

Pipeline Cleaning Robots: Technological Developments, Application Scenarios, and Future Perspectives

Yufei Mao *

Department of Mechanical Engineering, University of Birmingham, Birmingham, B152TT, UK

* Corresponding Author Email: yxm347@student.bham.ac.uk

Abstract. Pipeline-cleaning robots are an essential component of mechatronic systems, widely used for infrastructure maintenance in both industrial and municipal applications. This paper discusses technological advancements from 2010 to 2024 and analyzes the core functional modules of pipeline-cleaning robots, including locomotion, perception, cleaning actuation, and energy systems. The research shows that different specific environments require different technical solutions. The industrial pipeline needs robots with wheeled mechanisms and combined mechanical-hydraulic cleaning for precise operations in structured environments. And municipal applications prefer robots that use adaptable tracked or legged systems with enhanced obstacle-negotiation capabilities, which are better suited to unstructured environments. Although significant advancements have been achieved, fundamental challenges persist across all domains. Energy constraints are the primary problem for long-distance operations in all of them. Tethered systems limit mobility, while battery-powered solutions face endurance constraints. In turbid or debris-laden environments, perception reliability can deteriorate. The current passive and active mechanisms cannot deal with sudden diameter changes. Additionally, the absence of standardized evaluation makes effective technology comparison and adoption hard. Future developments will focus on enhanced intelligence through advanced sensors, improved energy autonomy via new energy harvesting, and the use of soft robotics and innovative materials. This field is developing toward multi-robot cooperative systems and standardized frameworks, giving a crucial pathway toward ensuring the safety, efficiency, and longevity of global pipeline infrastructure through autonomous maintenance solutions.

Keywords: Pipeline-cleaning robot, Locomotion mechanism, Autonomous perception, Energy autonomy, soft robotics.

1. Introduction

Pipeline systems serve as the vascular networks of urban infrastructure and industrial production, widely used for water supply and drainage, and oil and gas transmission. However, during long-term operation, pipelines are prone to problems such as scaling, corrosion, and foreign-object deposition, which can reduce transmission efficiency and even lead to catastrophic failures, such as leaks or explosions. Traditional cleaning methods are low-efficiency, high-risk, and unable to cope with complex pipeline geometries. In comparison, pipeline cleaning robots offer automation, intelligence, and high reliability in pipeline maintenance.

The evolution of pipeline cleaning technology has progressed from early fluid flushing and simple mechanical scraping devices to adaptive, intelligently controlled robotic systems. It has also enabled the development of various locomotion mechanisms, such as wheeled, tracked, and legged, as well as both tethered and autonomous drive modes. The integration of sensing technologies, including high-definition cameras and ultrasonic sensors, has enhanced the environmental perception. These technological advancements expand the application of pipeline cleaning robots, enabling them to adapt to a wide range of operating environments, from large industrial pipelines to narrow residential pipes.

This paper provides a structured review of pipeline-cleaning robots, focusing on technological developments between 2010 and 2024. There are five sections at all: Section 1 is the introduction which introduce all of the paper; Section 2 shows the fundamental concepts and principles related to pipeline cleaning robots; Section 3 is about some various robotic solutions and their design characteristics; Section 4 discusses practical application scenarios and performance evaluations; and

Section 5 concludes with future research directions and potential advancements in intelligent pipeline maintenance systems.

2. Fundamental Principles of Pipeline Cleaning Robots

The pipe-cleaning robot is an extensive system, with its core functional module composed of subsystems that work together.

The motion module usually uses a wheeled or tracked type. The choice of motion module depends on the module's mobility efficiency and ability to cross obstacles, as required by the target environment. The motion performance directly determines the ability to clean up.

The cleaning module has two common types: mechanical and fluid. Mechanical types usually use a rotating brush and scraper, while fluid types use a high-pressure water jet. The design of the cleaning module should consider both cleaning efficiency and energy consumption.

The perception and determination module includes various sensors that enable the robot to navigate autonomously, avoid obstacles, and select the appropriate cleaning method. This module confirms the autonomous operation mode of robots.

The energy module also provides energy in two ways: a tethered system and batteries. The tethered can continuously provide power but has a limited operational time. The battery provides greater flexibility but has a shorter working time. So, the selection of the energy module is also determined by the working environment.

The structural module is the robot's frame, integrating all components and providing sufficient strength and environmental adaptability. The design of this module influences the overall performance and reliability, especially in harsh environments.

3. Key Technical Solutions for Pipeline Cleaning Robots

The locomotion mechanism determines its ability to move, steer, and adapt to internal pipe conditions. Different technical approaches have been categorized by driving principles and mechanical structures. Among these, wheeled drives are among the most common due to their simple design, ease of control, and generally high efficiency. For example, the cross-wheeled robot [1]. Utilizes a spring-based passive diameter adaptation mechanism to accommodate slight pipe size variations. And the tracked mechanisms, such as the intelligent inspection robot introduced by Peng et al., offer greater traction and are better suited to muddy or uneven pipes [2]. The helical drive through angled wheels is particularly effective in vertical pipe sections [3]. More recently, bio-inspired soft robots that mimic undulatory or jet-propulsion movements have opened new possibilities for navigating highly complex or deformable pipelines [4].

Each design operates well in a particular environment. Wheeled robots show high reliability in geometrically uniform industrial pipelines. However, their efficiency declines significantly when facing irregular surfaces or substantial obstacles [1, 5]. In contrast, tracked and legged designs have better traction and obstacle negotiation, making them particularly advantageous in unstructured environments such as municipal drainage systems. This advantage is accompanied by increased mechanical complexity, higher energy demands, and reduced translational speeds [2, 6]. Helical drives in vertical or slippery pipes are mechanically intricate and relatively slow, often limiting their application to small diameters [3, 7]. While soft robots show remarkable adaptability, practical challenges, such as limited driving force and low speed, remain obstacles to widespread use [4].

In summary, selecting a locomotion mechanism should consider stability, efficiency, and complexity. Recent trends use hybrid designs, such as wheel-leg combinations, to improve obstacle negotiation while decreasing mobility efficiency [3]. Despite being less actively controlled, passive adaptation mechanisms, such as the spring-based adjustment, are widely used for their simplicity [1, 8]. Looking ahead, the development of real-time perception will enable more intelligent, adaptive

mechanisms. This kind of mechanism can rebuild the robot itself, improving its efficiency in moving through pipes.

The perception system enables tasks such as navigation, condition monitoring, cleaning assessment, and ultimately autonomous operation. There are significant differences between the operating environments for sensors. Vision sensors are most frequently used for environmental mapping, defect identification, or target positioning. For example, Liu et al. used visual sensors for pipe orifice alignment, while Peng et al. used an underwater pan-tilt camera to extend the field of view [1, 3]. In turbid water, ranging sensors such as sonar or LiDAR are often added for obstacle detection and distance measurement [2, 5, 6, 9]. In industrial inspection scenarios, non-destructive testing sensors, including magnetic flux leakage and ultrasonic testing, have become standard for detecting corrosion, cracks, and wall thinning with high accuracy [10].

Each sensor type has its operating conditions. Cameras can provide rich visual data but are poor at low light or high turbidity, making them better for inspections in clear water [1, 2]. Ultrasonic sensors are low-cost and operate independently of light, but their resolution and range are limited. They are often deployed for fundamental obstacle avoidance [5, 9]. High-end non-destructive testing sensors, such as magnetic flux leakage sensors, are high-precision and reliable but expensive and bulky. So, they are typically reserved for industrial metal pipe inspections [10]. And the academic prototypes often employ simpler, more cost-effective sensing setups [3, 5, 7].

It is risky to rely on a single sensor in unstructured, unpredictable pipeline environments. Multiple sensors, such as combining cameras, LiDAR, and inertial measurement units, are increasingly adopted to enhance localization under harsh conditions [2]. Moreover, smart perception improvement is evident. Machine learning algorithms such as YOLO-v5 automatically identify and classify defects from sensor data, reducing human workload and improving inspection speed and accuracy [2]. Future perception systems will likely continue to evolve toward lighter, brighter, and more deeply integrated multimodal solutions.

Cleaning actuators are directly responsible for removing blockages or deposits. The two primary cleaning methods are mechanical and hydraulic. Mechanical cleaning involves physical removal of adherent scale using rotating brushes or scrapers [1, 5, 7, 10]. Hydraulic cleaning relies on high-pressure water jets to dislodge deposits without surface contact [1, 2, 8]. There are also specialized systems, such as the robotic arm used by Nyambane et al. to grasp and break up large debris in drainage pipes, designed for specific removal tasks.[6]

The best cleaning method depends on deposit characteristics. Mechanical brushes have strong cleaning power against hard deposits but may scratch the pipe wall and leave debris that requires flushing [1, 5]. High-pressure water jets can clean without contact and can flush away residues. However, they need an external water supply, which consumes more energy, and the spray generated will interfere with optical sensors [2, 8]. Robotic arms are very versatile for handling large objects, but operate slowly and are suited for targeted removal [6].

It is recognized that no single method is universally optimal; combined strategies are increasingly adopted. For example, Liu et al. used rotating brushes followed by high-pressure rinsing [1]. First, mechanically scouring deposits, then hydraulically flushing them away, so that there can be a comprehensive clean. The goal for the cleaning method in the next five years is adaptive cleaning. By implementing a sense-decide-act loop, the robot identifies deposit type, thickness, and distribution by its sensors, then automatically adjusts brushing speed, water pressure, or path to clean efficiently while minimizing energy waste and preventing pipe damage.

The energy and control systems determine the operational endurance and intelligence level. Power is typically supplied by wire or an onboard battery. Operation modes range from remote control to full autonomy. Tethered power provides unlimited energy and high-speed data transmission but is poor at mobility [1, 8]. And the battery power offers greater freedom of movement within a limited operating time [2, 5, 7]. In terms of intelligence, many systems still rely on remote operation or only fundamental obstacle avoidance, whereas advanced platforms can perform navigation and tasks fully autonomously [1, 5, 6, 8].

Each strategy is suitable in a different environment. The tethered systems are good at short-range, data-intensive tasks such as detailed inspection or operations requiring continuous high-pressure water [1, 8]. Batteries perform better at long-distance inspections where mobility is critical [2, 7]. Similarly, remote control offers greater flexibility but requires human operation, while fully autonomous systems improve efficiency in complex environments but require sophisticated perception and decision-making capabilities [1].

Energy availability is a significant bottleneck for long-duration missions. The current research focuses on improved power management through low-power electronics, innovative sleep modes, and emerging technologies such as wireless charging and energy harvesting from the pipeline environment [4]. In terms of intelligence, the trend is toward greater autonomy, using AI techniques such as SLAM and path planning for self-operation [1, 2]. For now, hybrid power systems with a tether, a battery, and semi-autonomous control are the preliminary solutions. In the long term, overcoming the challenges of energy self-sufficiency and full autonomy is essential for widespread deployment worldwide.

4. Application Scenarios and Performance Analysis

As shown in Table 1, pipeline robots are not one-size-fits-all; their designs are tailored to different pipeline environments. Industrial pipelines and municipal networks have different requirements for pipe size, operating conditions, and mission objectives, so different robot characteristics are needed. This section analyzes and compares representative robots in these two environments.

Industrial pipelines, such as those in heat exchangers, oil and gas transmission systems, and chemical plants, were among the earliest applications for pipeline robots. These environments are often geometrically regular but physically demanding. Industrial pipes usually have consistent diameters and layouts, but may operate at high temperatures and pressures, or under corrosive conditions. Cleaning and inspection tasks require high reliability, thoroughness, and safety, often within strict maintenance windows, so that robots must be precise and efficient.

Table 1. Different Comparison Dimension

Comparison Dimension	Industrial Pipeline Robots	Municipal Pipeline Robots
Typical Environment	Structured, consistent diameter, high temperature/pressure, corrosive flows	Unstructured, variable diameter, junctions, sludge, water, debris
Primary Design Focus	Motion precision, cleaning intensity, and inspection reliability	Obstacle-crossing capability, environmental adaptability, and operational flexibility
Locomotion Mechanism	Wheeled, Tracked	Tracked, Legged, Hybrid
Cleaning Strategy	Combined mechanical brushing & high-pressure water jets	High-pressure water for sludge; robotic arms/scrapers for solid obstructions
Perception System	High-definition vision; High-accuracy NDT (MFL, UT)	Vision + Sonar fusion for turbid water
Energy & Control	Tethered power; Highly autonomous/fully autonomous operation	Battery power; Remote control or semi-autonomous operation
Key Performance Metrics	Cleaning time per tube (<30 s), cleaning rate (>90%), spatial precision (mm-level)	Obstacle clearance height, runtime, amount of waste removed, and flow restoration
Representative Challenges	Balancing precision & reliability under harsh conditions (temp, pressure, corrosion)	Trade-off between traversability and operational efficiency (speed, energy consumption)

Wheeled or tracked drives are commonly used in straight, uniform pipes due to their high efficiency [1, 2]. For example, Liu et al. designed a cross-wheeled robot to operate in a heat exchanger tube [1]. To remove hard scale or rust, most systems use both mechanical brushing and high-pressure

water jets to clean quickly and effectively [1, 8]. The performance of the equipment is usually measured by the time required for single-pipe cleaning, which should be no more than 30 seconds, and should avoid pipe damage [1].

In the inspection aspect, using high-accuracy non-destructive testing (NDT) is a standard way. Other tools, such as magnetic flux leakage (MFL) or ultrasonic (UT) sensors, allow robots to measure wall thickness and identify defects before and after cleaning [10]. In this case, detection speed and spatial precision are critical.

Electricity and control equipment usually use wires to deliver energy and data, enabling exact, autonomous operations [1, 8].

Typical applications include heat exchanger maintenance and long-distance oil/gas pipeline inspection. Cleaning and inspecting in a single pass are essential for safety and integrity management [1, 10].

Municipal networks such as water supply, sewers, gas, and storm drains are critical urban infrastructure. But they are complex, variable, and often difficult to access.

These networks exhibit wide variations in diameter, including junctions and bends, and often contain water, sludge, and debris. So, robots must minimize public disruption, requiring them to have strong obstacle-crossing ability, adaptability, water resistance, and operational efficiency.

The tracked and legged robots work better on rough, slippery surfaces. Nyambane et al., for instance, deployed a crawler robot for work in muddy sewers [2, 6]. Helical drives are more advantageous for vertical shafts. The key performance metrics for municipal cleaning include obstacle clearance height and the ability to navigate complex layouts [3].

In turbid water, relying solely on vision is often insufficient, so sonar is frequently used to aid navigation [6,9]. The cleaning strategy usually depends on the debris type; robotic arms or scrapers are used to remove solid obstructions, while high-pressure water clears sludge [6-8].

Battery power is preferred due to its extended range, but achieving full autonomy remains a significant challenge in such chaotic environments [2, 7]. Many systems rely on remote control or semi-autonomous operation, and performance is judged by runtime and ease of use [6].

Representative applications include sewer cleaning, where robots extract debris without sending personnel into hazardous spaces, and water main maintenance, where robots clean and inspect to ensure water quality [6, 8].

Robots have different technological characteristics in industrial and municipal applications. Industrial robots focus on motion, cleaning efficiency, and detection ability in more regular environments. However, for municipal robots, flexibility, obstacle-crossing ability, and environmental adaptability are more important because the operating environment is harsher and more complex. In terms of speed, industrial robots can achieve 0.1-0.3 m/s in straight sections, whereas municipal robots typically operate below 0.05 m/s in complex environments [1, 6]. Regarding cleaning efficiency, the combination of high-pressure water jets and mechanical brush systems can achieve over 90% removal rates at the industrial scale. In contrast, the cleaning efficiency of municipal robots is highly dependent on conditions [1, 8]. These all show how municipal robots differ from industrial robots.

Regardless of the application environment, pipeline-cleaning robots face several fundamental problems. The most significant issue is the energy supply. It is the core challenge of long-term operation, whether using a wired system or batteries. And it will become more severe in a municipal environment, making it more complex. Next is perception accuracy, especially in low-light environments. It will reduce the accuracy of vision and sonar sensors, leading to errors in autonomous navigation and identification. Another deficiency is mechanical adaptability. The passive type is not good at handling sudden pipeline changes, while the active system faces control problems. The final hurdle is the difference in the evaluation standard. There are significant differences in the performance variations across groups. And the test environment differs from the operational environment. These problems make it hard to compare and adopt technologies.

Industrial robots face a core bottleneck: reliability. The key challenge is achieving accurate location and detection in high-temperature, high-pressure, and chemically corrosive environments. There are significant limitations to practical application by now. For example, a robot that is good at cleaning may not be good at detecting cracking. Similarly, while MFL detection technology offers high precision, its practical application is hindered by the complexities of deployment in intricate pipeline networks [1, 10].

The core contradiction of municipal robots lies between operational efficiency and mobility. Crossing substantial obstacles often requires high energy consumption and low speed, and simple machinery, such as wheeled structures, is difficult to cope with in complex environments where mud and gravel coexist [6]. In addition, the irregular layout of the municipal pipe network and public safety risks, such as methane gas, place higher requirements on robots for sealing protection and safe operation.

5. Conclusion

Over the decades of development, the pipeline robot has evolved from a fundamental tool into an advanced mechatronic system. By analyzing this development history, we can see that differences in technology depend on the working environment. Industrial robots usually use wheeled or tracked types to achieve precise operation. At the same time, municipal pipelines need more adaptive methods, such as using leg or mixed types in more complex environments. By now, the technological breakthrough includes improving perception by combining more sensors, cleaning more obstacles with a mix of cleaning methods, and using mixed energy to extend the operational time range.

Despite these advancements, promoting pipeline robots for practical applications remains difficult. The first problem is the lack of energy autonomy, whether it is powered by cables or battery-powered systems, which limits its range and duration. In turbid or low-visibility conditions, the unreliable performance of perception systems decreases the reliability of autonomous navigation. In addition, both active and passive are poor at handling changes in internal diameter and complex structures. Finally, this aspect is the lack of a standard evaluation method, which hinders performance comparison and delays application processing.

Future research will focus on addressing these challenges. Developing high-density batteries, new energy technology, and wireless charging is essential to solving the energy problem. Improving perception in complex environments by developing real-time 3D is also a promising future direction. Using soft robotics and innovative materials to build an adaptive robot is a solution to the adaptive problem. Adaptive robots should be able to change their shape in different environments. Finally, integrating all of these technologies into a single, standardized multi-robot cooperation system can enable large-scale task execution.

Although these problems are severe, it is essential to develop a more intelligent, complex, and cooperative robot that can protect the safety and efficiency of global pipeline infrastructure. By integrating these technologies, papers can overcome current limitations and implement automated pipeline-cleaning methods. Finally, paper can make the maintenance of global infrastructure more sustainable and reliable.

References

- [1] Liu, Q., et al. Development of a pipeline-cleaning robot for heat-exchanger tubes. *Electronics*, 2025, 14 (12), 2321.
- [2] Rashid, M. Z. A., et al. Recent trends of the in-pipe inspection robotic system from academia and industry perspectives. *IOP Conference Series: Materials Science and Engineering*, 2021, 1051 (1), 012034.
- [3] Peng, F., et al. Design of intelligent pipeline detection and cleaning robot. *Journal of Physics: Conference Series*, 2024, 2785 (1), 012025.

- [4] Korendiy, V., Kachur, O., Predko, R., Kotsiumbas, O., Brytkovskyi, V., & Ostashuk, M. Development and investigation of the vibration-driven in-pipe robot. *Vibroengineering Procedia*, 2023, 50, 1 – 7.
- [5] Fang, J., Zhuang, Y., Liu, K., Chen, Z., Liu, Z., Kong, T., Xu, J., & Qi, C. A shift from efficiency to adaptability: recent progress in biomimetic interactive soft robotics in wet environments. *Advanced Science*, 2022, 9 (8), 2104347.
- [6] Nyambane, E. N., Mwaura, C., & Kamau, L. Use of a robot to clean drainage structures. In *Proceedings of the Sustainable Research and Innovation Conference*, April 2022, pp. 186 – 191.
- [7] Shukor, A. S., Aman, M. N. S., & Arsat, Z. A. Design of an autonomous pipe-cleaning robot for small-scale hydroponic systems. *International Journal of Autonomous Robotics and Intelligent Systems*, 2025, 1 (1), 25 – 36.
- [8] John, B., & Shafeek, M. Pipe inspection robots: a review. *IOP Conference Series: Materials Science and Engineering*, 2022, 1272 (1), 012016.
- [9] Shafi, A., Khan, M., Brenosa, J., Flores, M. A. L., Espinosa, J. C. M., Choi, J. G., & Ashraf, R. Scalable comprehensive automatic inspection, cleaning, and evaluation mechanism for large-diameter pipes. *International Journal of Intelligent Systems*, 2025, 40 (1), 2441962.
- [10] Yang, Z., Fan, Y., & Yan, Y. Development of an adaptive wall-pressing mechanism for an in-pipe cleaning robot. *Journal of Physics: Conference Series*, 2022, 2365 (1), 012023.