costly. The American company Weatherford has developed the MultiCal360 multi-channel pipe diameter inspection robot [32], as shown in Figure 14. The robot is

1.75 meters long, weighs 387 kg, and has a maximum speed of 4 m/s. It has a maximum range of 720 km and a maximum operating time of 200 hours.



1-moving blade; 2-fixed blade; 3-active support mechanism; 4-controller; 5-support mechanism; 6-connecting plate; 7-DC motor.

Figure 13. Robot inside a high-speed fluid pipe

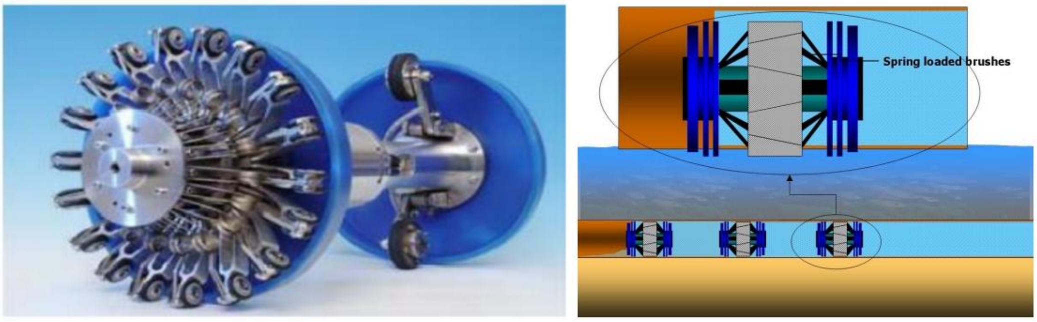


Figure 14. Wetherford Pipeline Robot

2.6. Comparison of Different Types of Pipeline Robots

Different robots rely on their specific structures to adapt to different working environments. However, each structure has its own strengths and plays different roles in various operational situations. Based on the descriptions of domestic and international pipeline robots mentioned above, a comparison of different types of pipeline robots is made, as shown in the following table:

Table 1. Comparison of Pipeline Robot Performance Characteristics

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

As can be seen from the table above, different types of pipeline inspection robots each have their own advantages and disadvantages. Wheeled robots are fast and simple in structure, but their driving capability needs improvement. Tracked robots can be used in scenarios requiring greater traction. They offer higher stability and traction, with strong obstacle-crossing ability. Screw-type pipeline robots have complex structures, and their steering and driving capabilities need to be enhanced, but they can adapt to complex pipeline environments. Bionic pipeline robots have weaker traction, move more slowly, and can cause some wear to the inner walls of pipelines, but they can maneuver flexibly in complex pipelines. Medium pressure-differential pipeline robots are suitable for long-distance pipeline inspections, but they have difficulty passing through pipelines of varying diameters and making sharp turns within pipelines.

3. PIPELINE ROBOT MACHINE VISION TECHNOLOGY

3.1. Machine Vision Technology

Machine vision technology is an interdisciplinary field that involves multiple disciplines. It mainly uses computer and image processing technologies to simulate and realize human visual functions, analyzing, understanding, and processing images or videos [33]. A complete machine vision system typically includes: external lighting, camera lenses (such as microscope lenses, zoom lenses, fixed-focus lenses, infrared lenses, etc.), industrial cameras (such as CCD cameras, CMOS cameras), image processing components, and image processing system modules [34].

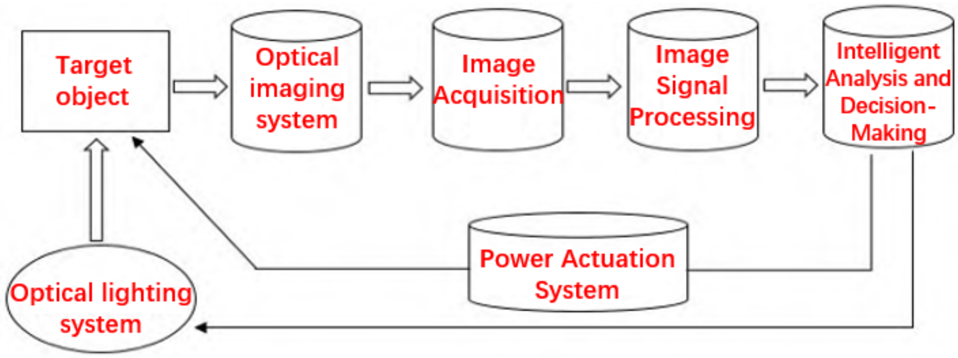


Figure 15. Technical Mechanism of Machine Vision

3.2. Application of Machine Vision Technology in Pipeline Inspection

Pipeline inspection includes the detection of pipeline shape and surface defects. On one hand, it is necessary to conduct qualitative and quantitative analysis of defects such as cracks, corrosion, and holes on the inner wall surface. On the other hand, it is important to quickly and accurately obtain the 3D coordinates of point clouds on the inner wall for deformation detection and 3D reconstruction of the pipeline. Therefore, simultaneously achieving both qualitative and quantitative detection of pipeline shape and surface defects has always been a key and challenging aspect in engineering [35].

3.2.1. Defect Detection Based on Visual Imaging

Visual imaging inspection is a method that uses advanced optical, electronic, and mechanical technologies. A pipeline robot equipped with a camera is sent into the pipeline to carry out a direct and accurate inspection and assessment of the condition of the inner walls of the pipeline. Common imaging inspection methods include CCTV inspection technology, CCD inspection technology, and CMOS inspection technology.

(1) CCTV Inspection Technology

CCTV inspection, also known as closed-circuit television inspection, emerged abroad in the 1950s and was applied on-site. It mainly consists of three parts: a pipeline robot, cables, and a control terminal. Operators control the pipeline robot to enter the interior of the pipeline, transmit images to the terminal, and then assess the captured images, thereby simply and effectively detecting the type of internal pipeline defects and their precise locations. CCTV inspection technology is primarily used in gas pipeline inspections [36].

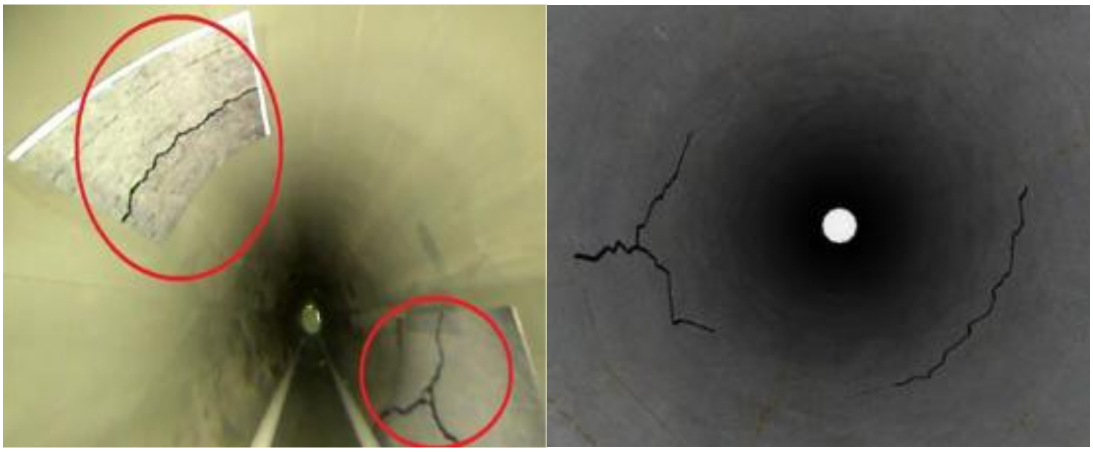
Figure 16. CCTV Detection Principle

German IPEK series pipeline inspection robots are a representative type of CCTV robots. This series of robots can accommodate pipes of all materials with diameters ranging from 150 to 1500mm. The robots are equipped with a two-degree-of-freedom gimbal and a high-definition camera, along with a dynamically adjustable lighting system, allowing them to capture images inside the pipes.

Figure 17. CCTV Inspection Robot

(2) CCD Detection Technology

The working principle of CCD camera image acquisition is to use a pipeline robot to place the camera inside the pipeline to capture image information, and then use software on a computer to process the pipeline images, ultimately determining the condition of defect information. The camera uses a three-chip CCD to capture images without using color filters [37]. It splits the light signal into red, green, and blue through a dichroic prism, with the red and blue lights each undergoing two reflections. The three colors are captured by three identical CCDs. This method of capture is considered full capture and lossless reception. Karkoub M et al. proposed a new method for capturing panoramic videos using CCD cameras and conical mirrors [38], which are transmitted to monitoring stations to inspect the inner surface of natural gas pipelines.



(a) (b)

Figure 18. (a) Image of the inside of the pipe captured by the pipeline robot, (b) Filtered image captured inside the pipe

(3) CMOS Detection Technology

The working principle of CMOS image sensors is that each photosensitive element integrates one or more amplifiers (active devices), allowing each electrical signal to be amplified within the photosensitive element, thereby improving the sensitivity of the CMOS image sensor and providing good noise reduction capabilities [39]. CMOS sensors use a row-by-row scanning method to read pixel data, allowing for faster signal reading speeds, making them suitable for real-time video capture in pipeline scenarios.

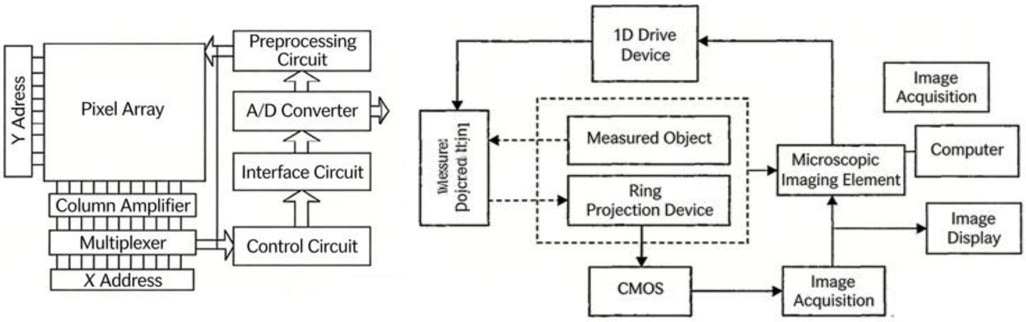


Figure19. (1) Principle of CMOS Image Sensor, (2) Schematic Diagram of CMOS Detection System

3.2.2. Three-Dimensional Pipeline Reconstruction

3D reconstruction refers to obtaining the image depth information of real objects or scenes through cameras or depth sensors, analyzing the two-dimensional or three-dimensional data of objects and scenes, processing the depth information of points, lines, and surfaces in three-dimensional space [40], and using the topological structure between inner surface 3D points to reconstruct the inner walls of pipelines in 3D, achieving 3D visualization of pipeline inner wall morphology and defects.

Figure 20. 3D Reconstruction Flowchart

The effectiveness of three-dimensional pipeline reconstruction mainly depends on the extraction of the pipeline's inner wall structure and texture features, which is challenging for pressure pipelines due to their sparse features and weak textures. Zhang Y et al. proposed an improved inter-frame registration algorithm based on point cloud fitting and constrained by column axial vectors [41], which can improve the accuracy of point cloud registration in scenes lacking features and textures, and overcome certain environmental uncertainties. Wu Fan and others proposed a bridge-style point cloud stitching method based on cooperative targets and monocular vision [42]. This method does not rely on any structural texture features of the pipeline inner wall, has a fast stitching speed, and is not affected by the scale of the point cloud. The reconstruction results are shown in Figure 21.

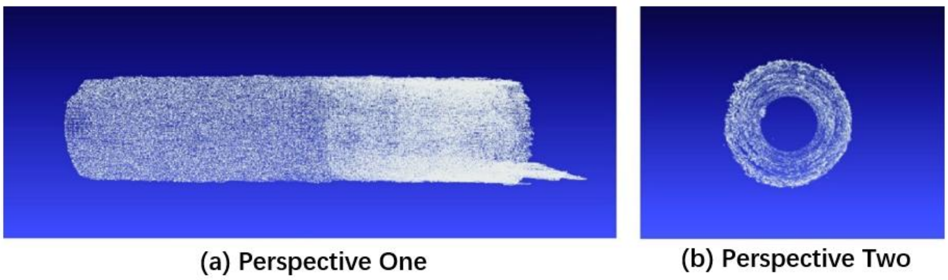


Figure 21. 3D reconstruction results of the pipeline inner wall

3.2.3. Vision-Based Measurement

Vision-based pipeline measurement technology mainly uses devices such as cameras, laser sensors, and 3D vision systems to perform non-contact measurement and inspection inside pipelines. These technologies can capture images or three-dimensional data of the pipeline interior in real time, and through algorithmic processing and analysis, obtain information on the pipeline's geometric dimensions, shape, defects, and more. The measurement methods used in pipeline robots are primarily monocular vision measurement and binocular vision measurement [43].

(1) Monocular vision measurement

The pipeline robot is equipped with an image acquisition device to capture 2D image information of the scene and reconstruct the 3D information of the scene through a monocular stereo vision algorithm. The principle is that a single camera obtains the relevant parameters through calibration. According to the principle of similar triangles, if the distance Z of a target point is known, the other two dimensions of the point in space can be determined, establishing its relative position to the measured object, and then the object can be measured in combination with image processing [44].

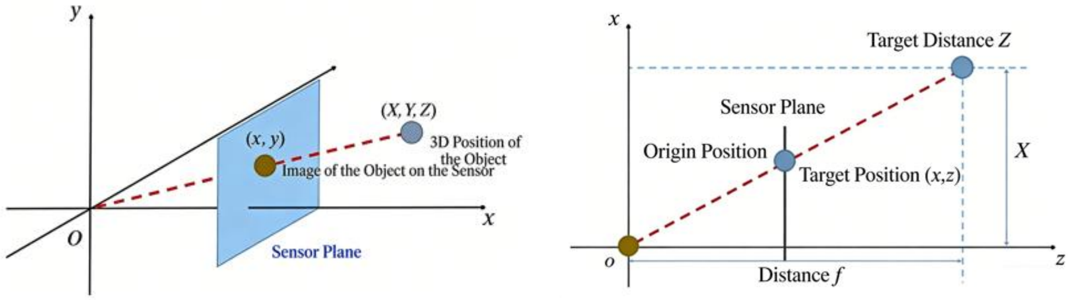


Figure 22. Monocular Vision Measurement Principle

Monocular vision measurement relies on information collected by only one camera, so its accuracy for spatial measurements is not very high. In response to this, Jianghai He et al. proposed a defect monocular ranging model based on the pinhole camera model, which accurately locates the longitudinal distance of pipeline structural defects through image processing of the pipe diameter. This model has good robustness and stability [45].

(2) Binocular vision measurement

Binocular vision measurement involves capturing the same target object simultaneously with two cameras. After obtaining two two-dimensional images, the pixel position deviations are calculated, and then the three-dimensional coordinates of the measured object in space are determined based on geometric principles. The principle of binocular stereo vision is shown in Figure 23. Binocular vision measurement is widely used in pipeline measurement [46]. The deformation measurement technology of binocular vision proposed by Yue Z and others can effectively capture the deformation of pipelines, compensating for the low accuracy of traditional measurement methods.

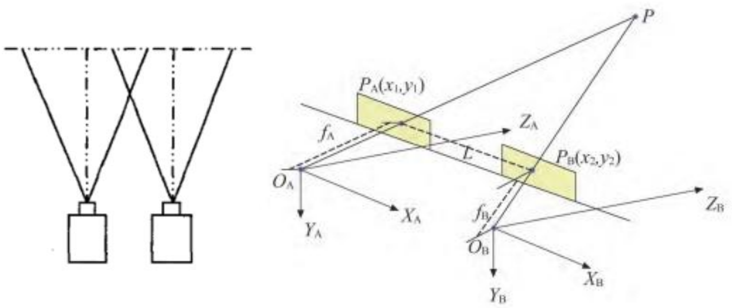


Figure 23. Principle of binocular measurement

3.3. Machine learning drives pipeline inspection

In recent years, pipeline inspection technology based on machine vision has made great progress. Among them [47], machine learning algorithms have shown significant advantages in addressing issues caused by high image complexity and diverse defects. Machine learning algorithms are widely used in pipeline inspection. Common algorithms include support vector machines [48], neural networks, and deep learning. With their high efficiency and accuracy, machine learning has made substantial contributions to the field of pipeline inspection.

Hou W et al. developed an automatic weld defect detection model based on deep neural networks, achieving an accuracy of over 90%. D. Van-Khoa Le et al. studied a pipeline defect detection system based on case-based reasoning [49]. This method mainly applies the machine learning approach of support vector machines (SVM), using a pipeline robot equipped with a light source to enter the pipeline and capture defects, as shown in Figure 24. Yang and others proposed a CNN-based weld image classification model that does not require denoising, feature extraction [50], or enhancement by improving the convolution kernel and activation function.

Figure 24. Detection Technology of Support Vector Machine

4. MAIN ISSUES AND OUTLOOK

Vision-based pipeline inspection robots are widely used in the field of pipeline inspection. They mainly rely on machine vision and image processing technology to detect and analyze the internal condition of pipelines. As a result, many researchers have studied machine vision inspection methods for pipelines and have achieved significant results. Although some methods can achieve an inspection accuracy of over 90%, there are still many issues that need to be addressed in practical applications.

4.1. Pipeline Passability Issues

Pipeline passability is a complex and critical research area, directly affecting the effectiveness and efficiency of robots operating inside pipelines. For complex bends such as branched or curved pipes, pipeline robots often find it difficult to pass through smoothly.

4.2. Feature Extraction Problem.

In pipeline inspection, feature extraction is a crucial step, as it directly affects the accuracy of subsequent defect identification, classification, and localization. The features extracted by inspection equipment are mostly shallow features of the signals, making it difficult to generalize to complex pipeline operating conditions. (4) Small Target Problems

4.3. Real-time Issues

Real-time performance is key to the efficiency of detection. When high-resolution devices are used to capture images, the high image resolution benefits detection accuracy. However, computing with a large amount of network parameters on limited computer processing power requires careful consideration of how to balance real-time performance with detection accuracy. At the same time, a large amount of data needs to be processed and analyzed quickly to extract useful information in a timely manner.

4.4. Small Target Problems

Tiny defects are small in size, low in resolution, and have indistinct features, making them difficult to detect using traditional image processing methods. Detecting them through deep learning requires specialized datasets for tiny defects and more accurate algorithms. However, most existing algorithms are designed for general targets and are limited by image resolution, making small target detection a persistent technical bottleneck.

4.5. Limited Dataset Issue

Machine learning methods require a large amount of data for support. The environment in which pipeline systems operate is complex, making data collection difficult. The available data is limited, preventing the model from fully learning the features and patterns of the pipeline, which can lead to overfitting during the model training process, thereby affecting the accuracy of detection results.

Overall, the inspection results of vision-based pipeline inspection robots are presented in the form of images and videos. They are highly versatile, and the camera angle and focus can be adjusted as needed to obtain more comprehensive information about the interior of the pipeline. They offer significant advantages in pipeline inspection.

In summary, detection technology still needs further improvement. Future research can be carried out in the following aspects:

(1) The robot's structure should have sufficient stability and durability, improving its traction, load-bearing capacity, and adaptability to pipe diameters, to cope with possible vibrations and impacts in pipeline environments. Different mechanical structures should be designed to meet various practical needs, developing more flexible and adaptable machines.

(2) Introduce a feature pyramid structure to fuse feature maps from different stages, fully leveraging the suitability of shallow features for small target detection, thereby improving multi-scale detection capability. Increase the types and quantities of small target samples in the dataset.

(3) Use pre-trained models from related fields or tasks to initialize the current task's model. Through transfer learning, existing knowledge and experience can be utilized to accelerate the training process of the new model, thereby improving detection efficiency.

(4) A single sensor may not fully capture the complex internal environment of pipelines during detection. Sensor fusion technology should be employed, combining data from multiple sensors such as infrared sensors and LiDAR to enhance the comprehensiveness and accuracy of environmental perception.

(5) Model design can incorporate lightweight concepts, such as using group convolution, depthwise separable convolution, or other lightweight convolution methods to reduce computation in the convolution process, or directly use lightweight network models for feature extraction, such as MobileNet, SqueezeNet, ShuffleNet, and EfficientNet.

5. CONCLUSION

With the development of robotics technology and increasing pipeline safety requirements, pipeline inspection robots have continuously advanced. This paper reviews research on vision-based pipeline inspection robots over the past five years and classifies them according to their characteristics. Among them, the mechanical structure of pipeline robots is the most common research topic, roughly divided into five types: wheeled pipeline robots, tracked pipeline robots, screw-type pipeline robots, bionic pipeline robots, and differential-pressure pipeline robots. The performance characteristics of various types of pipeline robots are compared, and it is noted that wheeled and tracked pipeline robots, due to their simple structure and ease of design, have already achieved large-scale commercialization. Researchers both domestically and internationally have conducted extensive studies on optimizing the performance characteristics of pipeline robots, and the technology has now become relatively mature.

In terms of visual inspection, the main detection methods include defect detection, 3D pipeline reconstruction, localization, and measurement, with the appropriate method chosen based on task requirements. With the rise of artificial intelligence, this field still holds significant research potential. Based on the issues mentioned above, factors limiting the development of pipeline robots are summarized, and several potential solutions are listed as references, providing a basis for research on vision-based pipeline inspection robots and promoting the advancement of pipeline inspection technology.

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