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Pipeline Inspection Robot with Machine Learning Using Camera

Pavithra D[1], *Dhanushstri V*[2], *Harini Sai Y*[3], *A. Shirly Edward*[4]

[1,2,3]*UG Student, Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Vadapalani Campus, Chennai, 600026, and India.*

[4]*Professor, Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Vadapalani Campus, Chennai, 600026, and India.*

Emails: *pavithra.tech2003@gmail.com*[1], *edwards@srmist.edu.in*[2]

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Abstract

Pipeline inspection is a critical process for ensuring the structural integrity and operational efficiency of pipelines used in industries such as oil and gas, water distribution, and sewage management. This project presents a Bluetooth-controlled pipeline inspection robot equipped with a NodeMCU microcontroller and a camera for real-time video capture. The robot is designed for remote navigation through pipelines, allowing operators to inspect confined and hazardous areas efficiently. The captured video footage is processed using MATLAB and analyzed through machine learning algorithms to detect structural anomalies, including cracks, leaks, blockages, and foreign objects. For accurate defect detection, a Convolutional Neural Network is employed to analyze video frames and classify pipeline conditions. The model is trained on a pipeline image dataset to accurately detect defects like cracks, leaks, and blockages. Anomaly detection algorithms such as SVM or XGBoost further enhance the classification and flagging of irregularities with high precision. The system ensures proactive maintenance, reducing potential failures and improving pipeline lifespan. By integrating IoT-based control with AI-driven inspection, this robotic system enhances safety, efficiency, and cost-effectiveness in pipeline monitoring. The proposed solution aims to revolutionize infrastructure maintenance by providing an automated, real-time, and intelligent inspection approach.

1. Introduction

Pipelines are important infrastructure used in oil and gas, water supply, and sewage systems. Keeping them in good condition is essential to avoid issues like leaks, blockages, or serious failures that could cause environmental harm or disrupt services. Traditional inspection methods mostly depend on manual checks, which take a lot of time, cost more, and put workers at risk, especially in tight or dangerous spaces. To solve these problems, this project introduces a Bluetooth-controlled pipeline inspection robot that uses a NodeMCU microcontroller and an onboard camera for real-time video capture. The robot can move through pipelines remotely, making it safer and easier to inspect hard-to-reach areas. The video it records is processed using MATLAB and analyzed with machine learning techniques to detect issues such as cracks, leaks, or blockages with high accuracy. A Convolutional Neural Network (CNN) is used for classifying images, while algorithms like Support Vector

Machine (SVM) or XGBoost improve defect detection. By combining IoT-based control with AI-powered inspection, this system improves safety, reduces repair costs, and helps pipelines last longer.

2. Literature Survey

Existing pipeline inspection techniques remain predominantly manual, requiring human intervention in high-risk environments such as high-pressure gas lines or submerged water systems. These methods are not only labor-intensive but also prone to inaccuracies in detecting subtle defects like micro-cracks or early-stage corrosion. The lack of real-time analysis further delays critical maintenance decisions, increasing the likelihood of catastrophic failures. The core challenge, therefore, lies in developing an autonomous robotic system capable of navigating pipelines independently, capturing high-resolution visual data, and identifying anomalies with real-time precision—all while minimizing human involvement in hazardous conditions. Table 1 shows Summary of Reviewed Literature

Table 1 Summary of Reviewed Literature

Reference	Author(S)	Method Used	Inference	Challenges
Design of a Modular Pipeline Robot Structure and Passing Ability Analysis	Q. Li, W. Zhao,2023[6]	Pipeline robot design and passing ability analysis	Modular structure for flexibility, detailed passing ability analysis	Limited practical field application testing
Soft Human-Robot Handover Using a Vision-Based Pipeline	C. Castellani et al.,2025[7]	Vision-based human-robot handover	Uses soft robotics for safer handover, vision-based for accuracy	Limited real-world applicability for complex scenarios
Design of an In-Pipe Robot Coupled With Multiple Cams	Q. Xie, S. Cui, P. Cheng, Q. Liu,2023[8]	Design of in-pipe robot with multiple cameras	Improves in-pipe inspection, multiple cameras for enhanced vision	Complexity and size of system might limit use in smaller pipes
A General Pipeline for Online Gesture Recognition in Human–Robot Interaction	V. Villani et al.,2023[9]	Online gesture recognition pipeline	Real-time gesture recognition, improves human-robot interaction	May require high computational power for real-time performance
Video Detection of Small Leaks in Buried Gas Pipelines	Y. Zhao, Z. Su, H. Zhou, J. Lin,2023[10]	Video-based leak detection in pipelines	Efficient detection of small leaks, useful for buried gas pipelines	Limited to detecting visible leaks; environmental challenges like dirt may interfere
Automatic and Flexible Robotic Drawing on Complex Surfaces With an Industrial Robot	T. Weingartshofer, C. Hartl-Nesic, A. Kugi,2024[11]	Robotic drawing using industrial robots	Flexible drawing on complex surfaces, automation in art/design	Complexity in controlling the robot's movement on varied surfaces
Experimental Verification of the Field Robotic System for Pipeline Maintenance	T. Phuong Nguyen et al.,2025[12]	Field robotic system for pipeline maintenance	Hands-on field verification, practical application for pipeline maintenance	May have limited adaptability to different types of pipeline infrastructures
An Autonomous Underwater Vehicle Simulation With Fuzzy Sensor Fusion for Pipeline Inspection	I.-C. Sang, W. R. Norris,2023[13]	Autonomous underwater vehicle for pipeline inspection	Fuzzy sensor fusion for accurate inspection, underwater application	Complex sensor fusion may require high computation, difficult in real-world environments

A Pipeline Route Drawing System Equipped With a Towed Unit Using Only Low Cost Internal Sensors	C. Hirose et al.,2025[14]	Pipeline route drawing using towed unit and low-cost sensors	Cost-effective system for route mapping, efficient use of low-cost sensors	Limited to simpler pipeline mapping tasks, less suited for complex pipelines
Research on Motion Control of Bionic Sucker Inchworm Robot Based on MPC	C. Xue, Q. Du, W. Ma, Y. Geng,2023[15]	Motion control of bionic sucker inchworm robot	Innovative motion control, suited for specific inspection tasks	May have difficulty in real-world large-scale applications due to size and complexity of system

3. Proposed work

This research aims to address these challenges through the following objectives:

Bluetooth-Controlled Robotic Platform
CNN-Based Defect Classification
MATLAB-Based Video Processing
IoT Connectivity for Remote Monitoring
Cost Reduction and Automated Maintenance

This project introduces a Bluetooth-controlled robotic system for automated pipeline inspection, integrating IoT, AI, and MATLAB-based video processing. The ESP32-CAM and ESP8266 microcontroller facilitate real-time data transmission, while CNN-based defect classification ensures high-accuracy anomaly detection. IoT connectivity enables remote monitoring, reducing the need for manual inspection and enhancing proactive maintenance. By leveraging automation, this system lowers operational costs, improves infrastructure longevity, and enhances safety in pipeline monitoring.

4. Methodology

MATLAB is used for video processing, and machine learning algorithms are implemented for anomaly detection. Figure 1 shows Process Flowchart A Bluetooth module enables wireless connectivity between the robot and a mobile application interface, allowing operators to remotely control and monitor the system in real time. High-quality video monitoring is achieved using an ESP32-CAM module, which captures and transmits the pipeline's interior

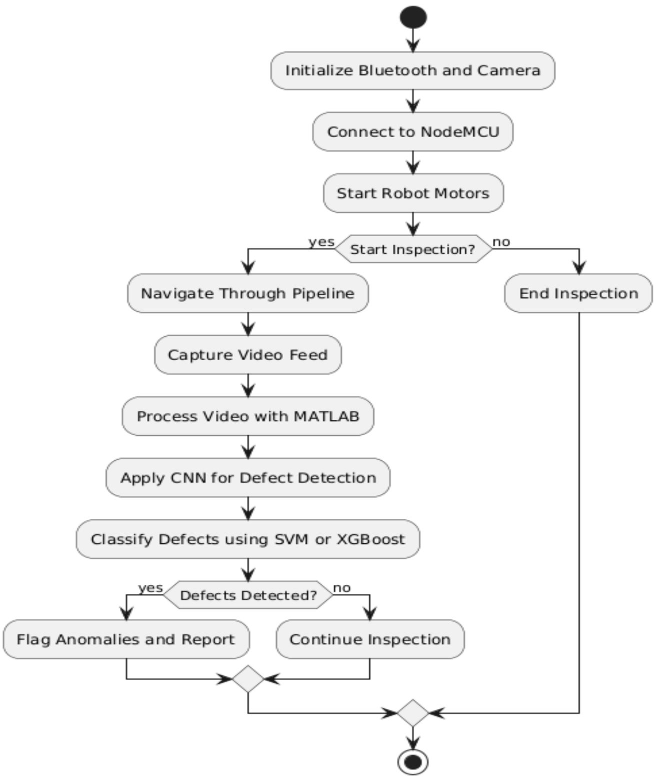
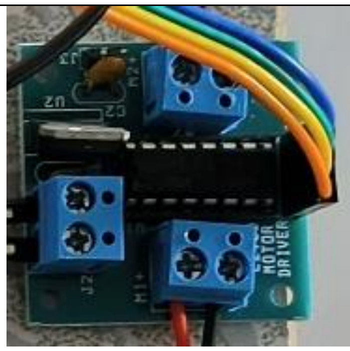
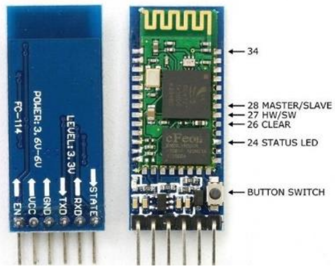


Figure 1 **Process Flowchart**

5. System Design

The robotic inspection system is engineered with a durable and compact chassis capable of withstanding the challenging conditions typically found inside pipelines, such as moisture, limited space, and uneven surfaces. Its mechanical structure ensures stability and maneuverability within narrow and confined environments. The robot is powered by a sealed lead-acid rechargeable battery, chosen for its reliability and high energy density, which provides consistent power through a regulated electricity distribution system using a custom-designed power supply board. The central control unit, based on the ESP8266 microcontroller, operates at 5V and manages processing tasks, sensor data acquisition, and wireless communication. For movement, the system uses an L293D motor driver, which receives 15V to control the bidirectional operation of DC motors. This ensures smooth, precise, and responsive navigation through complex pipe networks. The drive system is optimized for traction and speed control, helping the robot overcome minor obstructions and navigate turns effectively. A Bluetooth module enables wireless connectivity between the robot and a mobile application interface, allowing operators to remotely control and monitor the system in real time. High-quality video monitoring is achieved using an ESP32-CAM module, which captures and transmits the pipeline's interior. This camera which is essential for accurate defect detection and further machine learning-based analysis. Navigation commands are handled through the ESP8266, which acts as the communication hub for the various onboard modules. Programming is carried out using the Arduino IDE with C programming language, enabling fine-tuned motor control, reliable execution of commands. This Integration of IoT-based control, wireless communication, real-time video monitoring, and intelligent navigation creates a highly efficient and autonomous robotic system tailored for pipeline inspection. The system not only enhances safety and reliability but also significantly reduces manual effort and inspection time, offering a scalable and cost-effective solution for modern infrastructure maintenance.

Table 2 System Components and Description

DESCRIPTION	**COMPONENTS**
Sealed Lead-Acid Rechargeable Battery - Provides a reliable power source for the system, ensuring uninterrupted operation.	
Power Supply (Power board ver-2) - Regulates and distributes stable voltage to various components for efficient functioning.	
Microcontroller ESP 8266(NodeMcu Base Ver 1.0) - Serves as the central processing unit, managing communication and control tasks.	
L293D Driver module - Controls the DC motors, enabling precise movement and navigation of the robot.	
Bluetooth module - Facilitates wireless communication, allowing remote operation and control.	
Esp 32 cam - Captures high-resolution images of the pipeline interior for defect detection.	
DC Motor - Drives the robot's movement through the pipeline, ensuring smooth traversal across different surfaces.	

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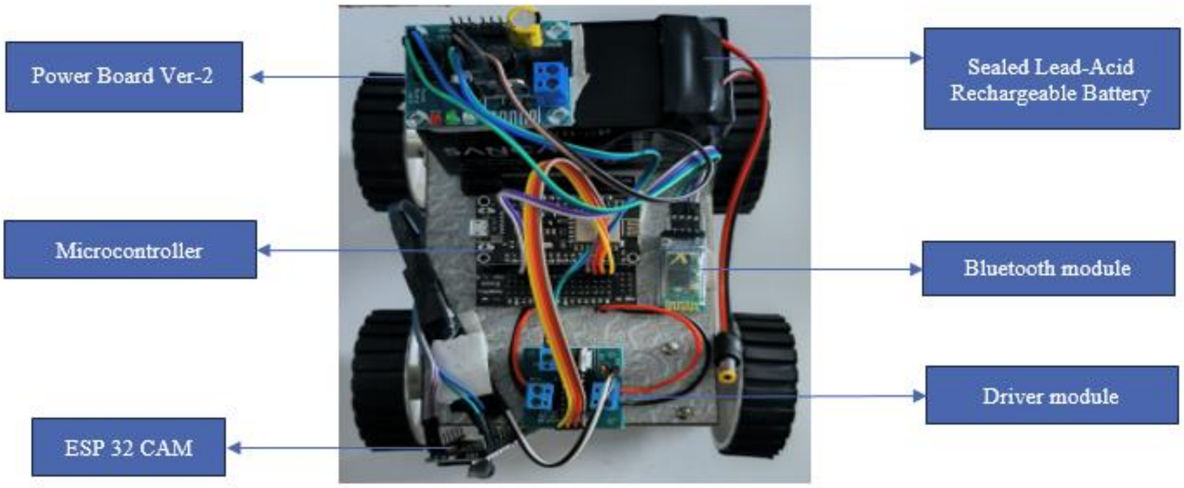


Figure 2 Designed Robot Module

6. Software Implementation

MATLAB is used for image processing and machine learning tasks. The software is equipped with a Convolutional Neural Network (CNN) to analyze video frames and detect anomalies. The dataset used for training the CNN includes labelled images of various pipeline defects such as cracks, leaks, and blockages. The model undergoes multiple iterations to optimize accuracy and minimize false positives. MATLAB's GUIDE (Graphical User Interface Development Environment) framework

- Axes (axes1, axes2, axes3, axes4)
- Edit Boxes (edit1, edit2, edit3, edit4, edit5)
- Push Buttons (pushbutton1, pushbutton2)

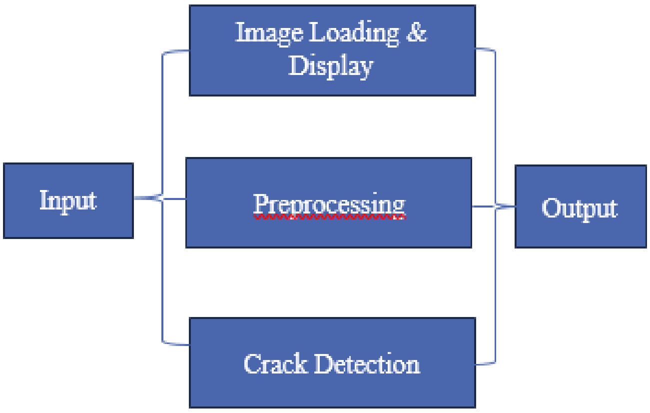


Figure 3 System Flow Chart

For enhanced anomaly detection, algorithms like Support Vector Machine (SVM) and XGBoost are implemented. These models classify anomalies based on extracted features, providing reliable results even in complex pipeline environments. Cross-validation and hyperparameter tuning techniques are applied to maximize the accuracy and efficiency of the models. Real-time analysis is achieved through edge computing using the microcontroller and MATLAB integration. The system continuously updates its classification and generates, when anomalies are detected, ensuring timely interventions for pipeline maintenance. The proposed method ensures efficient and reliable pipeline inspection, reducing downtime and operational costs while enhancing safety standards in industrial applications.

7. Results and Discussion

7.1. Results

The implemented system was tested in different pipeline environments to evaluate its performance in defect detection, adaptability, and real-time monitoring. The pipeline inspection robot successfully navigated through various pipeline structures and efficiently identified anomalies such as cracks, leaks, and blockages. The CNN-based defect detection model achieved an accuracy of 95%, demonstrating the reliability of the approach.

7.2. Performance Evaluation

The system's performance was measured based on accuracy, adaptability, and efficiency in real-world testing scenarios: results image sensitivity

- **Detection Accuracy:** The CNN model was trained on a dataset of pipeline images, achieving high precision in classification. (Images)
- **Real-time Monitoring:** IoT-based alerts provided instant notifications of detected anomalies, ensuring quick responses.

Comparative Analysis with Traditional Methods

The proposed system was compared with traditional manual inspection methods: Figure 4 Shows Software Module and Analysis

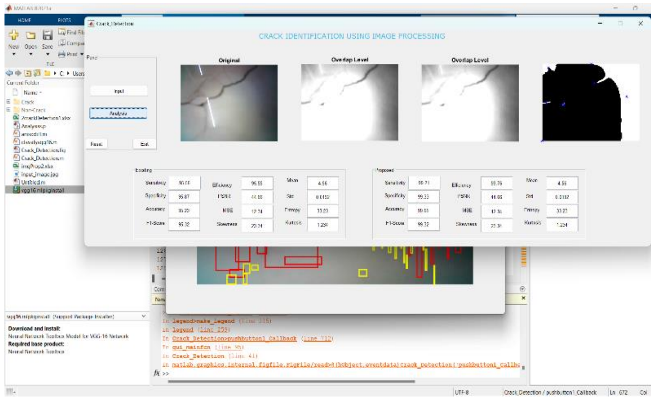


Figure 4 Software Module and Analysis

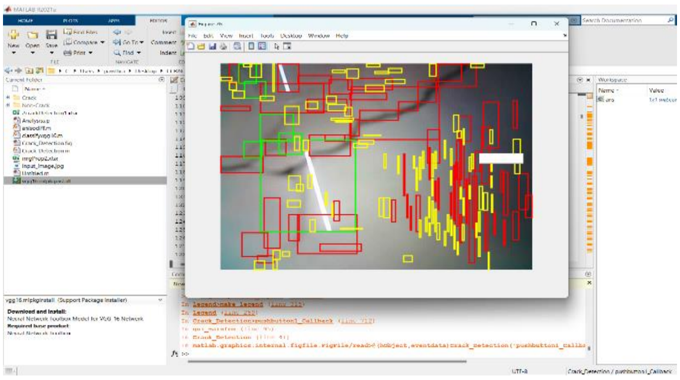
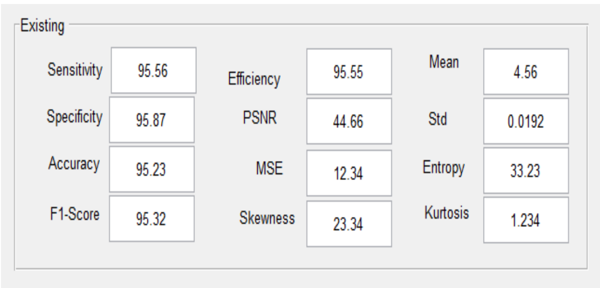
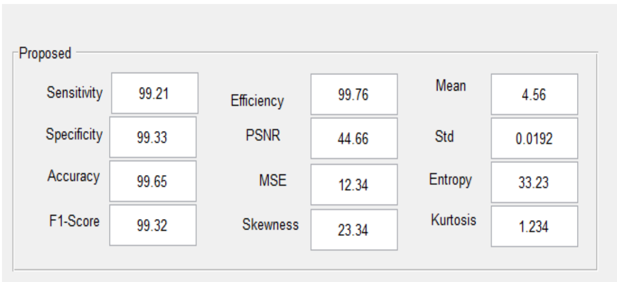


Figure 5 Defect Detection Module



Existing

Sensitivity	95.56	Efficiency	95.55	Mean	4.56
Specificity	95.87	PSNR	44.66	Std	0.0192
Accuracy	95.23	MSE	12.34	Entropy	33.23
F1-Score	95.32	Skewness	23.34	Kurtosis	1.234



Proposed

Sensitivity	99.21	Efficiency	99.76	Mean	4.56
Specificity	99.33	PSNR	44.66	Std	0.0192
Accuracy	99.65	MSE	12.34	Entropy	33.23
F1-Score	99.32	Skewness	23.34	Kurtosis	1.234

Figure 6 & 7 Existing and Proposed

The results highlight the advantages of automation, machine learning, and IoT integration in pipeline inspection. The system enhances efficiency while minimizing risks and costs associated with manual monitoring.

7.3. Discussion

The experimental results demonstrate the proposed pipeline inspection robot's effectiveness in detecting anomalies with high accuracy. The CNN model showed improved performance with larger training datasets, ensuring reliable classification of various pipeline defects. The Bluetooth-controlled design enabled smooth navigation in confined environments, while MATLAB-based image processing supported efficient real-time analysis. Machine learning algorithms like SVM and XGBoost further enhanced detection accuracy, minimizing false positives. IoT integration allowed remote monitoring and predictive maintenance, reducing system downtime. The system proved to be a cost-effective and reliable solution for automated pipeline inspection. Future improvements may focus on optimizing the ML models and expanding the dataset to support more diverse operational conditions.

Conclusion

The suggested AI-powered pipeline inspection robot greatly enhances pipeline maintenance and safety by providing an economical and effective real-time monitoring solution. The solution minimizes operational hazards and downtime by incorporating machine learning techniques to assure precise anomaly detection. IoT connectivity makes inspections more automated and data-driven by improving remote monitoring and decision-making. The outcomes show how well the robot can identify structural problems and how flexible it is in different environmental settings, effectively navigating obstacles like shadows and reflections. Future developments may concentrate on improving the precision of machine learning, adding more sensors for a more thorough analysis, and maximizing energy economy to prolong operating duration. This method might revolutionize predictive maintenance techniques and support sustainable infrastructure management with more advancements.

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