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A Review of the Current Research Status and Intelligent Development of Small-Diameter Natural Gas Pipeline Inspection Robots

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Abstract

For small-diameter natural gas pipelines widely distributed in gathering and transportation networks, the confined space, frequent bends, and complex branch configurations pose significant challenges to routine inspection and safe operation and maintenance. This paper presents a comprehensive review of the current state of research on inspection robots for small-diameter pipelines and examines the unique constraints imposed by ultra-narrow environments on robotic structural design and intelligent perception. First, through a comparative analysis of mainstream locomotion mechanisms-including wheeled, tracked, and helical drives-it is identified that adaptive structures featuring active diameter-adjustment capabilities and modular design are essential for enhancing a robot's flexibility and compliance when navigating bends. Second, the integrated application of detection techniques such as magnetic flux leakage, ultrasonic testing, and visual inspection in small-diameter environments is discussed, with particular emphasis on the advantages and limitations of machine vision in real-time monitoring. Finally, addressing the limitations of embedded computational resources, this study explores the development trends of pipeline inspection technologies toward lightweight, autonomous, and intelligent systems, in conjunction with lightweight deep learning algorithms. The findings indicate that constructing intelligent systems with multimodal sensing capabilities and edge computing performance is a key pathway to achieving proactive, full-lifecycle operation and maintenance of small-diameter pipelines.

Keywords

Small-Diameter Pipelines; Inspection Robots; Deep Learning; Intelligent Development

1. Introduction

With the profound restructuring of the global energy landscape, natural gas-recognized as an efficient and relatively clean fossil fuel-plays an indispensable bridging role in the transition toward the “dual-carbon” goals. Owing to its large transport capacity, low transmission loss, and high level of safety, pipeline transportation has become the dominant mode for long-distance and cross-regional delivery of natural gas [1]. However, pipelines are often subjected to prolonged high-pressure operation and complex corrosive environments, including soil and atmospheric exposure, making them susceptible to defects such as corrosion pits, cracks, and deformation. If not promptly detected and repaired, these defects may not only lead to resource loss but also trigger severe safety incidents, including explosions and fires, thereby posing serious threats to public safety [2].

Within extensive pipeline networks, small-diameter pipelines are widely distributed throughout gathering and transportation systems. Compared with long-distance, large-diameter pipelines, these smaller pipelines are characterized by confined spaces, frequent bends, and complex branching structure [3]. Conventional excavation-based inspection methods are prohibitively expensive and significantly disrupt transportation and industrial activities. Meanwhile, existing mainstream inspection robots are constrained by sensor size, power output limitations, and insufficient adaptability, making stable operation in such ultra-narrow environments exceedingly challenging. Consequently, the development of high-performance, intelligent inspection robots tailored for small-diameter pipelines has emerged as a prominent research focus in the field of pipeline operation and maintenance.

This paper aims to provide a comprehensive overview of recent advances in pipeline inspection robots. First, by analyzing the unique constraints imposed by small-diameter environments, the core design requirements for inspection systems are identified. Subsequently, the motion characteristics and applicable scenarios of various locomotion mechanisms-such as wheeled, tracked, and helical drives-are systematically examined in confined spaces. Furthermore, the integrated application of inspection techniques, including magnetic flux leakage, ultrasonic testing, and machine vision, is comparatively analyzed in the context of small-diameter pipelines. Finally, in conjunction with advanced algorithms such as deep learning, the development trends of pipeline inspection technologies toward lightweight, autonomous, and intelligent systems are discussed, providing valuable insights for the future design of high-performance pipeline inspection robots.

2. Pipeline Classification and Inspection Requirements

2.1. Research Background and Engineering Application Requirements

Pipeline transportation, characterized by its scalability, high continuity, and low energy consumption, has become the backbone of oil and gas delivery systems [4]. With the rapid advancement of China’s natural gas industry and pipeline infrastructure, the scale of related engineering projects has continued to expand, placing increasingly stringent demands on operational reliability and maintenance standards. However, constrained by the intrinsic properties of pipeline materials and the combined effects of long-term service conditions-such as chemical corrosion, physical erosion, and external mechanical loads-pipelines inevitably develop various forms of damage. Common defect evolution modes include stress-induced cracking, welding defects, localized corrosion, mechanical damage, and perforation, all of which pose serious threats to the safe operation of pipeline systems [5].

Small-diameter pipelines play a vital role in modern industry and municipal engineering, being widely employed in water supply, sewage systems, natural gas distribution, oil transportation, and diverse industrial processes. As the scale of domestic pipeline networks continues to expand, the safety of pipeline operations faces mounting challenges. Given the flammable and explosive nature of oil and gas media, any leakage or accident may not only disrupt energy supply but also trigger severe public safety incidents [6]. The factors affecting pipeline stability are complex, and their safety is closely linked to economic and social development, energy security, environmental sustainability, and the protection of life and property, even extending to national strategic security.

Nevertheless, due to the confined internal space and often considerable length of small-diameter pipelines, conventional inspection methods are difficult to implement effectively in such environments, resulting in significant detection challenges-particularly within complex pipeline networks. Therefore, it is of great urgency to develop and design inspection robots specifically tailored for small-diameter pipelines, capable of autonomous navigation and exhibiting high adaptability within these constrained and demanding conditions.

Figure 1. Long-distance oil pipeline

Figure 2. National natural gas pipeline

Pipeline robots, as specialized devices designed to perform in-pipe inspection and maintenance tasks, possess a certain level of intelligence. They can typically integrate multiple sensors and functional modules, such as CCD imaging systems and actuators for internal cleaning and defect detection. These systems are capable of accomplishing operations-such as identifying defects on the inner wall of pipelines-that are difficult to achieve manually. Their design generally requires careful consideration of factors including pipe diameter, internal environmental conditions, and specific task requirements. Through well-conceived structural configurations tailored to real-world operating conditions, pipeline robots can significantly enhance operational efficiency as well as the quality of inspection and maintenance.

2.2. Classification of Pipe Specifications

Based on commonly used pipe diameters, pipes can be divided into five major categories: micro pipes, small pipes, medium-small pipes, large pipes, and ultra-large pipes [7].

Small-diameter pipes are extensively used in urban water supply, drainage, natural gas transmission, and oil pipelines. As these pipelines gradually age, incur damage, and face changing external environments, their safety and reliability have become a critical concern in engineering management. Consequently, regular pipeline inspection and maintenance are of paramount importance. Traditional inspection methods-such as manual inspection and excavation-based detection-suffer from high costs, low efficiency, and significant operational risks. For small-diameter pipes in particular, these conventional approaches often prove inadequate for effective inspection. Small-diameter in-pipe inspection robots have therefore emerged as a novel technology, capable of performing precise internal inspections without compromising the pipe structure, thereby enhancing the efficiency and safety of pipeline management. Research on these robots represents not only a technological breakthrough in the field of oil and gas pipeline robotics, but will also exert a profound influence on the practical application of pipeline inspection, maintenance, and management. Looking ahead, with sustained technological progress, more intelligent, efficient, and accurate small-diameter pipeline inspection robotic systems are likely to emerge, further strengthening the safety and sustainability of critical infrastructure.

2.3. Analysis of the Operating Environment in Natural Gas Pipelines

1. Geometric Constraints

The station pipeline network features numerous L-shaped, U-shaped, and S-shaped bends, often in conjunction with diameter-changing fittings. The robot must therefore possess exceptional compliance and traversability.

2. Medium Characteristics

Natural gas is highly flammable and explosive, requiring the robot’s electromechanical system to comply with stringent explosion-proof standards and to generate no mechanical sparks during operation.

3. Surface Condition

The inner pipe wall may be contaminated with residual liquids, oil stains, or rust particles. This can impair the imaging quality of optical sensors and places rigorous demands on the traction capability of the drive mechanism.

3. Pipeline Robot Structures and Drive Types

In-pipe inspection robots are engineered to accommodate a wide range of pipeline operations, owing to the considerable variation in working environments and pipe diameters. At present, these robots are classified primarily by their drive mechanisms and inspection technologies, enabling the most appropriate robot type to be selected for a given task based on actual requirements.

According to differences in drive form, in-pipe inspection robots can generally be categorized into externally driven types, self-propelled types, and those that achieve locomotion by exploiting the pressure differential of the conveyed medium. In externally driven configurations, common designs include wheeled, tracked, and support-structure robots, all of which receive operational power from external control and supply systems. Self-propelled types are typified by peristaltic, helical-propulsion, and multi-legged structures, relying on built-in batteries to deliver continuous power for movement. Pressure-differential propulsion is most often encountered in fluid-driven robots, where the pressure difference between the front and rear ends of the device serves as the principal source of forward thrust.

(1) Wheeled Pipeline Robot

Leveraging its structural advantages, the wheeled pipeline robot achieves independent control of each drive wheel through dedicated motors. By exploiting differential wheel speeds, the robot can effortlessly execute straight-line travel, steering, and bend negotiation, enabling it to adapt efficiently to complex in-pipe environments. Figure 3 shows an internally supported wheeled pipeline robot developed by Sungkyunkwan University, South Korea [8]. The robot adaptively selects a suitable driving mode according to the prevailing conditions, thereby demonstrating excellent pipeline adaptability.

Figure 3. Internally Supported Wheeled Pipeline Robot

(2) Tracked Pipeline Robot

By virtue of its distinctive mechanical structure, the tracked pipeline robot demonstrates remarkable obstacle-surmounting capability and high reliability in complex in-pipe environments, as shown in Figure 4 [9]. The large contact area between the track and the pipe wall results in low ground pressure, which endows the robot with grip and anti-slip performance far superior to those of wheeled robots when traversing slippery pipelines fouled with sludge, grease, or debris. This high-traction characteristic not only ensures stable climbing on inclined or vertical pipe sections, but also provides ample power reserve for carrying heavy-duty inspection equipment or cleaning tools.

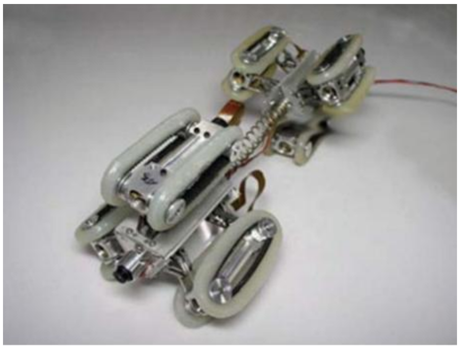

Figure 4. Tracked Pipeline Robot

Figure 5. Supported Pipeline Robot

(3) Support-Type Pipeline Robot

The support-type pipeline robot is structurally complex and is commonly referred to as a variable-diameter pipeline robot. This robot achieves propulsion through the alternating support of multiple sets of wheel-legs. Its structural design is distinctive, endowing it with strong traction capability and excellent maneuverability. As shown in Figure 5, an integrated pipeline inspection robot developed by Ling Zhangwei et al [10]. combines a tracked traveling mechanism with a support-type variable-diameter structure, and can be applied to the inspection of horizontal sections, vertical pipe sections, elbows, and reducer joints in industrial pipelines with outer diameters of 219 mm and 273 mm.

(4) Peristaltic Pipeline Robot

The primary advantage of the peristaltic pipeline robot lies in its adaptability and traversability in complex pipeline environments. Mimicking the locomotion mechanism of organisms such as earthworms, it moves through the coordinated action of radial support and axial elongation-contraction of its body segments, enabling reliable locomotion in tiny pipelines with varying diameters, bends (e.g., L-shaped, U-shaped, and S-shaped), vertical sections, and even those filled with liquid media. Its motion principle generally eliminates the need to exert excessive additional pressure on the pipe wall; instead, it generates powerful traction through a self-locking mechanism, allowing it to smoothly negotiate bends and diameter-changing sections. As shown in Figure 6, German researcher Bernhard Klaassen and his team developed a multi-joint worm-type pipeline robot system named MAKRO in 2000 [11]. This device employs tetherless (cable-free) control and is suitable for operation in pipelines with relatively large diameters, but is incapable of running in vertical pipe sections. Figure 7 presents a peristaltic pipeline robot developed by A. Brunete et al [12]. from Spain. Its structure is composed of seven joint modules, including support, rotation, and extension units. During operation, the support units generate constraint forces through contact with the pipe wall, while the extension units provide propulsion, rendering it suitable for small-diameter pipeline applications.

Figure 6. MAKRO Robot System

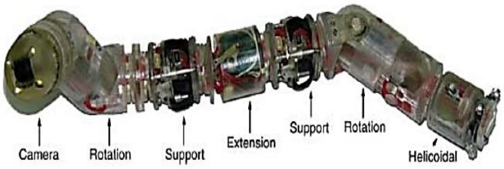

Figure 7. Peristaltic In-pipe Robot

(5) Helical Pipeline Robot

The advantage of the helical pipeline robot lies in its unique helical drive mode, which endows it with exceptional environmental adaptability and motion stability. By rotating its drive wheels at a certain inclination angle, it generates propulsive force, enabling smooth traversal through horizontal, vertical, and even complex curved pipelines while maintaining steady motion with minimal deviation and a low risk of rollover. Helical pipeline robots are typically characterized by a compact structure, high travel efficiency, and substantial driving force, and they can flexibly accommodate pipe diameter variations through variable-diameter mechanisms or adaptive linkage systems.

As shown in Figure 8, the helical pipeline robot designed by Liu Min et al. at Xi'an University of Technology consists primarily of a helical traction mechanism, a power unit, and an image acquisition and control system, arranged in sequence, with the individual modules connected by helical spring [13]. The wheel-leg of each unit is equipped with an elastic structure: on the one hand, the elastic force keeps the wheels firmly pressed against the pipe wall, and on the other hand, it provides a certain degree of adaptability to pipe diameter changes.

As shown in Figure 9, Ren Tao et al. at Southwest Petroleum University designed an active helical-drive pipeline robo [14]. They further constructed a kinematic model of the active helical pipeline robot in both straight and curved pipe sections, analyzed the key factors influencing its bend-traversing performance, and proposed a variable helix-angle method for bend passage along with the corresponding implementation concept.

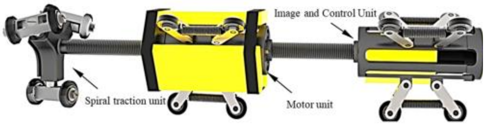

Figure 8. The overall structure of the spiral pipeline robot

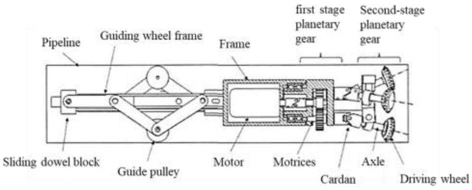

Figure 9. Active spiral-driven pipeline robot

4. Current Research Status of Pipeline Inspection Technologies

At present, non-destructive testing methods commonly employed for pipelines in industry primarily include magnetic flux leakage testing, ultrasonic testing, eddy current testing, radiographic testing, visual inspection, penetrant testing, and magnetic particle testing.

(1) Magnetic Flux Leakage Testing [15]

This method magnetizes the pipe under inspection locally by applying an external magnetic field until it reaches a saturated state. Under ideal conditions, the magnetic flux lines are confined within the pipe wall and form a closed circuit. When defects such as corrosion, pits, or cracks exist on the surface or within the wall, the permeability of the defective area is far lower than that of the parent metal, causing a local increase in magnetic reluctance. As a result, a portion of the magnetic flux lines cannot pass through the interior and instead leak out, forming what is known as a "magnetic flux leakage field."

(2) Ultrasonic Testing [16]

When applied to pipelines, ultrasonic testing exploits the propagation characteristics of acoustic waves in the pipe wall to detect variations in wall thickness and both internal and external defects. During inspection, a probe is coupled to the outer surface of the pipe, emitting high-frequency pulsed sound waves that enter the pipe wall either perpendicularly or at an angle.

(3) Eddy Current Testing [17]

When used on pipelines, eddy current testing is based on the principle of electromagnetic induction to identify defects on the inner and outer surfaces of the pipe wall and to measure changes in wall thickness. In operation, the excitation coil within the probe is energized with an alternating current, generating an alternating magnetic field at and near the pipe surface, which in turn induces eddy currents in the pipe wall.

(4) Radiographic Testing [18]

This technique primarily employs the attenuation behavior of X-rays or gamma rays as they penetrate the pipe wall-attenuation that varies with material density and thickness-to reveal internal defects. During testing, the radiation source is positioned outside the pipe, while a film or digital detector is placed on the opposite side or inside the pipe.

(5) Visual Inspection [19]

In the context of pipelines, visual inspection is essentially a non-destructive testing method that relies on optical imaging technology to directly observe the inner pipe wall. The principle involves sending a miniature high-definition camera into the pipe interior; an accompanying lighting system provides illumination for the otherwise dark environment. The camera captures real-time images or video of the inner wall, and the signals are transmitted to an external display terminal via cable or wireless communication.

5. Summary and Prospects

Based on a comprehensive review of current research both in China and internationally, most oil and gas pipeline robots still suffer from insufficient versatility. Although passive pipeline robots are technologically mature and widely deployed in long-distance trunk lines, their motion is highly susceptible to disturbances caused by fluctuations in the flowing medium within the pipe; consequently, precise speed control and attitude adjustment remain critical challenges yet to be fully addressed. In small-diameter environments in particular, the extremely confined internal space and complex geometric constraints pose enormous difficulties for the miniaturization of drive mechanisms and the highly integrated design of control components. Owing to their notable advantages in speed regulation and control strategies, passive and wheeled mechanisms are nevertheless expected to remain the mainstream development trend for future small-diameter pipeline robots. Drawing on the current research status, this section presents an outlook on the future development of small-diameter natural gas pipeline robots.

(1) Modularization and Self-adaptation in Structural Design

For the L-shaped, S-shaped, and variable-diameter pipe sections commonly found in station yards and urban distribution networks, developing a locomotion mechanism that features synchronized, modular, and autonomously variable-diameter capability is the core requirement for improving traversability in complex, irregular pipeline networks.

(2) Lightweight and Intelligent Inspection Algorithms

To address the fundamental limitation of embedded computing power, deep learning models should be intensively optimized. While preserving high detection accuracy for defects such as corrosion and cracks, real-time edge computing and image recognition must be achieved, thereby overcoming the persistent issues of missed detections and false alarms associated with conventional methods.

(3) High-Precision Positioning and Elastic Compensation Techniques

In order to rectify the elastic deformation errors introduced by tether cable tension during long-range inspections, future in-depth studies should focus on multi-sensor fusion positioning algorithms that integrate odometry wheels and inertial navigation, and a real-time elastic compensation mechanism should be incorporated to enhance defect location accuracy.

(4) Energy Efficiency and Communication Link Stability

Future advances should further develop high-efficiency energy conversion systems to satisfy the requirements of untethered operation and must overcome the electromagnetic shielding effect exerted by metallic pipe walls, thereby guaranteeing the real-time transmission and accuracy of both command signals and high-definition image feedback.

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