Autonomous Robot On-Pipe Leak Detection

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Abstract

The research addresses the critical need for efficient and cost-effective pipe inspection methods in modern infrastructure, focusing on the maintenance of water and gas delivery systems. The objective is to improve defect detection and maintenance processes in pipes, reducing downtime and operational costs. The proposed method involves deploying pipe inspection robots, with an emphasis on on-pipe robots tailored for specific applications such as urban gas lines, small feeder pipes, and sewer systems. These robots are categorized into seven sub-types, including wheel-type, inchworm-style, AI-powered sewer inspection, caterpillar-style, and helical motion robots, each designed for unique inspection challenges. A newly developed versatile on-pipe inspection robot is highlighted for its ability to inspect a variety of plastic and metal pipes in both horizontal and vertical orientations. This robot features a body, foreleg system, rear leg system, and springs, enabling smooth navigation through pipes. The performance of this robot shows substantial improvements in inspection efficiency and accuracy, proving its effectiveness as a modern solution for infrastructure maintenance.

Keywords: Pipe Inspection Robots, On-Pipe Inspection, Pipeline Maintenance, Water and Gas Pipelines, Infrastructure, Defect Detection, Inspection Efficiency

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1. Introduction

In contemporary society, pipes serve as vital infrastructure for essential services like water and gas supply, as well as for transportation in industries. Traditional out-of-pipe approaches, such as acoustic leak detection and audits, often struggle with reliability and accuracy in precisely identifying leak locations within the pipeline network. This leads to inefficiencies and delays in remediation efforts, posing risks of resource wastage and environmental harm. Moreover, the scalability and efficiency of many existing techniques, including acoustic methods, are hindered by manual operation and slow procedures, making them less suitable for comprehensive and timely leak detection across extensive pipeline infrastructures [6].

To address these challenges, employing robots for pipe inspection offers a faster and more cost-effective solution. This proposed study focuses on the development and application of advanced on-pipe inspection robots designed to enhance the efficiency and accuracy of pipeline maintenance. These robots are categorized into seven sub-types: pig type, wheel type, caterpillar type, wall press, walking type, inchworm type, and screw type robots, each offering unique advantages for specific inspection tasks [7-9].

A newly developed on-pipe inspection robot is introduced, designed to accommodate a wide range of pipes, including both plastic and metallic, arranged either horizontally or vertically. The robot comprises a body, foreleg system, rear leg system, and springs [10-11]. Each leg system consists of three legs arranged at 120-degree angles to effectively navigate through pipes of different diameters. Springs facilitate smooth movement within pipes of varying sizes. The proposed method significantly improves the inspection process, offering a more effective and reliable solution for maintaining modern infrastructure [12-14].

2. Objective

The primary goal of this system is to develop and deploy a climbing robot capable of performing detailed inspections for leaks in pipelines across a range of industrial sectors. While initially tailored for the gas and oil industries, the robot is designed to meet inspection needs in other industrial processes as well. This adaptable climbing robot is engineered to traverse intricate pipeline networks, aiding in the detection and evaluation of leaks to maintain the safety and integrity of vital infrastructure.

3. Problem Statement

The current system for pipeline inspection using RGB image capture introduces noise during image segmentation, leading to potential inaccuracies in fault detection. Temperature variations can cause false anomaly detections, compromising reliability. The complex network architecture, with numerous constraints and variables, adds to the system's difficulty in design and optimization. Additionally, the high memory requirements limit scalability and deployment in resource-constrained environments. The proposed climbing robot aims to overcome these limitations by providing a more accurate, reliable, and efficient inspection process, enhancing the safety and integrity of vital infrastructure across various industrial sectors.

4. Literature Survey

Hong [1], describes the recent advancements in depth estimation from stereo RGB image pairs using convolutional neural networks (CNNs) have shown promise. However, prevalent deep learning algorithms for depth estimation often rely on patch-based Siamese networks, which struggle to incorporate contextual and environmental texture information effectively. Electric inspection robots face challenges due to complex environments and occlusion. A novel disparity estimation neural network has been proposed to address these issues, improving the robots' depth perception and overall performance. The network includes the PSMNet module and a lightweight pruning module, demonstrating effective performance in electric inspection applications.

Dalei, Wu [2], proposed a robotic sensor network, consisting of sensor nodes (SNs) and relay nodes (RNs), provide accurate and real-time inspection for underground pipelines. SN localization is crucial for leak detection and maneuvering within complex pipelines. This research introduces algorithms for the self-localization of in-pipe SNs. It considers SN movement dynamics and leverages velocity measurements along with received signal strength (RSS) data from aboveground RNs. Different localization algorithms based on the Kalman filter are explored, with simulation results validating their effectiveness. The framework contributes valuable insights for designing robotic sensors in various pipeline systems, including oil and gas pipelines.

Horodinca [3], introduces a novel in-pipe inspection robot architecture consisting of two articulated parts connected by a universal joint. One part moves along the pipe using wheels parallel to the pipe's axis, while the other part follows a helical motion with tilted wheels rotating around the pipe's axis. A single motor drives the motion, and suspension systems adapt to changes in tube diameter and pipe curves. The robot operates autonomously, equipped with batteries and a radio link. Prototypes for various pipe diameters demonstrate their simplicity and suitability for tasks like scrubbing or inspection.

Gargade [4], describes the innovative in-pipe inspection robot designed to reduce human involvement in hazardous tasks. Comprising foreleg and rear leg systems, along with a body, the robot utilizes three worm gear systems in each leg, enabling movement within the 140mm to 200mm diameter range. Meticulous design and assembly using SolidWorks 11 ensure structural integrity, verified through stress analysis in both SolidWorks 11 and Ansys 13. Engineered for offline visual inspection, the robot finds applications in various pipeline inspections, promising safer and more efficient industrial operations.

Li [5], proposed a hierarchical integer linear programming optimization algorithm method to identify crucial inspection points for autonomous robots navigating complex pipeline systems. Unlike conventional systems, which focus on mobility and control, this approach emphasizes global planning for comprehensive and automated inspections. Simulations conducted in a virtual environment demonstrate the effectiveness of the computational framework in detecting scanned pipelines, leaks, clogs, and deformations by an autonomous prototype robot.

5. Proposed System

The on-pipe inspection robot operates based on a systematic workflow utilizing its integrated components to ensure efficient pipeline inspection. The robot is equipped with a geared DC motor that drives its movement along the pipeline. As the robot traverses through the pipe, the gas sensor (MQ-6) continuously monitors the environment for any gas leakage. Upon detecting a gas concentration, the sensor generates an analog electrical signal proportional to the gas level. This analog signal is then fed into the ESP8266 microcontroller, which features an integrated ADC for converting the analog signal into digital values. The microcontroller is pre-programmed to interpret these values and activate the buzzer to signal a gas leakage alarm. This was done using the Arduino IDE platform to provide uninterrupted operation until the leak was detected.

Simultaneously, an ultrasonic sensor tracks the distance traveled by the robot from its starting point. This provides a precise location of the fault or anomaly detected within the pipeline. The robot's movement is facilitated by its foreleg and rear leg systems, allowing the robot to navigate pipes of varying diameters effectively. The springs integrated into the leg systems ensure smooth movement within different pipe sizes, accommodating both plastic and metallic pipes arranged either horizontally or vertically.

For enhanced functionality and real-time monitoring, the Blynk App is employed to display and track anomalies or defects detected during the inspection process. This allows operators to remotely monitor the robot's progress and quickly identify and address any issues in the pipeline. Overall, the robot offers a comprehensive solution for offline visual inspection of various pipelines, including gas, water, and drainage systems, with its application extending to industries and regions like the Gulf countries for inspecting oil and gas pipelines.

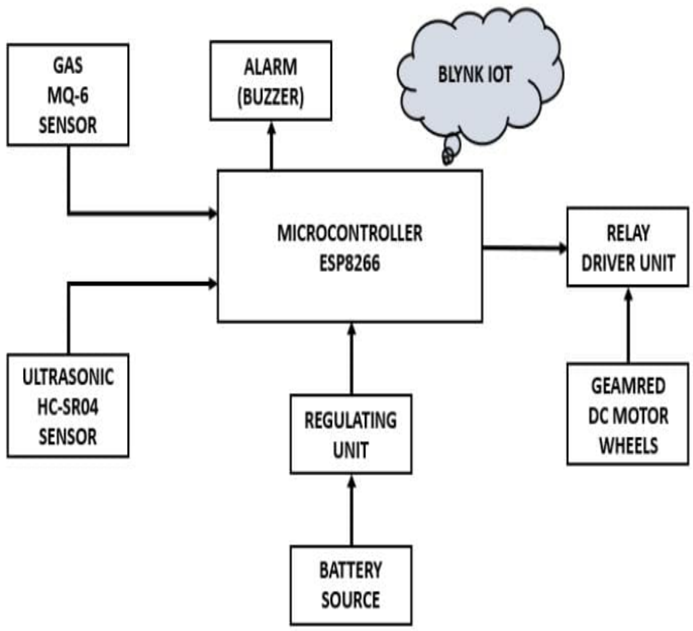

Figure 1. Block Diagram of the Proposed System

The proposed system is shown in Figure 1. which incorporates essential components such as a microcontroller, MQ6 sensor, relay, ultrasonic sensor, and buzzer, specifically designed to detect leaks in gas, water, or other pipelines. As the robot navigates the pipeline, it utilizes its suite of sensors to detect gas leaks and track their movement, ensuring comprehensive inspection coverage. Moreover, the inclusion of spring legs in the robot facilitates smooth traversal through pipelines, allowing it to adapt seamlessly to varying pipe materials and orientations. The integration of the Blynk app enables real-time monitoring of the robot's progress and detected anomalies, empowering operators to swiftly address any issues that arise.

This comprehensive system, driven by a geared DC motor, ensures effective pipeline inspection, with the MQ-6 sensor monitoring gas levels and the ESP8266 module providing Wi-Fi connectivity for seamless communication and control. An ultrasonic sensor precisely tracks the robot's movement, aiding in pinpointing pipeline irregularities. With the integration of foreleg and rear leg systems, the robot exhibits enhanced navigational capabilities across different pipe sizes. The Blynk App further enhances operator efficiency by providing dynamic visualization of the robot's movement and detected anomalies, facilitating proactive maintenance and intervention. Overall, the robot offers a comprehensive solution for offline visual inspection of various pipelines, including gas, water, and drainage systems, with its application extending to industries and regions like the Gulf countries for inspecting oil and gas pipelines.

6. Working of Proposed System

The on-pipe inspection robot operates using a 4 DC geared motor that facilitates its movement along pipelines, allowing it to conduct meticulous inspections. This robot is equipped with specialized sensors to monitor the pipeline environment effectively. The gas sensor (MQ-6) is continuously active, scanning for any gas leakages by detecting variations in gas concentrations. The MQ-6 sensor is calibrated based on the environment, with default gas concentration level set to 1000 ppm. The preset load resistance in the MQ-6 range from 12k-ohms to 40k-ohms. When the MQ-6 sensor identifies a significant gas level that may indicate a leakage, it generates an analog electrical signal. This signal is then transmitted to the ESP8266 microcontroller, programmed with Arduino IDE to ensure the effortless operation of pipeline leak detection and equipped with an integrated Analog-to-Digital Converter (ADC). The microcontroller processes this signal and, upon confirmation of potential leakage, trips the relay supply and ideally stands at the position of the leak and triggers a buzzer alarm to alert operators to the detected anomaly.

Alongside gas leakage detection, the robot also utilizes an ultrasonic sensor to track its distance from the sending point which uses the sender (PWM) and receiver (Echo) to calculate the distance traveled from its starting point. This feature provides precise localization of any detected anomalies or faults within the pipeline, ensuring accurate identification and assessment.

For real-time monitoring and data visualization, the robot integrates with the Blynk App, which displays a dynamic graph representing the robot's movement and the anomalies detected along its path. The graph plots the distance traveled (Y-axis) against time (X-axis). When the robot encounters a leakage, the graph shows a straight line parallel to the X-axis, indicating the point of halting due to the detected fault. In contrast, during normal operation without any leaks, the graph displays oscillating values, reflecting continuous movement along the pipeline.

In the event of detecting a leakage, the robot automatically halts its inspection to allow for further assessment or repair at the identified location. It triggers the buzzer alarm, signaling the need for operator intervention. Once the issue is addressed, the robot resumes its inspection, continuing its journey along the pipeline to identify any additional anomalies or faults.

In summary, the on-pipe inspection robot's operational workflow involves continuous monitoring for gas leakages, precise distance tracking, and real-time data visualization. Upon detecting a leakage or anomaly, it halts, sounds an alarm, and awaits operator intervention before resuming its inspection, ensuring a thorough and efficient assessment of the pipeline's integrity.

7. Software Results and Discussion

In the implemented on-pipe inspection robot, the Arduino IDE is used to program the microcontroller using C++ language. The Blynk platform is used to display a graph that provides real-time visualization of the robot's movement and anomaly detection. Figure 2. Graph is plotted with the X-axis representing Time and the Y-axis representing Distance traveled by the robot from the starting point. When the robot encounters a leakage in the pipe, the graph displays a straight line parallel to the X-axis, indicating a constant distance traveled due to the robot halting at the leakage point. In contrast, under normal conditions without any leakage, the graph oscillates between peak and fall values, reflecting the continuous movement of the robot along the pipeline.

Upon detecting a leakage as shown in Figure 3, the robot triggers the buzzer to sound an alarm, signaling the presence of a fault in the pipeline. The robot stops its movement at the detected leakage location to allow for further inspection or repair. After addressing the issue, the robot continues its inspection process, moving along the pipeline to identify any additional anomalies. This real-time monitoring and alert system ensure timely detection and response to pipeline leakages, enhancing the efficiency and effectiveness of the inspection process.

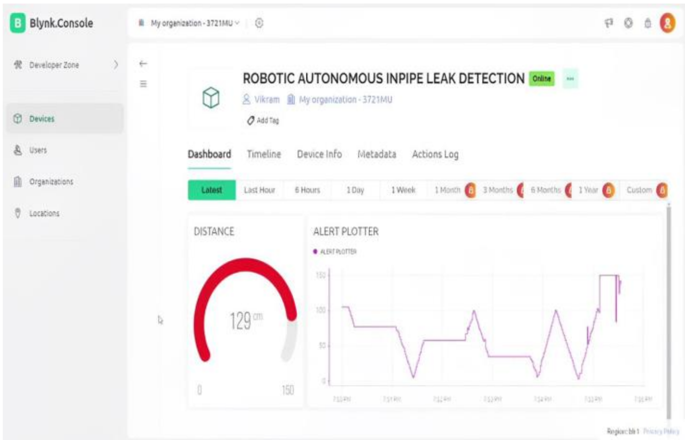

Figure 2. Output from Blynk Console / App

Leakage Detected No Leakage Detected

Figure 3. Time and Distance from Contact of the Leaks

8. Hardware Results and Discussion

The hardware arrangements and inspection of leakage detection are discussed below,

8.1 Hardware Arrangements

The hardware arrangements of the proposed design given in Figure 4. showcases the propulsion mechanism of the robot powered by a four DC geared motor, facilitating its climbing ability along the pipe. The embedded circuitry integrates MQ-6 and HC-SR04 sensors to detect gas leakage and distance traveled. a buzzer to indicate fault detection, a battery to power up the pipeline inspection robot, and a relay circuit to control the position of motor. This hardware setup is programmed in C++ to efficiently carry out its inspection tasks.

Figure 4. Hardware Arrangements

8.2 Inspection of Leakage

Inspection of leakage detection model as shown in the Figure 5, occurs during the inspection process, if a leakage is detected by the MQ-6 sensor, it promptly notifies the ESP8266 microcontroller. Subsequently, the buzzer is activated to alert the operator of the detected fault. Sure, here's a modified version. If the robot detects a leak, it halts inspection to facilitate repair or further assessment. In the absence of any leaks, it continues inspecting until it has covered the entire pipeline, then returns to the starting point.

Figure 5. Inspection of Leakage

8.3 Circuit Model

The Figure 6. depicts the circuit model which showcases the component used in the Figure 4, where the ESP8266 module acts as the main controller. It connects to the ultrasonic sensor for distance measurement and the MQ-6 sensor for gas detection. If the module detects a high gas level, it sets off an alarm through Relay 1 and turns off the motor's power for safety. Relays 2 and 3 control the robot's movement: Relay 2 runs the motor, and Relay 3 manages its power.

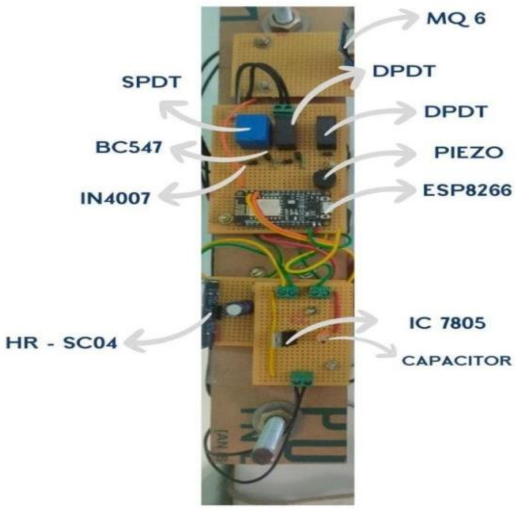

Figure 6. Circuit Model

9. Conclusion

The on-pipe inspection robot has demonstrated its effectiveness in assessing pipelines, particularly in swiftly detecting gas leaks through live monitoring. Looking forward to this, there are several promising avenues for enhancing its functionality. By incorporating state-of-the-art sensors and refining its autonomous navigation capabilities, the robot can adapt to complex pipeline layouts with greater ease. Predictive maintenance features can also be integrated to anticipate and address potential issues proactively. Moreover, broadening its compatibility to inspect T-joint and curved pipes will increase its versatility. Features like wireless recharging, remote operation, and cloud connectivity are poised to further streamline its operations. By embracing these innovations, the robot is on track to become an advanced and versatile tool for pipeline inspection, setting new standards in efficiency and safety across various sectors and geographical areas.

References

[1] Yu, Hong, and Feng Shen. "Disparity estimation method of electric inspection robot based on lightweight neural network." In 2021 6th International Conference on Intelligent Computing and Signal Processing (ICSP), pp. 929-932. IEEE, 2021.

[2] Wu, Dalei, Dimitris Chatzigeorgiou, Kamal Youcef-Toumi, and Rached Ben-Mansour. "Node localization in robotic sensor networks for pipeline inspection." IEEE Transactions on Industrial Informatics 12, no. 2 (2015): 809-819.

[3] Horodinca, Mihaita, Ioan Doroftei, Emmanuel Mignon, and André Preumont. "A simple architecture for in-pipe inspection robots." In Proc. Int. Colloq. Mobile, Autonomous Systems, vol. 61, 2002: p. 64- 68.

[4] Gargade, Atul, Dhanraj Tambuskar, and Gajanan Thokal. "Modelling and analysis of pipe inspection robot." International Journal of Emerging Technology and Advanced Engineering 3, no. 5 (2013): 120-126.

[5] Li, Xin, Wuyi Yu, Xiao Lin, and S. S. Iyengar. "An optimization algorithm for the NP-hard 3D gallery guarding problem and its application on autonomous pipeline inspection." IEEE Transaction on Robotics (2011).

[6] Fuchs, Helmut V., and Rainer Riehle. "Ten years of experience with leak detection by acoustic signal analysis." Applied acoustics 33, no. 1 (1991): 1-19.

[7] Bracken, M., and O. Hunaidi. "Practical aspects of acoustical leak location on plastic and large diameter pipe." In Leakage 2005 Conference Proceedings, Halifax, NS, 2005.: pp. 448-452.

[8] Hunaidi, Osama, Wing Chu, Alex Wang, and Wei Guan. "Detecting leaks in plastic pipes." Journal-American Water Works Association 92, no. 2 (2000): 82-94.

[9] Hunaidi, Osama, and Wing T. Chu. "Acoustical characteristics of leak signals in plastic water distribution pipes." Applied Acoustics 58, no. 3 (1999): 235-254.

[10] Mays, Larry W. "Water distribution systems handbook." (2000).

[11] Jackson, Robert B., Adrian Down, Nathan G. Phillips, Robert C. Ackley, Charles W. Cook, Desiree L. Plata, and Kaiguang Zhao. "Natural gas pipeline leaks across Washington, DC." Environmental science & technology 48, no. 3 (2014): 2051-2058.

[12] Shao, Lei, Yi Wang, Baozhu Guo, and Xiaoqi Chen. "A review over state of the art of in-pipe robot." In 2015 IEEE International Conference on Mechatronics and Automation (ICMA), IEEE, 2015 pp. 2180-2185.

[13] Yu, Leijian, Erfu Yang, Peng Ren, Cai Luo, Gordon Dobie, Dongbing Gu, and Xiutian Yan. "Inspection robots in oil and gas industry: a review of current solutions and future trends." In 2019 25th International Conference on Automation and Computing (ICAC), pp. 1-6. IEEE, 2019.

[14] R. Bradbeer, S.O. Harrold, B.L. Luk, Y. Li, L.F. Yeung and H.W. Ho, “A mobile robot for inspection of liquid filled pipes”, Workshop on Service Automation and Robotics, June 2000.

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