# RESEARCH PROPOSAL

Submitted by Sumesh M

## RESEARCH TITLE

Development of an Adaptive In-Pipe Inspection Robot for Real-Time Pipeline Integrity Monitoring system and its effects and impact on small scale industrial sector.

## 1. Introduction

Pipelines serve as one of the most essential and economical methods for transporting fluids, such as gas, oil, water, and sewage, over long distances. However, pipelines are prone to aging, corrosion, and damage, which can compromise their functionality and safety. Such issues can lead to leaks, environmental damage, costly repairs, and even safety hazards for communities. Regular and thorough inspection of pipelines is therefore essential to ensure operational integrity and prevent failures. Traditional inspection methods can be costly, labor-intensive, and inefficient in detecting early signs of wear or damage, particularly in pipelines with confined spaces, variable diameters, and long distances.

In small-scale industries, pipeline infrastructure is crucial for transporting essential resources such as gas, oil, water, and chemicals. Due to budgetary constraints, frequent manual inspections are often impractical, leaving pipelines vulnerable to wear, corrosion, and other forms of damage over time. Small-scale industries face unique challenges, as they often lack the sophisticated monitoring systems utilized by larger corporations to ensure pipeline integrity, yet failures in these pipelines can cause substantial operational disruptions, safety risks, and environmental damage.

This research proposes the design and development of an adaptive in-pipe robot equipped with an adjustable mechanism that allows it to navigate through pipelines of varying diameters. The robot will be able to autonomously perform inspections, gather data, and provide real-time information about the structural condition of pipelines. The design includes a unique scissor-like mechanism that enables adaptation to pipe diameters, making it highly versatile for use in various types of pipeline infrastructure. This interdisciplinary research integrates robotics, mechanical engineering, and automation to develop an effective tool for pipeline inspection and maintenance.

## 2. Research Objectives

The primary objectives of this research are:

1. To **design an adaptive in-pipe robot** that can navigate pipelines with varying diameters while remaining stable and operational in confined spaces.
2. To **develop a scissor-like, pantograph-based mechanism** that allows the robot to adjust its size as needed, enabling efficient movement and inspection in pipelines of different sizes.
3. To **implement an inspection and data-gathering system** for real-time analysis of pipeline conditions, focusing on identifying wear, corrosion, and potential leak sites.
4. To **evaluate the robot's performance and adaptability** in simulated and real pipeline environments, ensuring robustness, efficiency, and reliability in varied conditions.
5. **Evaluate the robot's impact on small-scale industries** by analyzing improvements in inspection frequency, maintenance costs, and overall operational efficiency.

## 3. Background and Rationale

In-pipe robots are increasingly utilized in industries that rely on extensive pipeline networks. Various in-pipe robotic designs have been developed, but they often face challenges such as limited adaptability to changing pipe diameters, difficulties in maneuvering around bends or obstacles, and restricted ability to operate autonomously for extended periods. Most existing robots are designed for pipelines with specific diameters and may require frequent recalibration or structural modifications to function effectively in pipes of different sizes.

The proposed in-pipe robot addresses these limitations by incorporating a scissor-like pantograph mechanism with adjustable links, sleeves, and an elastic band system. This setup allows the robot to expand or contract its arms according to the pipe's diameter, ensuring consistent contact and stability. Furthermore, the adaptive mechanism reduces the need for recalibration, making the robot more efficient and versatile. By combining mechanical adaptability with autonomous navigation, this project aims to develop a robust solution to improve pipeline inspection practices and reduce operational costs associated with manual inspections and maintenance.

## 4. Literature Review

The field of pipeline inspection robotics has evolved considerably, with research highlighting various in-pipe robot designs, navigation mechanisms, and control systems. Key areas of exploration include:

- **Mechanical Adaptability**: Many current robotic designs incorporate spring-loaded or adjustable wheels for maneuvering. However, these approaches often face challenges in maintaining stability and uniform contact in pipes of varying diameters. Scissor-based mechanisms, such as pantograph designs, show potential for providing flexible and consistent adaptability without complex recalibration requirements.
- **Autonomous Navigation**: Advances in autonomous systems have enabled robots to navigate intricate networks with minimal human intervention. Robots with embedded sensors, cameras, and machine learning algorithms can identify obstacles and adapt navigation paths. However, successful deployment in confined and varying-diameter pipelines remains challenging.
- **Pipeline Condition Assessment**: Inspection robots typically rely on sensors for damage detection, corrosion analysis, and leak identification. Ultrasonic sensors, infrared cameras, and image processing algorithms are commonly used for condition assessment. Incorporating these technologies in adaptable robots is essential for comprehensive pipeline inspection solutions.
- **Sensor Integration for Integrity Monitoring**: Studies show that sensors like ultrasonic, infrared, and acoustic sensors are highly effective for pipeline integrity inspection. However, the integration of these sensors into compact, autonomous robots remains challenging due to size, power, and data processing limitations.
- **Cost-Effectiveness in Small-Scale Settings**: Small industries require tools that balance functionality and affordability. Research on low-cost, efficient robotics systems points to ESP32 microcontrollers as viable options due to their compact size, wireless capabilities, and compatibility with diverse sensors.

This research builds on existing work by focusing on adaptive mechanisms and improved stability to enable versatile use across pipelines of various sizes, combined with a data acquisition system for condition assessment.

## 5. Methodology

This research will adopt a multi-phase methodology, combining design, simulation, prototyping, and testing to develop and evaluate the proposed in-pipe robot.

### Phase 1: Conceptual Design and CAD Modeling

- **Design Framework**: Develop a CAD model of the in-pipe robot, focusing on the scissor-like pantograph mechanism, link assembly, and elastic band system. The robot will be structured with a cylindrical body and an adjustable arm mechanism to maintain adaptability to different pipe diameters.
- **Material Selection**: Select materials that are lightweight, durable, and corrosion-resistant, ensuring the robot's suitability for varied environments (e.g., oil, gas, water, sewage).

### Phase 2: Mechanical Simulation and Analysis

1. **Structural Analysis**: Perform finite element analysis (FEA) on the robot's frame and adjustable components to assess stress distribution, elasticity, and durability under various pipe diameters and conditions.
2. **Kinematic and Dynamic Simulation**: Use simulation software to evaluate the robot's movement dynamics within pipelines. Analyze the scissor mechanism's extension and retraction, verifying its ability to adapt to different diameters without compromising movement efficiency.
3. **Optimization**: Fine-tune the design based on simulation results to minimize power consumption, maximize speed, and enhance structural integrity.

### Phase 3: Prototype Development and Testing

1. **Prototype Assembly**: Construct a physical prototype using 3D-printed components and off-the-shelf parts. Assemble the pantograph-based scissor mechanism, motorized wheels, and inspection sensors.
2. **Laboratory Testing**: Test the robot in a controlled pipeline environment with variable diameters to assess performance, adaptability, and data collection capabilities.

3. **Data Collection System**: Integrate ultrasonic sensors, infrared cameras, or other inspection tools to capture real-time data on pipeline conditions. The robot will use wireless data transmission to relay information to a central monitoring system.

**Phase 4: Field Testing and Evaluation**

1. **Controlled Environment Testing**: Conduct testing in field-like conditions to evaluate the robot's adaptability, efficiency, and inspection accuracy in pipelines with typical obstacles, curves, and varying diameters.
2. **Data Analysis**: Analyze collected data to assess the robot's accuracy in detecting damages, corrosion, and potential leaks.
3. **Performance Metrics**: Measure key performance indicators, such as movement speed, adaptability, stability, data accuracy, and battery life, to determine the robot's viability for large-scale deployment.

## 6. Scope of the Study

The research will focus on:

- **Pipeline Types**: Testing will be limited to cylindrical pipelines commonly used for transporting fluids, particularly water, oil, and gas.
- **Diameter Range**: The robot will be designed to accommodate pipes within a specified diameter range, covering most standard pipelines in the industry.
- **Inspection Types**: The study will cover structural integrity inspections, including corrosion, wear, and crack detection, using non-destructive testing methods.

This scope ensures a manageable yet comprehensive examination of the robot's capabilities within the most common pipeline types and sizes.

## 7. Expected Outcomes

The anticipated outcomes of this research are:

1. **Versatile In-Pipe Robot**: A functional robot with an adaptive scissor-based mechanism capable of navigating pipes of varying diameters while maintaining consistent contact and stability.
2. **Enhanced Inspection Efficiency**: Improved data collection and real-time transmission capabilities for effective pipeline condition monitoring.
3. **Scalability and Practicality**: A scalable design suitable for industrial deployment across multiple sectors, including water, oil, and gas industries.
4. **Operational Cost Savings**: Reduced need for manual inspections, lowering inspection costs and downtime while enhancing safety.

## 8. Significance of the Study

This research contributes to the fields of robotics, pipeline maintenance, and industrial automation by providing an adaptable, efficient, and economically viable solution for pipeline inspection. By reducing the reliance on manual inspections and improving early detection capabilities, this project will have far-reaching implications for the safety, sustainability, and efficiency of pipeline infrastructure across industries.

## 10. Timeline

The proposed project timeline is structured to proceed through six main phases over an 18-month period. In the initial **Conceptual Design** phase, spanning the first three months, the focus will be on defining the design parameters and developing a robust conceptual framework for the in-pipe inspection robot. Following this, the project will enter the **Simulation and Optimization** phase, from months 4 to 6, where various design aspects will be digitally modeled and optimized for performance within simulated environments.

Once the design is refined, the **Prototype Development** phase will take place during months 7 to 9, in which the physical robot model will be assembled based on the optimized design specifications. This prototype will then undergo rigorous **Laboratory Testing** from months 10 to

12, where its functionality and adaptability will be evaluated in controlled conditions to ensure it meets project objectives.

The next stage, **Field Testing**, will be conducted over months 13 to 15. Here, the robot will be deployed in real-world pipeline environments to assess its performance under actual operating conditions. Finally, the **Data Analysis & Reporting** phase will take place from months 16 to 18, focusing on analyzing the collected data, drawing conclusions, and preparing comprehensive reports on the project's findings and potential implications for small-scale industries. This structured approach ensures a thorough development, testing, and evaluation process to maximize the effectiveness of the adaptive in-pipe robot.

## 11. Conclusion

This proposal outlines the design and development of an adaptive in-pipe robot for efficient pipeline inspection. With a unique scissor-based mechanism, this robot aims to overcome existing limitations, offering a robust and versatile solution for industries dependent on pipeline infrastructure. Through comprehensive testing and evaluation, this project will provide a significant advancement in pipeline inspection technology, with implications for sustainability, safety, and operational efficiency.

## 12.REFERENCES


1. Wu, Q.; Lee, C.M. A Modified Leakage Localization Method Using Multilayer Perceptron Neural Networks in a Pressurized Gas Pipe. Appl. Sci. 2019
2. Yan Zhao, Lixin Zhang, Xin Zha, Jin Liu, Ming Gao, "Research on Descaling Characteristics and Simulation Calculation of a Coaxial High-Frequency Electronic Descaling Device", Water 2021, 13, 789. https://doi.org/10.3390/w13060789 , https://www.mdpi.com/journal/water
3. Zhu, W.-F.; Chen, X.-J.; Li, Z.-W.; Meng, X.-Z.; Fan, G.; Shao, W.; Zhang, H.-Y. A SAFT Method for the Detection of Void Defect inside a Ballastless Track Structure Using Ultrasonic Array Sensors. Sensors 2019, 19, 4677.
4. Nishihara, T., Osuka, K., & Tamura, I. (2010, August). Development of a simulation model for inner-gas-pipe inspection robot: SPRING. In Proceedings of SICE Annual Conference 2010 (pp. 902-904). IEEE. Patent number: 978 (2010).

5. Kurata, M., Takayama, T., &Omata, T. (2010, September). Helical rotation in-pipe mobile robot. In 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (pp. 313-318). IEEE. (2010).
6. Lim, J., Park, H., Moon, S & Kim, B. (2007, December). Pneumatic robot based on inch worm motion for small diameter pipe inspection. In 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO) (pp. 330-335). IEEE. (2007).
7. Suzumori, K., Miyagawa, T., Kimura, M., & Hasegawa, Y. Micro inspection for 1-inpipes. IEEE/ASME transactions on mechatronics, 4(3),286-292. (1999)
8. Montero, R., Victores, J.G., Martínez, S., Jardon, A. and Balaguer, C. (2015), “Past, present and future of robotic tunnel inspection”, Automation in Construction, Vol. 59, pp. 99-112.
9. Lin, L.; Jiang, W.B.; Xu, X.S.; Xu, P. A critical review of the application of electromagnetic fields for scaling control in water systems: Mechanisms, characterization, and operation. NPJ Clean Water 2020, 3, 25.
10. Wentao Zhao, Liang Zhang, Jongwon Kim, “Design and Analysis of Independently Adjustable Large In-Pipe Robot for Long-Distance Pipeline”, Appl. Sci. 2020, 10, 3637; doi:10.3390/app10103637
11. R. K. Jain, Abhijit Das, A. Mukherjee, Santosha Goudar, Ankita Mistri, A. Mondal, “Design Analysis of Novel Scissor Mechanism for Pipeline Inspection Robot (PIR)”, Proceedings of the Advances in Robotics 2019 July 2019 Article No.: 61 Pages 1–6https://doi.org/10.1145/3352593.3352671
12. Qu, Y.; Durdevic, P.; Yang, Z. Smart-Spider: Autonomous Self-driven In-line Robot for Versatile Pipeline Inspection. The authors would like to the support from Danish Hydrocarbon Research and Technology Centre (DHRTC) through DHRTC Radical Project Program. IFAC Papers on Line 2018, 51, 251–256.
13. Kim, H.M.; Yoo, H.R.; Park, G.S. Analysis of the Magnetic Characteristics in MFL Type NDT System for Inspecting Gas Pipelines. In Lecture Notes in Electrical Engineering; Springer Science and Business Media LLC: Berlin, Germany, 2016; Volume 415, pp. 319–324.
14. Chang, F.S.; Hwang, L.T.; Liu, C.F.; Wang, W.S.; Lee, J.N.; Wang, S.M.; Cho, K.Y. Design of a Pipeline Inspection Robot with Belt Driven Ridged Cone Shaped Skate Model. In Proceedings of the 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO), Zhuhai, China, 6–9 December 2015; IEEE: New York, NY, USA, 2015; pp. 787–792.