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Research on the Design and Application of Bionic In-Pipe Crawling Cleaning Robots

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Abstract. In numerous fields such as industrial production, medical services, and environmental governance, pipeline systems serve as core infrastructure, undertaking critical functions like fluid transportation and waste discharge. However, after prolonged use, pipelines are highly susceptible to a variety of issues. These include the accumulation of dirt, blockages caused by foreign objects, and corrosion damage. Such problems not only affect transmission efficiency but may also lead to safety accidents and environmental pollution. Traditional pipeline cleaning methods, such as manual cleaning and high-pressure water jets, face limitations. In narrow, curved, and complex variable-diameter pipeline environments, these methods are often inefficient, unsafe, and unable to achieve thorough cleaning. To address this, bionic in-pipe crawling cleaning robots have emerged. This article explores the design and application of bionic in-pipe crawling robots, which mimic biological locomotion methods, such as earthworm peristalsis and snake-like slithering, to achieve navigation and cleaning in complex pipeline environments. The study reviews current technologies, details the robot's structural design, locomotion mechanisms, and sensor integration. It also analyzes applications in industrial, medical, and environmental monitoring fields, highlighting adaptability and efficiency. Challenges are identified, such as limited navigation accuracy and insufficient cleaning efficiency, while future trends like multi-robot collaboration and advanced materials are envisioned. Through theoretical simulations and literature synthesis, the robot's potential is validated, providing insights for enhancing reliability in diverse scenarios.

Keywords: Bionic robot, In-pipe crawling, Peristaltic motion, Pipeline cleaning, Sensor integration

1. Introduction

Bionic in-pipe crawling robots achieve crawling and cleaning functions inside pipelines by mimicking biological locomotion methods, such as earthworm peristalsis or snake-like slithering. These robots possess high adaptability and flexibility, capable of handling narrow, curved, and variable pipeline environments. Unlike traditional rigid robots, bionic designs allow robots to advance through body extension/contraction, wave-like motion, or attachment mechanisms, avoiding structural limitations. For example, in-pipe crawling robots based on tensegrity structures can utilize flexible mechanisms for efficient movement in pipelines [1]. Additionally, bionic robots

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are typically small in size and lightweight, facilitating entry into micro-pipelines, and possess autonomous operation capabilities, improving operational safety and efficiency [2]. Currently, in-pipe cleaning robots are widely applied in industrial, medical, and environmental monitoring fields. In industry, they clean dirt from pipelines; in medicine, they disinfect catheters; and in environmental monitoring, they maintain sewage pipelines. Technological developments include peristaltic and snake-like robots, combined with sensors for autonomous navigation. However, challenges persist: insufficient adaptability in complex pipeline environments, such as difficulties in handling sharp bends or variable-diameter pipelines; low cleaning efficiency, especially in long-distance operations; and difficulties in navigation and positioning due to environmental interference [3]. Furthermore, issues like maintenance costs and stability also hinder further popularization.

This article aims to explore the planning and arrangement of bionic in-pipe crawling robots. By optimizing motion control strategies, path planning, and cleaning mechanisms, the research seeks to enhance the cleaning efficiency and reliability of these robots in complex pipeline environments. The research integrates literature reviews, design principles, application scenario analyses, and experimental validations to provide valuable insights for future development.

2. Design principles and structure of bionic in-pipe crawling robots

2.1. Robot structural design

The overall structure of bionic in-pipe crawling robots includes the mechanical body, drive system, sensor configuration, and control system, with structural design directly affecting the robot's motion performance and adaptability. The mechanical body integrates flexible and rigid materials to optimize functionality. The main frame is constructed from lightweight, high-strength aluminum alloy, ensuring robust structural stability. Meanwhile, inter-segment connections employ flexible hinges made of polyurethane elastic materials, granting the robot bending capabilities for movement in curved pipelines. The drive system is the power source for the robot's motion and cleaning functions. Based on the functional requirements of different robot modules, a combination of multiple drive methods is adopted, including pneumatic drive, piezoelectric drive, motor drive, etc., to achieve bionic motion. The focus is on bionic locomotion methods, such as peristaltic motion through multi-segment body extension/contraction for advancement, and snake-like motion using joint bending to adapt to curves [4].

2.2. Design of bionic locomotion mechanisms

Bionic locomotion mechanisms are the core of bionic in-pipe crawling cleaning robots, determining the robot's mobility and adaptability within pipelines. This article takes earthworm peristaltic motion and snake-like slithering as research objects, deeply analyzing their motion principles, designing bionic locomotion mechanisms suitable for in-pipe environments, and verifying motion performance through modeling and simulation. The robot mimics earthworm peristalsis, achieving advancement through body extension/contraction and wave motion. Motion units include flexible segments and actuators, with mode switching realized through control algorithms, and parameter optimization considering speed and energy consumption. For example, utilizing peristaltic mechanisms for driving achieves efficient crawling [5]. In design, friction and adhesion are considered to ensure stable propulsion inside the pipe [6].

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2.3. Integration of sensors and control systems

The integration of sensors and control systems is key for bionic in-pipe crawling robots to achieve autonomous operation and efficient tasks. The robot is equipped with various sensors, including pressure sensors, displacement sensors, and environmental sensors, which provide real-time feedback on the robot's operating status inside the pipeline and surrounding environmental information. Pressure sensors monitor the contact pressure between the robot and the pipeline inner wall, ensuring appropriate contact force during motion to avoid slippage or pipeline damage due to excessive or insufficient pressure. Displacement sensors precisely measure the robot's motion distance and position changes, providing accurate data support for motion control. Environmental sensors detect parameters such as temperature, humidity, and gas composition inside the pipeline, helping the robot understand the pipeline conditions in real-time and adjust motion strategies accordingly. These sensor data are transmitted to the robot's control system, which performs autonomous navigation and path planning based on the feedback. For example, combined with obstacle avoidance algorithms, the robot can identify obstacles inside the pipeline in real-time and automatically adjust its motion direction to avoid collisions. The control system adopts a Central Pattern Generator (CPG) to achieve bionic gait control, simulating biological motion neural mechanisms to generate stable motion patterns and enhance the robot's adaptability in complex environments. Through the Central Pattern Generator, the robot can flexibly switch between different bionic motion modes, such as peristaltic and snake-like modes, based on varying pipeline shapes and motion requirements, thereby achieving efficient and stable motion. Additionally, the control system can optimize parameters based on sensor data, adjusting motion speed and energy consumption to maximize efficiency and operational performance while completing tasks [7].

3. Applications of bionic in-pipe crawling cleaning robots

3.1. Industrial field applications

In the industrial field,bionic in-pipe crawling robots play a crucial role, particularly in cleaning oil and natural gas pipelines, removing dirt, and inspecting structural integrity. These robots' unique capabilities lie in their flexible navigation of variable diameters and bends, making them excel in maintaining large-scale infrastructure, such as complex pipeline systems in petrochemical plants. Due to the complex internal environments of these pipelines, traditional manual cleaning methods are not only inefficient but also pose safety risks. Therefore, the emergence of bionic in-pipe crawling robots has brought revolutionary changes to this field. They can enter narrow and complex pipeline systems for efficient cleaning and structural inspections, ensuring safe pipeline operation and reducing production interruptions and economic losses caused by blockages or damage. Moreover, these robots can be equipped with various sensors and detection devices to monitor potential issues like corrosion and cracks inside pipelines in real-time, providing precise data support for maintenance and repair work. By enhancing the efficiency and safety of industrial pipeline maintenance, these robots not only reduce maintenance costs but also bolster the reliability and overall efficiency of the entire industrial production system.

3.2. Medical field applications

The applications of bionic in-pipe crawling cleaning robots in the medical field primarily focus on soft-bodied systems inspired by earthworms or worms, which can adapt to curved and narrow lumen

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environments for hospital pipeline maintenance and foreign object removal. In recent years, patents and design innovations have further advanced cleaning functions. Yu et al. simulated the motion of soft-bodied in-pipe crawling robots, covering V-type and TH-type pipeline cleaning robots [8]. These soft-bodied designs are suitable for cleaning tasks in confined spaces, such as removing foreign objects from medical pipelines and infection prevention. Blewitt et al. reviewed worm-like in-pipe inspection robots, highlighting load-carrying and vertical climbing capabilities, which support carrying cleaning tools for medical pipeline network maintenance, although primarily focused on inspection [9]. Overall, these bionic robots are transitioning from general in-pipe cleaning to medical applications, emphasizing design optimization to adapt to curved environments. Despite challenges in motion stability and load, their potential lies in non-invasive cleaning, such as hospital pipeline hygiene maintenance. In the future, with advances in materials science, this technology is expected to be further integrated into clinical pipeline cleaning, driving innovation in medical hygiene. Through the deployment of these robots, hospitals can more effectively maintain the cleanliness and safety of their internal pipeline systems. This reduces the risk of cross-infections caused by pipeline contamination and enhances the overall hygiene level of the medical environment for both patients and healthcare personnel.

3.3. Environmental monitoring

The application of bionic in-pipe crawling cleaning robots in the environmental sector has emerged as a crucial research direction at the intersection of robotics and environmental protection. These robots often mimic biological peristaltic or crawling mechanisms for cleaning industrial pipelines and wastewater systems, reducing pollutant accumulation and enhancing environmental sustainability. Fekrmandi and Hillard designed a bio-inspired peristaltic locomotion in-pipe crawling robot equipped with non-destructive evaluation modules [10]. Through tethered control, the robot can detect and clean pipeline interiors, suitable for environmental monitoring and pollution control scenarios, such as sewage treatment plant pipeline maintenance. These studies indicate that bionic in-pipe robots are evolving toward intelligence and autonomy, promoting environmental cleaning applications. Through regular cleaning and maintenance by these robots, pipeline service life can be effectively extended, reducing risks of leaks and blockages, thereby minimizing negative environmental impacts. Moreover, these robots can be integrated with environmental monitoring systems to collect and analyze real-time data on water quality and pollutant concentrations within pipelines. This provides a scientific basis for environmental management and decision-making. In the future, with continuous technological progress, these robots are expected to be applied in more environmental fields, making greater contributions to environmental protection and sustainable development.

4. Challenges and future development trends

Although bionic in-pipe crawling robots demonstrate immense potential, their development still faces numerous challenges. In high-pressure environments, the robot's motion control accuracy is limited, making precise operations difficult, which is particularly prominent in some industrial pipeline cleaning tasks with extremely high precision requirements. Additionally, for some stubborn residues inside pipelines, the cleaning efficiency of existing robots still needs improvement, which may lead to incomplete cleaning and affect normal pipeline operation. Long-term operational reliability issues cannot be ignored; robots may experience component wear and failures after prolonged work, increasing maintenance costs and downtime. In highly eccentric or blocked

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pipelines, the navigation capability of bionic in-pipe crawling robots is often compromised due to sensor limitations. This can easily lead to disorientation or an inability to effectively avoid obstacles.

To address these challenges, the future development trends of bionic in-pipe crawling robots will focus on multi-robot systems, intelligent control algorithms, and the application of advanced materials. Developing multi-robot systems for collaborative cleaning can improve cleaning efficiency and coverage, solving tasks difficult for a single robot through inter-robot cooperation. Utilizing machine learning to optimize intelligent control algorithms can enable robots to better adapt to complex environments, improving motion control accuracy and decision-making capabilities. Adopting advanced bionic materials, such as biological mucosa, can enhance the robot's durability and flexibility, allowing it to maintain good performance even in harsh environments [11].

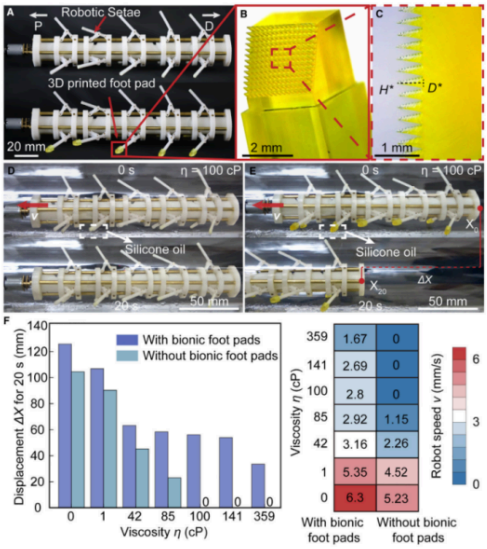


Figure 5. Fan-worm-inspired robot with bionic foot pads and its performance in artificial mucus-coated tubes [11]

Figure 5(A) depicts a fan - worm - inspired robot that is outfitted with replaceable bionic foot pads. Here, “P” represents “proximal” (the near end), and “D” represents “distal” (the far end). the fan - worm - inspired robot equipped with replaceable bionic foot pads (with microvilli-like structures on the contact side, as seen in Figure (B) and (C)) exhibits better performance in tubes coated with artificial mucus compared to those without bionic foot pads. In Figure (D) and (E), when the viscosity of artificial mucus is 100 cP, the robot with foot pads crawls effectively, while the one without slips. Figure (F) further quantifies that robots with bionic foot pads have greater displacement. These innovations will drive the further development of bionic in-pipe crawling robot technology, providing strong support for addressing existing challenges.

5. Conclusion

This study explores the design, motion control, and applications of bionic in-pipe crawling robots in industrial, medical, and environmental fields, revealing their significant advantages. Through peristaltic and snake-like mechanisms, these robots can flexibly adapt to complex pipeline environments, effectively enhancing cleaning efficiency and operational reliability. The research, through extensive literature synthesis, fully validates their immense potential in pipeline cleaning. However, the robots still face challenges in motion control accuracy and long-term stability, such as

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limited control accuracy in high-pressure environments and insufficient long-term operational reliability, which restrict their widespread application in some high-demand scenarios. Despite these challenges, the continuous advancement of technology offers promising prospects for overcoming these limitations. Future development directions such as multi-robot collaboration, intelligent algorithm optimization, and material innovation, are expected to provide effective solutions. Through collaborative operations of multi-robot systems, the shortcomings of individual robots can be compensated, improving overall performance. The application of intelligent algorithms will make robots more intelligent, better handling complex environments. Meanwhile, the use of advanced materials will enhance the robot's durability and adaptability. These advancements are anticipated to pave the way for the broader adoption and performance improvement of bionic in-pipe crawling robots in diverse pipeline environments. As a result, they will be better positioned to serve the industrial, medical, and environmental protection fields, ultimately making greater contributions to the development of human society.

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