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Review Article

Industry 4.0 Pipeline Inspection Robots: Challenges, Opportunities, and Innovative Solutions

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Abstract

Pipelines are the most popular and extensively utilised means of transporting gases and liquids today. Regular inspection is crucial for their proper functioning and sustainability. However, human inspection poses significant safety risks, necessitating alternative solutions. The fourth industrial revolution, 4.0 invented pipeline inspection robots, eliminating the need for humans to enter potentially hazardous pipelines. Despite advancements, pipeline robots still face challenges. This study explores issues, opportunities, and solutions related to pipeline inspection robots in industry 4.0. The incorporation of this technology aids in resolving numerous issues, including: fluid or gas pipeline leaks; rust accumulation; and broken pipes. This research discusses the drawbacks of pipeline inspection robots and potential opportunities and proposes solutions to optimise their performance.

Keywords: *Industry 4.0, Pipeline, Inspection Robot, Leakages, Problems, Solutions.*

I. Introduction

Pipelines are now the most widely used method of transport for gases and liquids [1–3]. Therefore, ongoing pipeline monitoring is necessary to assure its safety and health [4] Non-Destructive Testing (NDT) inspection techniques that are widely used includes optical testing, radiographic testing, ultrasonic testing, hydrostatic testing, among others [5]. However, because of the recent advancements in robotic technology [6, 7], which is being brought about by industry 4.0 they are now the preferable choice. Robots are a superior choice because it is challenging for people to access a small pipeline [8]. Recent years have witnessed significant advancements in In-pipe Inspection Robots (IPIR), with innovations categorised into distinct locomotion patterns. In the references listed below are examples of the Pipeline Inspection Gauge (PIG) [9, 10], screw [11, 12], inchworm [13–19], wall press [20–24], walking [25–29], caterpillar [30–34], and wheel type [35–50]. These popular forms of movement have drawbacks in addition to their benefits [40].

1.1 In-pipe Inspection Robot Types (IPIR)

The Pipeline Inspection Gauge (PIG) type can be utilised for large distances [51–55] and moves inside pipelines using water pressure. The inside surface of the pipelines is not harmed by the screw-helical type's motion when it moves [56–60]. The inchworm may pass through pipelines because of its strong grasp despite its poor traction [13–17]. Using contact force, the wall press type steadily passes through the pipelines [20–24]. The walking kind employs legs to move and has a complex mechanism, which causes reduced surface wear and slippage [25–29]. Caterpillars move inside pipelines using tracked wheels, and its system enables them to adjust to the circumstances there [30–34]. The wheel type is more mobile than the other varieties and can travel inside pipelines by simply rotating its wheels [35, 36, 43–45]. Due to the pipeline's curved and branching pipes, these robots must overcome numerous obstacles. It encounters motion singularity and erratic motion while doing this [46–50, 37].

1.2 Motion Singularity

The "Motion Singularity" is the loss of contact or traction between a robot and pipeline intersections such curved pipes, L-branch pipes, and T-branch pipes [41, 42]. Due to its powerful traction force and substantial contact area, the caterpillar robot offers more stability and is the most widely used IPIR. The pipeline is kept in contact with the inner surface no matter how the pipeline is turning by using tracked wheels [30, 34, 41]. If one of the wheels loses contact with the inner surface of the pipe, it is unable to pass through it, leading to motion singularity [41]. A caterpillar robot that is travelling through T-branch pipes uses two modules in place of one to prevent motion singularity. Three caterpillar wheels are mounted on the first module at a 120° angle to one another, and the second module is infix at a 60° angle to the front module [41]. The "Famper" pipeline exploration robot loses contact with the inner surface of the pipeline when turning at Y and T-branch pipes, which results in motion singularity. The caterpillar wheels were positioned at a 5-degree inclination with regard to the robot body rather than set straight to compensate for the loss of contact. "Motion singularity" is thereby avoided [42]. A two-wheel chain robot that avoids the motion singularity is shown in [61].

1.3 Irregular Motion

According to published research, conventional wheeled robots frequently employ wheels that are symmetrically positioned at a 120° angle to ensure even loading and improved stability while moving through pipelines. The wheeled robots achieve this stability through the wall press feature [30, 41], [62–64]. According to Li et al. [36, 43], the addition of six wheels corrects the uneven motion that happens along the circumferential axis of the pipeline in forward motion produced by the three-wheel arrangement in wheeled IPIR. The wheeled robot has a three-wheel layout and moves inside the pipelines using two different types of wheels. When moving forward, the robot's single three-wheel design tries to rotate in the pipeline's circumferential direction [65]. Only straight pipelines have been the subject of investigations about their motion. The orientation of the robot at the completing end is different from the starting end in circumstances [66] where it tries to roll over in order to maneuver through the curved pipeline. Additionally, steering inside branching pipes is challenging due to how the wheels are positioned. This study focuses on the development of a wheeled IPIR with a single three-wheel arrangement to prevent the motion singularity and the irregular motion while maintaining same orientation before and after entering the curved pipeline [67]. Contribution In this research article, a wheeled type of IPIR was proposed and developed to address the issue of irregular movement and motion singularity in pipelines. The wheels on this robot are different from those on conventional robots in that they are not fixed at a 120-degree angle from one another. The placement of the wheels ensures that they remain in constant touch with the pipe surface and prevents the robot from rolling over while travelling down a curved pipeline. It also aids the robot's navigation through branched pipes [67].

II. Pipeline inspection robot-related problems experienced by clients

1. Are Pipeline Inspection Robot Maintenance Procedures Users-Friendly?

The ease of maintenance procedures worries the pipe inspection robot. The maintenance times will climb in tandem with a linear increase in the frequency of robot operation. Consumers are worried about how simple these steps will be to execute; after all, they don't have unlimited time or energy to devote to the complete upkeep of inspection robots.

2. Key Factors that Affect the Service Life of Pipeline Inspection Robots

A number of variables affecting the service life of pipeline inspection robots are included in the problem that has customers upset. Customers place a high value on a robot's ability to maintain a stable running status and consider longer service life to be essential. Customers do not investigate short-running time inspection robots, which can easily lower their cost-effectiveness and raise the price they pay.

3. Essential Factors to Consider during Pipeline Inspection Robots Operations

Customers may lead a dependable pipe crawler robot to penetrate pipelines deeply and quickly finish the work of detecting various pipes, streamlining the operation processes in the process. The several issues that need to be taken into consideration throughout the operating stage are the subject of the customer's question. The corresponding links need to be made clear sense they are concerned that incorrect operation will interfere with the robot's ability to function [70].

III. Critical factors for effective pipeline inspection robots in operations and maintenance

1. Extreme security: Enter the pipeline using the pipeline robot to quickly assess its interior conditions and/or remove any potential hazards. Because of the high labor intensity and greater safety risks associated with manual labor; these jobs are not good for employees' health. The Easy Sight pipeline robot's intelligent operation may significantly enhance the operation's performance in terms of safety.
2. Labor-saving: Small and lightweight, the pipe inspection robot can be controlled by one person. The controller can be put on the vehicle, which will save time and room.
3. Improved effectiveness and caliber: In addition to accurate positioning, the Easy Sight smart pipeline robot can display real-time data such as date and time, crawler inclination (pipeline slope), air pressure, crawling distance (meters of line), laser measurement results, and azimuth (optional). The function keys allow you to control the lens angle of view clock display as well as the display status of this information (positioning of pipeline defects).

4. Great level of protection: There is no need to be concerned about the quality of the pipe camera because it has a high level of protection, airtight protection, and the material is waterproof, anti-rust, and corrosion resistant.
5. Receiving and releasing cables won't interfere with one another with a high-precision cable reel, and the length is configurable. The pipe inspection robot can inspect pipelines with diameters ranging from 100 mm to 2000 mm. It can raise productivity and save labor in addition to enhancing task precision. Additionally, it can maintain the pipeline in some locations where manual labor is not appropriate and quickly identify the internal sources of pipeline degradation [68].

Conclusion

In this work, we compare the proposed wheeled type IPIR with the existing wheeled type IPIR. According to the current design, the three wheels are positioned 120 degrees apart from one another. We replicate both the proposed and traditional wheeled types of IPIR. The angles that work best are 120°, 135.12°, and 104.88°. The force and velocity analysis results for each wheel show how this design causes the wheels to come into contact with the pipelines. When navigating the curved pipeline, the developed robot did not encounter the uneven force that the robot with a wheel mounting angle of 120° did [67]. The implications of the in-pipe wheel robots are also covered [69].

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