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A Comprehensive Review on Smart In-Pipe Inspection Robots: Technologies and Trends

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Abstract: - The maintenance and inspection of buried and inaccessible pipelines have been a major challenge for many years because of restricted access, environmental risks, and the intricate geometry of pipeline networks. In-pipe robots have become a sophisticated solution, providing autonomous and semi-autonomous systems to travel, inspect, and diagnose pipeline infrastructure. This review presents an extensive overview of the state of the art and future trends in smart in-pipe robotic systems. The paper categorizes current robots by their locomotion approaches—wheeled, tracked, snake-like, screw-driven, bio-inspired, and hybrid mechanisms—and critically assesses their merits, demerits, and suitability for operation. In addition, the inclusion of artificial intelligence, especially hierarchical reinforcement learning and machine learning frameworks, has increased the autonomy and flexibility of these robots to operate in dynamic and feature-sparse environments. The integration of IoT frameworks and sensor fusion in real-time has made continuous data capture and predictive maintenance possible. From the analysis of industrial deployments, case studies, and real-world challenges, this review identifies main design bottlenecks in mechanical flexibility, sensor durability, and energy efficiency. It also specifies promising future areas like soft robotics, self-healing materials, miniaturized actuation, and swarm-based pipeline inspection. This paper integrates results from more than fifty global studies, providing a reference point for researchers, engineers, and infrastructure planners seeking to create the next generation of intelligent and resilient in-pipe robotic systems.

***Keywords**: In-pipe inspection robots, pipeline maintenance, robotic locomotion, artificial intelligence, reinforcement learning, soft robotics, sensor fusion.*

1. Introduction

Pipelines are some of the most important infrastructures for transporting vital resources like water, natural gas, crude oil, and industrial fluids over long distances geographically. The reliability and integrity of pipelines are crucial to maintaining continuous supply, public safety, and protection of the environment. Still, over time, pipelines are subject to many forms of degradation such as corrosion, scaling, cracking, and mechanical deformation, and ultimately lead to leakage, contamination, and under worst-case situations, catastrophic failure [1], [2]. Traditional methods of inspection through monitoring by observation, radiographic inspection, and ultrasonic manual testing are invariably wanting in remedying the lack imposed by hidden or buried pipes. These are time-consuming, error-prone, and risk safety hazards in dangerous environments. These limitations have been overcome with the advent of automation through the use of in-pipe inspection robots—small, sensor-based robotic platforms that can move within pipelines and harvest diagnostic information with high accuracy [3]. In-pipe robots are designed with an array of locomotion devices like wheeled, tracked, legged, and snake-like geometries to move through a range of pipeline geometries. With on board sensing equipment like visual, ultrasonic, magnetic flux leakage (MFL), and laser-based equipment, the robots can identify anomalies, measure structural deformations, and map the internal condition of pipelines in real time [4]. Recent developments in machine learning (ML) and artificial intelligence (AI) have improved the operational capacities of these robot systems even more. AI provides real-time detection of defects, path planning, predictive maintenance, and autonomous decision-making. Using AI with in-pipe robots not only decreases human intervention but also enhances frequency, accuracy, and reliability of inspection [5]. Intelligent systems can learn from changing pipe conditions, learn during inspection, and function in changing environments, thus being well suited for contemporary infrastructure monitoring.

This survey seeks to present a full investigation of in-pipe inspection robots using robotics and AI technologies, highlighting the integration of the two. The article classifies existing robotic designs, surveys cutting-edge intelligent sensing and control structures, emphasizes real-world applications, and pinpoints technical issues and future research areas. Based on the integration of over 50 global research studies, this publication is a guidebook for researchers, industry professionals, and policymakers interested in developing or implementing advanced pipeline inspection technologies.

2. Types of In-Pipe Inspection Robots

Inside tight channels, pipeline inspection robots have to negotiate challenging, sometimes erratic conditions. Different locomotion methods have been created depending on the geometry, size, direction, and surface condition of the pipeline. Based on locomotion techniques, this part classifies and assesses the four main kinds of in-pipe robotic systems: wheeled/tracked, snake-like/articulated, bio-inspired/peristaltic, and legged/screw-drive/hybrid mechanisms.

2.1 Wheeled and Tracked Locomotion Systems

The most conventional and most commonly used in-pipe robot setups are wheeled and tracked locomotion systems. Generally small, energy-efficient, and straightforward in design, wheeled robots are appropriate for straight, uniform diameter pipes. Noting that wheels allow faster speeds and lower power use, especially in clean, clear pipes, Kumar et al. [6] offered a thorough study of hybrid locomotion in wheeled in-pipe robots. Many times, these systems have changeable components to keep traction and centralise the robot. Wheeled robots, on the other hand, struggle with pipeline complexity including steep inclines, bends, or uneven diameters. In dirty or irregular pipe walls, they might not perform well; in steep or vertical settings, they tend to lose grip. By comparison, tracked robots offer improved stability and traction. By keeping bigger contact areas with the pipe surface using continuous belts or treads, they help to appropriately transfer load and preserve motion in difficult circumstances. Rahman et al. [7] investigated the potential of tracked robots and underlined their efficiency in severe conditions including sewage systems or corroded gas pipes. Still, tracked robots are heavier, use more energy, and turn more than their wheeled equivalents. This renders them less appropriate for pipelines with tight geometries or tiny bends. Some designs have tracks that add mechanical complexity and raise the risk of failure from jamming or belt misalignment. Though strong, its low mobility and maintenance needs stay important trade-offs when measured against more sophisticated systems. Ultimately, while tracked and wheeled robots are ideal for organised pipeline inspection, they lack flexibility under ageing or dynamic infrastructure.

Figure 1. Snake Robot for Pipe Inspection

Image Source: https://www.utoday.nl/science/63800/Snake_robot_for_pipe_inspection_

Figure 1 shows a snake-like robot that can be used to inspect pipelines has been designed by researchers at the University of Twente. Its articulated nature enables it to move in and out of bends and curved pipe geometries easily.

2.2 Articulated and Snake-like Robots

Particularly good at negotiating complicated, limited, and curved pipeline systems, snake-like robots provide great versatility. Mimicking biological snakes, these robots consist of a sequence of connected segments or joints that allow for great motion range. In narrow or vertically inclined settings, their serpentine motion improves stability by maintaining constant contact with the pipe wall. Liu et al. [8] presented a thorough study of snake robots in restricted environments highlighting their ability to negotiate steep corners, T-junctions, and uneven geometries that provide major obstacles for tracked or wheeled robots. Usually, every section of a snake robot has its own actuators and sensors, hence enabling distributed control. Especially for long-distance pipeline inspections, its modular design allows more fault tolerance and flexibility. But this degree of control adds complication as well. Coordinating the movement of several joints, Verma et al. [9] said, calls for complex control algorithms and real-time feedback, hence raising the computing load and the possibility of system fault propagation. Each segment has to be powered and manipulated separately, hence energy use is also an issue. The type of their movement also causes snake-like robots to travel more slowly than wheeled or tracked ones. Usually, payload capacity is constrained, which limits the use of more sophisticated or heavier sensors. These robots, however, shine in uses needing great mobility, including examining ageing municipal pipelines, subterranean utility corridors, or non-linear industrial piping networks.

Snake robots' flexible shape enables for more dispersed sensor placement, hence allowing thorough scanning and data collecting throughout the whole pipe wall. Future versions of snake-like robots are anticipated to be more autonomous and efficient, overcoming some of the present speed and payload constraints with the inclusion of machine vision, real-time SLAM, and AI-based control.

2.3 Bio-Inspired and Peristaltic Robots

Especially for traversing complicated situations demanding conformity with uneven internal surfaces, bio-inspired robots are a developing field of interest in pipeline inspection. Often using successive contraction and expansion to produce motion, these robots replicate the movement of worms, caterpillars, or soft-bodied creatures. The inflated peristaltic system is a major illustration. Essential for examining deteriorated or ageing pipes, Atalla et al. [10] presented a mechanically inflatable robot able to alter its body diameter to pipe width variations while traversing tight spaces. For pipelines with changing geometries, vertical slopes, or sections filled with fluids, peristaltic movement is very beneficial. These robots' bodies fit the pipe's inner surface, hence lowering the possibility of jamming or structural damage. Fang et al. [11] created an earthworm-inspired underwater robot that showed promise for usage in water supply and drainage systems by proving efficient locomotion under submerged settings. Bio-inspired robots have one difficulty in their limited speed. Wheeled or tracked substitutes move faster than peristaltic motion, which uses sequential actuation to actuate sequentially. Additionally, many peristaltic robots rely on pneumatic or hydraulic actuators, which often require external power or tethers—complicating mobility in long or branched networks. Internal space limitations also limit the size and quantity of sensors onboard, hence reducing their appropriateness for high-resolution inspection activities. The advantages of soft robotics—flexibility, lower danger of pipe damage, and the capacity to function in delicate or sensitive settings—however, make bio-inspired robots extremely useful in some applications. Improvements in battery miniaturisation and microfluidic actuation could assist to offset the present limitations. In applications like leak detection, chemical pipeline inspection, or structural health monitoring, these robots offer an adaptive and non-invasive inspection solution.

2.4 Screw-Drive, Legged, and Hybrid Robots

More specialised types of movement have developed to fill the voids created by conventional designs. Highly efficient at negotiating pipelines with obstacles or major geometric variation, legged robots function much like spiders or insects. Walking, climbing, or moving inside pipes are done by these robots using synchronised leg motions. Transeth and Pettersen [12] addressed the behaviour of such robots in obstacle-filled pipelines, highlighting their capacity to surmount steps, debris, and elevation variations. By spinning either their body or an attached spiral shell, screw-drive robots push themselves forward via a helical mechanism. Long pipes with little impediments are well-suited for this kind of movement. With little need for complicated steering or balance correction systems, Nansai et al. [14] built a screw-drive robot showing great efficiency and stability in controlled situations. But, if not adequately managed, these systems could wear on the pipe walls and may have restrictions in curved pipelines. Hybrid robots seek to optimise flexibility and efficiency by combining many locomotion modes [13]. Often, these designs have parts from wheeled, tracked, legged, or articulated systems to allow real-time mode switching. Among the first hybrid designs to combine snake-like articulation with stiff components, Hirose and Yamada [15] produced robots able to adjust to pipe curvature without compromising speed.

Although hybrid systems are mechanically complicated and more costly to construct and operate, they show potential. The combination of several propulsion techniques calls for sophisticated control systems and real-time decision-making algorithms to transition between locomotion modes. Furthermore, hybrid robots might be large, which restricts their application in pipelines with tight dimensional limits. Notwithstanding these obstacles, hybrid and sophisticated locomotion systems point to the future of autonomous pipeline inspection. These robots could one day offer the adaptability of snake-like robots, the speed of wheeled systems, and the terrain negotiating capacity of legged designs—all in a single platform with better control software and miniaturisation.

3. Integration of Smart Technologies and Artificial Intelligence into In-Pipe Inspection Robots

3.1 Complex Pipeline Network Autonomous Navigation and Localisation

Achieving precise localisation and navigation inside pipe networks—often GPS-denied, limited, and maze-like—is among the most important difficulties in the creation of in-pipe robots. Traditional remote-controlled robots need continuous human supervision, hence restricting operating scale and efficiency. Autonomous navigation has become a key emphasis of present study with the arrival of artificial intelligence (AI) and sensor fusion.0606. Using on board inertial sensors and pipe-specific models, Kazeminasab and Banks [16] devised a localisation system designed for water distribution systems that removes the need on external beacons or GPS. This approach allows robots to independently identify junctions, bends, and obstructions and enhances real-time location accuracy. McKenna et al. [18], likewise, showed a SLAM-based approach for pipeline robots with autonomous route planning as well as environmental mapping. Their methodology created a navigation-aware robotic system using LiDAR and inertial measurements combined via deep learning techniques. Algorithms for autonomous navigation have to consider pipe geometry changes, intersections, and potential accidents as well. Particularly for petrochemical networks where operational hazards are considerable, Akhyani [19] tackled these problems by integrating pipeline infrastructure modelling with real-time mapping. The research indicated that artificial intelligence-driven SLAM combined with pipeline metadata greatly enhances decision-making as well as mapping accuracy. Offering a strong basis for long-term autonomous operation, these systems can adaptively redirect in response to dynamic changes or breakdowns. Apart from SLAM, little-slip motion is being investigated as a method to guarantee robot stability during autonomous traversal. Using minimal-slip concepts, Marvi et al. [20] took motivation from biological snakes and created a motion planning algorithm that maximises sidewinding movement on unstable terrains including sandy slopes. Applying this to in-pipe robots provides improved traction, particularly in vertical or fluid-filled pipes. Supported by artificial intelligence, these navigation systems today constitute the foundation of smart robotic inspection and are absolutely vital for the operation of robots in submerged, industrial, and urban pipes without constant human control.

3.2 Machine Learning for Pipe Health Monitoring, Fault Prediction, and Obstacle Detection

Modern in-pipe inspection robots depend on machine learning (ML), which enables smart perception and predictive analytics. ML algorithm integration lets robots examine sensor data for real-time crack detection, material degradation, and anomaly identification. By eliminating dependence on post-processing and manual interpretation of inspection data, these qualities enhance efficiency and decision-making. Using reinforcement learning strategies, Guo et al. [17] trained a quadruped robot able to modify its stride to fit tight and uneven pipeline segments. Significantly better performance in limited and deformable settings was obtained by their model, which optimised movement patterns using real-time feedback from onboard sensors. Robots working in erratic or degrading infrastructure need this adaptive learning capacity. Abolmaali [23] underlined, in the interim, the use of artificial intelligence in predicting pipeline lifetime and spotting important failure areas before visual indicators appear. Machine learning models can predict the likelihood of pipe rupture or corrosion advancement using real-time sensor readings and time-series data from prior inspections. Particularly in vital water or gas pipelines, this proactive strategy not only improves maintenance planning but also lowers the probability of catastrophic breakdowns. Kato et al. [24] showed more use of smart robotic devices for rehabilitation planning. Their autonomous robot system identified deformation and sedimentation patterns in real time using AI-based image analysis. This permitted quick evaluation of structural integrity and facilitated focused repair actions, hence reducing time and expenses for maintenance of big pipelines. Detecting micro-cracks is another usage of vibration-based sensing coupled with ML classifiers. Monastyrskyi et al. [25] accomplished in-line crack detection in metal pipes using resonance acoustic vibration methods combined with neural networks. A consistent early fault identification tool, their model shown great sensitivity and few false positives. Driven by artificial intelligence, these techniques are turning passive inspection robots into active, decision-making agents with autonomous health monitoring and real-time diagnoses.

3.3 Real-Time Data Processing and Sensor Fusion

Advanced in-pipe robots depend on a set of varied sensors—including ultrasonic probes, LiDAR, IMUs, cameras, and gas detectors—that provide significant amounts of multimodal data. Sensor fusion methods are used to combine this data so that robots may have a consistent knowledge of their surroundings and operating state. Environmental noise, signal occlusion, or physical constraints could cause individual sensors to produce erroneous or lacking data without this fusion. Kesteloo [21] built the PIRATE robot, a pipeline inspection robot that used sensor fusion for both navigation and inspection. PIRATE used laser scanners for dimensional analysis, cameras for visual inspection, and IMUs for localisation. These modalities combined allowed strong localisation even in long, featureless pipeline parts. Common problems in subterranean settings, sensor redundancy guaranteed resistance against signal degradation or transient sensor failure. Jeon et al. [22] presented a large-diameter in-pipe inspection robot with a smart fusion system that integrated structural health analysis with real-time water quality monitoring. The robot could monitor pipe corrosion, evaluate pipe cleanliness, and identify chemical imbalances all at once. A whole pipeline health report for a single inspection cycle was produced by the synchronised interpretation of optical, chemical, and mechanical data.

Real-time data processing also includes edge computing inside the robot itself. Embedded processors filter and analyse vital information on the fly instead of sending all raw data to a distant server. This not only cuts communication overhead but also allows instant anomaly detection and response, such as pausing for closer observation or re-routing to avoid impediments. Sensor fusion also helps to calibrate AI models employed for fault prediction and navigation. For example, whereas crack detection gains from combining thermal and acoustic sensors, SLAM systems improve significantly when visual odometry is paired with inertial data. Together, these technologies produce strong, situationally aware robots able to perform smart inspection in dynamic and demanding pipeline settings.

3.4 Issues in AI-Driven In-Pipe Robotics and New Directions

Although artificial intelligence integration presents significant benefits for in-pipe inspection robots, it also brings fresh difficulties such computing load, data labelling, generalisability, and ethical questions about autonomous decision-making in vital infrastructure. In small-diameter robots, space and energy limitations generally restrict high-performance onboard computing, which is a major obstacle for real-time deployment of sophisticated deep learning models.

Training data is another ongoing problem. Vast quantities of labelled data are needed for machine learning models, making gathering in various and underground pipeline settings challenging. Model training is made more difficult by variability in lighting, material, corrosion levels, and fluid present. It is still a technological challenge to generalise a model trained on one pipeline kind to another. To solve this, transfer learning and synthetic data production employing simulation settings are being investigated.

Jeon et al. [22] underlined the importance of cooperative data platforms, where inspection data from several areas and robot kinds may be combined to build more strong AI models. Most AI models stay customised to particular use cases in the lack of such libraries, hence lowering scalability. Ensuring safety and robustness in autonomous robots is also crucial; erroneous AI judgements could cause robots to become stuck, harm the pipeline, or even overlook important flaws. Notwithstanding these difficulties, encouraging paths are appearing. 5G and edge-AI chip integration is facilitating on-board inference and quicker data transfer. Cloud robotics is being investigated; for more analysis, portion of the computation is offloaded to cloud servers. The emergence of bio-inspired artificial intelligence control systems, such as reinforcement learning agents imitating animal behaviour in constrained settings, also provides improved flexibility. Research is increasingly converging towards not just increasing individual robot intelligence but also allowing swarms of cooperative robots that communicate and coordinate tasks in huge pipeline grids.

4. Case Studies and Field Deployments of In-Pipe Inspection Robots

4.1 Teleportation and Remote Deployment: Lessons from ACES and Industrial Integration

Teleported pipeline inspection robots have played a crucial role in filling the gap between complete autonomy and practical deployability, especially in industrial environments with dangerous or intricate conditions. One of the strongest case studies is the ACES system, which was created by Lucet and Kfoury [26], and is based on a teleoperated robotic platform for internal pipe inspection. The ACES robot was built to keep real-time communication with an operator as it moves through long and narrow pipes. In contrast to completely autonomous robots, ACES provides a compromise between explicit human control and real-time flexibility and is particularly well-suited for pipes with non-deterministic obstacles or mission-critical equipment. ACES was tested in simulated test beds modeling water distribution and utility pipes. Its modularity enabled integration of numerous sensors such as high-definition cameras and ultrasonic sensors for defect identification. One of its richest features was the responsive feedback loop, which would allow the operator to modify the speed, orientation, and sensitivity of the sensors based on immediate visual input. This reduced drastically the amount of time spent recouping losses from lost portions or spurious obstacle detection.

Additionally, the incorporation of teleoperation provides enhanced safety and flexibility in hazardous or radiation-exposed pipelines, where complete autonomy could be unsafe or untrustworthy. The example also pointed out constraints like reliance on uninterrupted communication links, which can be lost in underground metallic systems. Solutions like signal repeaters and tethered data transmission have, however, been demonstrated to overcome such problems. The ACES example shows how much even as autonomy advances, the worth of human-in-the-loop systems continues to hold prominence, especially where the decision needs to be quick yet contextual. This model is a hybrid paradigm since it enables existing robotic technologies to be used in field operations without delay for full autonomy. Future deployments will mix remote operation with selective autonomy, particularly in cross-industry application scenarios such as energy, water utilities, and chemical processing plant infrastructure.

Figure 2. Ratty the Robot Pipe Inspector

Image Source: https://constructionmanagement.co.uk/meet-ratty-the-robot-pipe-inspector/

Created by the Manufacturing Technology Centre (MTC), "Ratty" is an autonomous robot rat intended to travel and survey underground pipes. It has a laser-based navigation unit and runs untethered, enabling it to map complicated pipeline networks autonomously.

4.2 Long-Distance Inspection and Energy Optimization in Pipeline Networks

One of the greatest challenges to scaling pipeline inspection activities is making robots able to travel extended distances in pipeline networks while being power-efficient, structurally sound, and communicative. Kazeminasab and Banks [27] tackled this by developing an extended robotic inspection framework that was optimized for long pipeline deployment. The research was keen to investigate the employment of power-efficient locomotives in conjunction with intelligent routing algorithms that reduce power-hungry maneuvers. Their robot was field-tested in extended municipal water supply pipes and used a modular battery-swapping mechanism that increased its operation time. In addition, by using low-power communication protocols and sleep-wake cycles in its embedded systems, the robot saved energy when idle or waiting for remote commands. These methods are currently being explored in designing next-generation autonomous robots that are anticipated to last more than 8–10 hours without needing human intervention. Hierarchical planning structures were also proposed to manage navigational complexity in long-distance environments. Botteghi et al. [28] built upon this idea using hierarchical reinforcement learning (HRL) where high-level controllers generate macro-paths and low-level controllers perform motor actuation and obstacle negotiation. The two-layered structure enables the robot to acquire efficient navigation tactics in large and irregular pipeline grids. Both researches proved that distant inspection is possible with the integration of smart planning, power management, and adaptive hardware. Still, there are challenges. Long-term battery usage in extended missions can compromise mobility and sensor quality, and thermal phenomena in underground pipes can be detrimental to electronics. Additionally, signal loss increases as the robot travels deeper into pipes, highlighting the necessity for buffering, compression, or regular upload checkpoints for data. These case studies emphasize the requirement of not only advanced mobility but also power-conscious planning and system-wide optimization. Their application in urban pipeline networks, oil refineries, and nuclear waste conduits reflect an increasing maturity of robotic solutions aimed for scale.

4.3 Smart Sensor Integration within Industrial Field Deployments

The success of in-pipe robots increasingly hinges on their ability to combine various sensing systems for structural monitoring, defect detection, and fluid analysis. In real-world applications, deployments require mobility, as well as simultaneous real-time acquisition of data from multiple modalities—optical, acoustic, thermal, and chemical. Jeon et al. [29] reported the design and field deployment of an in-pipe inspection robot for large-diameter water pipelines that featured a multi-sensor platform with leak detection, pipe corrosion assessment, and fluid property measurement during one mission. This system showed how sensor fusion can minimize the necessity of multiple passes or tools for inspections. The robot automatically tuned sensor parameters according to internal pipe conditions, e.g., from ultrasonic to visual inspection in clean versus sedimented regions. This flexibility allowed complete inspections while maximizing energy consumption and mission time.

Additional evidence is found in the commercial case studies presented by SewerVUE Technology [30]. Their robots, used in North America for city-wide pipeline inspections, employ combined laser, LiDAR, sonar, and HD camera systems to generate high-resolution 3D pipe interior models. These 3D maps are subsequently utilized to detect pipe deformation, sediment deposits, joint displacement, and crack formation. The reports highlight that such systems significantly minimize post-inspection analysis time and enhance decision-making by utility operators. Field experience has also pointed out problems with multi-sensor robots, such as calibration drift, data synchronization, and environmental interference. Temperature changes, vibrations, and turbidity in water can all skew readings or degrade accuracy. Solutions are real-time sensor self-calibration routines and environmental compensation algorithms, now common in high-end inspection platforms.

In total, these case studies confirm that intelligent sensor integration is no longer an option but an imperative in real-world robotic fielding. Being able to inspect, diagnose, and report once, in one pass, is transforming the manner in which cities, industries, and governments care for their life-critical infrastructure systems.

4.4 Human–Robot Interaction and Adaptive Robotics in Operational Pipelines

With autonomous development, the capacity of robot systems to meaningfully interact with human operators, dynamic environments, and unexpected situations becomes crucial. The evolution of adaptive control systems and natural human–robot interfaces (HRI) is critical to improving robot reliability and use in the field. A recent example was provided by NTT DATA and Mitsubishi Chemical Corp. [31] that highlighted the application of collaborative robotic systems for real-time inspection and reporting in petrochemical pipelines. The robots were integrated with cloud platforms, thus allowing remote control and monitoring and yet providing local manual override on-site. These adaptive systems enabled human technicians to initially guide the robot and then have it execute sub-tasks autonomously, such as detecting corrosion or gas leaks. The platform utilized haptic feedback and augmented reality (AR) to enable operators to visualize pipe internal conditions, enhancing inspection accuracy and minimizing fatigue. This illustrates how high-level human interaction can be combined with autonomous subsystems for improved performance in real-world operations.

Another novel application is the use of vine-like robots in pipe systems. Behnke et al. [32] studied the interaction behaviors of these robots in T-junctions and corners—typical geometries of urban pipe networks. Their system employed body elongation and environmental feedback to modify its motion through the pipe network. This biomimetic strategy exhibited high adaptability and low mechanical complexity, enabling it to navigate regions normally inaccessible to rigid robots. These field deployments highlight the increasing significance of hybrid intelligence—where human and robotic autonomy work together. In addition, they reinforce the necessity for robots to perceive, learn, and react to pipe geometry, operator commands, and task demands in real-time. In the coming years, pipe-line robots are expected to be integrated with real-time learning modules, emotional feedback loops (in HRI), and even swarm-team behavior—where several robots cooperate to enable quicker and safer inspection of large pipeline systems.

5. Design Challenges and Future Research Directions

5.1 Structural Complexity and Mechanical Adaptability under Constrained Conditions

The major design problem of creating in-pipe inspection robots involves the development of mechanisms that are capable of adapting to the limited and variable geometry of pipeline systems. These transitions are among different diameters, sharp bends, T-junctions, and vertical sections. The adaptation of locomotion and structure to support such variations is a unifying theme in robotics research. Mills et al. [33] surveyed a broad array of in-pipe locomotion systems, noting that flexibility to accommodate different pipe diameters and curvatures is essential to successful navigation. The survey categorized designs as modular, soft-bodied, and hybrid mechanical systems and noted the compromises between flexibility, payload, and control complexity. Soft robots are highly adaptable, but low payload and vulnerability to damage from the outside world are still limitations. On the contrary, stiff or articulated structures can support more sensors but usually collapse in tight bends or vertical changes. Researchers now look into telescopic and reconfigurable structures to solve these issues. These types of structures, however, need sophisticated actuation strategies and high-resolution control logic, which add complexity and expense to development. Another problem is mechanical fatigue and wear, especially in sewer networks or aged pipes with worn-out internal surfaces.

A second mechanical factor is the use of energy-efficient, compact actuators. Linear actuators, pneumatics, and shape-memory alloys are utilized in miniaturized forms but lack the power density necessary for load-bearing or long-range missions. Research is also moving towards compliant mechanisms and variable-stiffness structures to enable robots to deform according to pipe conditions. Furthermore, environmental sealing, corrosion protection, and water resistance are of paramount importance in robots working within chemically hostile or underwater pipelines.

The interaction between mechanical resilience and mobility is a point of contention in universal deployment. Future design has to strike a balance between these factors and stay scalable, manufacturable, and affordable for utilities. Normalized testing standards for robotic endurance between various pipeline classes may provide insight into design advancement and increase near-term deployment rates.

5.2 Control Systems, Autonomy, and Communication Limitations

Apart from physical design, intelligent and reliable autonomy of pipe robots is a daunting challenge. Pipelines do not usually have external signals such as GPS, and the internal environment can be visually and acoustically sparse in features. Consequently, robots have to be dependent on onboard sensors and real-time decision-making. Ibrahim and Baballe [34] pointed out that Industry 4.0 integration of pipeline robots is challenged by poor autonomy, data latency, and brittle communication links. Although AI and ML are promising, there is still much human supervision needed in current implementations. One ongoing concern is localization. Visual odometry, LiDAR, and IMUs drift over long distances or in homogeneous pipelines. SLAM algorithms must be updated constantly by sensor fusion, but even these can fail in underwater or sludge pipes. Even communication with the robot is restricted in metal or underground environments. Short-range wireless systems such as Bluetooth or Zigbee quickly lose connection, and tethered systems can limit mobility.

Ambati et al. [35] have spoken of hybrid control structures in which high-level decisions are made onboard but sensitive operations such as recovery from failure or path planning are performed remotely or via cloud servers. Edge computing is a solution but is limited by space, power, and heat dissipation within small robots. Additionally, the integration of feedback loops for motion correction, slip compensation, and obstacle avoidance demands high-fidelity sensing and rapid processing—technically challenging and power hungry. Incipient research is combating these issues using neuromorphic processors, energy-efficient FPGAs, and cooperative swarm behavior, but all such technologies remain in experimental stages. In the future, it will be necessary to develop lightweight, real-time control platforms together with secure low-latency communication protocols. Standardization of control logic, data formats, and autonomy levels can simplify development and speed up deployment in industry-specific applications.

5.3 Sensor Integration, Field Robustness, and Reliability

Sensor integration within small in-pipe robots is essential for real-time diagnostic purposes, but reliable sensing within severe conditions is still challenging. Ab Rashid et al. [36] noted that sensor efficiency fades rapidly through moisture, temperature fluctuation, sludge, or chemical contamination. For example, cameras and LiDAR sensors can be clogged by debris and water droplets, whereas gas sensors can be contaminated. Multimodal sensors—tactile, acoustic, thermal, and visual—are being combined in order to overcome the limitations of single modalities, but doing so creates synchronization, calibration, and data-fusion problems. Redundancy and reliability are essential in real-world deployments. Pipebots Consortium [37] reported the shortcomings of available inspection robots and found that the majority of field failures were a result of sensor drift, power, or environmental cue misinterpretation. Their roadmap recommends developing robust self-diagnostic and field-replaceable modular sensor units that can be hot-swapped or recalibrated. Additionally, energy consumption goes up significantly with high-frequency sensing, and there is a need for intelligent sensor scheduling based on task criticality or pipe zone.

Another concern is data management. All three high-resolution video, vibration signatures, and chemical sensing generate substantial amounts of data, and storage and processing become bottlenecks. Partial solutions include onboard compression and pre-classification to lower post-processing burdens. Zhang et al. [38] studied worm-like robots and stressed that their mode of locomotion provides high adaptability but limited space for sensors restricts real-time intelligence and fault prediction. Reliability will also need to be fault tolerant with respect to both mechanical and software faults. Reserve systems for power, movement, and control and auto-recovery procedures may preserve mission continuity. Plug-and-play parts and modular designs, already stressed for field-readiness, will continue to enable more facile repair and transferability from pipeline size to pipeline size. In the future, field durability must be incorporated at the initial stages of design using stress modeling, redundancy studies, and domain-based field tests.

5.4 Research Gaps, Emerging Materials, and Next-Generation Frameworks

There are still several research gaps existing in spite of recent developments in in-pipe robotics. They include the creation of miniaturized robots that operate within pipelines with diameters less than 75 mm. Most industrial systems make use of large-diameter robots that are inappropriate for household or thin sewer pipes. Li et al. [39] pointed out this problem and proposed the combination of compliant materials and flexible electronics to construct scalable, miniaturized robots. Such robots would have the potential to access sparse inspection zones, especially in city infrastructure. Another underexplored front is long-duration autonomy in feature-scarce environments. Edwards et al. [40] suggested a visual localization strategy tailored for sewer networks with poor features. Their method combined geometric heuristics with deep learning-based estimators for stable navigation. Such systems require further validation in dynamic, water-filled pipes. Nguyen et al. [41] also researched autonomous control of miniaturized robots in networks that are not known, and the emphasis was on safe exploration and return-to-home capabilities. These investigations indicate the possibility of sophisticated AI to overcome mechanical or environmental limitations.

Materials science is also powering the next generation of pipe robots. Self-healing polymers, bio-inspired materials, and electroactive fabrics have the potential to enable robots to heal themselves or alter their shape when undertaking missions. Such intelligent materials can enhance energy efficiency, enable greater adaptability, and extend lifespan. But their endurance in industrial settings requires further investigation. Finally, reinforcement learning is gaining traction as a control strategy. Botteghi et al. [42] proposed a hierarchical reinforcement learning (HRL) structure that separates tasks into low- and high-level acts, rendering training more mission-specific and scalable. HRL may be an essential paradigm for autonomous robots to navigate uncertain and dynamic pipe environments. Future studies have to be geared towards integrating these fields—materials, control, sensing, and autonomy—into integrated platforms. Interdisciplinary efforts between robotics, AI, civil engineering, and materials science have to come together to construct solid, smart, and deployable pipeline inspection systems for the future.

6. Emerging Trends and Innovations in In-Pipe Inspection Robotics

6.1 Developments in Bio-Inspired and Inflatable Locomotion Mechanisms

Bio-inspired robotics has unveiled new promising avenues towards adaptive in-pipe inspection robots. Specifically, soft robots that take their morphology after organisms like earthworms or caterpillars have the characteristic of peristaltic movement, thus being able to traverse pipelines of very variable geometries. Recent development by Atalla et al. [43] presented a mechanically-inflatable, bio-inspired robot which is able to dilate or contract according to the change in pipe diameter. This system enables the robot to develop traction internally and eliminates the requirements for wheels or treads, thus decreasing the mechanical complexity. Incorporating inflatable structures not only provides better compliance with pipe curves but also enables shock absorption as well as stablization on motion. Moreover, these robots are able to handle irregularities like corrosion pits, sludge, or displacement of joints that are normally troublesome for conventional rigid-body robots. Yet, the requirement for air compressors or soft actuators imposes size, energy, and pressure control design constraints. Future research will likely address these challenges through the integration of miniature onboard pumps, intelligent materials such as dielectric elastomers, and energy-efficient actuation. These soft robots are also extremely advantageous in fragile pipes, for instance, old irrigation or municipal ones, where mechanical damage caused by conventional wheeled or tracked robots might cause leakage or pipe collapse. Lightweight, modular, easy to deploy, and easy to retrieve in hostile locations are other advantages they present. Also, by pairing inflatable locomotion with sensor arrays, new options emerge for accurate wall profiling and defect mapping while inspecting. The next challenge is to scale these technologies to accommodate diverse pipe sizes and operating conditions. Extended field testing, on-site stress testing in real-world conditions, and material wear and tear analysis are of urgent importance.

Combining them with AI-powered navigation systems will make them even more autonomous, safe, and smart for large-scale industrial pipeline applications.

6.2 Hierarchical and Adaptive Intelligence in Robot Autonomy

In line with the growing trend of deep learning and reinforcement learning, the in-pipe robotics research area is migrating toward intelligent autonomy capable of self-adaptation in dynamic conditions without direct pre-programming. The most influential contribution in this direction is the emergence of Hierarchical Reinforcement Learning (HRL), which decomposes task execution into high-level planning and low-level motor control. Botteghi et al. [44] used this idea in pipeline inspection, enabling robots to learn macro-level objectives (such as segment completion) while refining navigation through local-level obstacle negotiation. HRL-based models have a much lower computational complexity than traditional flat reinforcement learning, particularly in long and sparse-feature pipelines. The models support modularity and better scalability, as sub-policies for a variety of pipe conditions can be shared across diverse missions. The approach also speeds up training by minimizing state-space exploration in simulations. Deploying HRL-trained models to real-world environments is challenging, however, due to issues with model transferability, sensor noise, and generalization to new scenarios.

The future of autonomous in-pipe robots rests on the convergence of HRL with other AI paradigms such as imitation learning and meta-learning, which allow robots to learn new tasks without delay using prior knowledge. Integrating these learning systems with real-time sensor feedback and fault-detection modules will also improve safety and reliability. Another key trend is the integration of adaptive decision-making. Rather than adhering to strict inspection routes, robots can now vary speed, sensing rate, and route according to pipe condition, environmental risks, or inspection priority. This adaptability also reflects the behavior of human experts and enhances efficiency and data quality. Research in this area is likely to advance toward self-aware, introspective robots that can assess their own performance and adapt strategies during a mission.

With enhanced autonomy, regulatory systems will have to cope with the safety and ethical aspects of robots performing on their own in key infrastructure. Such AI systems will have to be extensively tested to validate whether they meet performance and reliability levels across a range of industry sectors.

6.3 IoT and Networked Robotics Integration for Smart Infrastructure

Merging Internet of Things (IoT) design with in-pipe robotics is an emerging trend, specifically for large-scale pipe monitoring. IoT structures allow robots to exchange real-time information with control centers, cloud infrastructure, or even other robots within an organized swarm. Chhabhaiya and Bhojane [47] suggested an IoT-enabled internal pipe inspection robot with cloud connectivity for data logging, anomaly notifications, and remote diagnostics. Their approach included live visualization of pipe interiors on cloud dashboards, which is beneficial for utility operators. This connection makes independent robots part of a smart infrastructure network, such that inspection data can be fused with GIS information, maintenance histories, or climatic conditions. Predictive maintenance becomes possible here, as issues are remediated before becoming serious failures. Moreover, robots deployed with environmental probes can send situational context to other network subsystems, and they increase pipeline awareness

The largest benefit of IoT implementation is operational scale. Inspection bot networks can in real time be coordinated, segmented into routes, and allocate critical areas of attention. Yet such concerns as security for networks, bandwidth constraints, and latency are still obstacles for broad implementation. Standardization and interoperability in hardware platforms, too, present significant challenges. Mills et al. [48] highlighted that modularity in mechanical and communication parts will be essential to achieve plug-and-play robotic units that can be quickly deployed between various pipeline segments. In the meantime, future trends are towards digital twins—virtual copies of entire pipeline systems supplied with real-time robotic data—which can model inspection scenarios and optimize routing and maintenance plans. With infrastructure increasingly being digitized, the cooperation of IoT and in-pipe robotics will be instrumental in turning pipeline monitoring reactive into proactive, promising more efficiency, cost-effectiveness, and eco-friendly protection.

6.4 Materials, Miniaturization, and Roadmaps for Future Research

Advances in materials and miniaturization technologies lead the way to the next-generation development of in-pipe robots. The need for smaller, lighter, more efficient designs arises from the imperative to inspect those portions of pipeline systems previously not accessible because they were too narrow in diameter or presented too much geometrical complexity. Zhang et al. [49] presented a systematic review of worm-like robots and emphasized material-led breakthroughs in flexibility, structural robustness, and locomotion management. Utilization of soft composites, shape-memory alloys, and bioinspired materials is making robots capable of bending, stretching, and conforming like living things. Ren et al. [50] took this conversation further by modeling-based techniques for the prediction of the mechanical response of such robots under different loads and operational states. Their modeling provides insight into how materials act in dynamic, high-friction, or submerged conditions. Such predictive models are essential for pre-testing design variations prior to physical prototyping to save time and cost during development. One of the important trends is the use of multifunctional materials—materials that can be used as structural members as well as sensors or actuators. This obviates the need for large sensor modules and enables robots to be kept compact without compromising functionality. Work is also aimed at energy-harvesting materials that transform motion or environmental heat into energy, minimizing battery usage for extended missions.Verma et al. [46] and Kumar et al. [45] both pointed out that mechanical configuration innovation has to go hand in hand with actuation and material intelligence advancements. Their reviews indicate that robotic pipeline inspection in the future will see a transition from electromechanical systems to biologically inspired, self-adaptive, and even self-healing systems.

In the future, the research world is urging for international cooperation between disciplines—civil engineering, AI, materials science, and robotics—to create standard platforms, open-source test data sets, and field validation methods. These combined efforts will speed up the introduction of dependable, intelligent, and scalable robotic inspection systems that will transform underground infrastructure monitoring.

7. Conclusion

In-pipe robots have become revolutionary machinery in pipeline maintenance and monitoring of infrastructure in most industries, such as water supply, oil and gas, chemical plants, and urban utility. This review has systematically examined the development of robot technologies, including major developments, practical applications, and avenues for future research. The intersection of mechanical innovation, intelligent autonomy, and integrated sensing platforms has transformed the way pipelines are evaluated, making preventive maintenance possible and minimizing risks related to system failure. Section 2 offered a general description of locomotion methods, highlighting the ways in which wheeled, tracked, snake-like, bio-inspired, and hybrid mechanisms all provide unique benefits depending on pipeline geometry, environmental conditions, and operational objectives. As pipelines grow more complex and aged, the need for flexible and adaptive systems that can move through narrow, curved, or submerged pipelines with little human involvement is on the rise. In Section 3, the functional role of smart technologies and AI integration was discussed in detail. Contemporary in-pipe robots are no longer passive searchers but smart agents with localization algorithms, machine learning models for detecting faults, and sensor fusion. These capabilities add accuracy to operations, allow for real-time diagnostics, and minimize reliance on post-processing. AI also aids decision-making, route optimization, and mission-specific adaptations, making these systems vital elements of the larger Industry 4.0 system.

The following sections addressed real-world deployments, technical difficulties, and trends in research. Case studies showed how robots are being utilized today in the field, ranging from teleoperated to completely autonomous units able to navigate over large distances and make high-resolution inspections. At the same time, design and operations challenges like power constraints, sensor degradation, communications failure, and autonomy bottlenecks remain paramount. However, continuous innovations in materials, miniaturization, and hierarchical control systems promise effective solutions for getting past these difficulties. Lastly, the convergence of research trends in Section 6 suggests an interdisciplinary future where robotics, artificial intelligence, IoT, and materials science come together to form intelligent, scalable, and affordable robotic platforms. These will not only monitor but also predict, adapt, and even repair infrastructure anomalies—changing pipeline maintenance from a reactive to a proactive paradigm. As the world's infrastructure continues to age and grow, the creation and deployment of durable, autonomous in-pipe inspection robots will be critical to sustainable urban development, environmental conservation, and operational resilience. This area, full of innovation, can transform the way we deal with one of the most important yet invisible elements of our contemporary civilization.

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