

Tunnel eye: AI Based Visual Inspection For Refinery Pipelines

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Abstract—In this study, the creation of an autonomous pipeline inspection robot designed to minimize the potential flaws in modern fluid delivery systems is described. In general, pipelines form the key components of any municipal or hydrocarbons network. However, despite their significance in ensuring smooth functioning of the whole system, pipelines are vulnerable to various types of damages such as fracturing under stress, corrosion, and sediment buildup inside pipes. Unless these issues are discovered ahead of time, they can result in major environmental accidents and disrupt operations significantly.

The presented paper introduces the process of creating and using the autonomous pipeline inspection robot designed to facilitate precise monitoring of pipes. It utilizes a Raspberry Pi-based control module equipped with the high-definition camera and navigation sensors to facilitate instant flaw detection. The use of the wired communication method provides an effective data transfer capability and eliminates any risks associated with electromagnetic interference in highly conductive environments.

Overall, the solution presented in this paper is characterized by affordability, efficiency, and safety, which makes it especially useful in small-scale industrial settings and scientific purposes. As the experimental studies have shown, the developed robot can provide accurate video footage and navigation capabilities that will minimize the need for people entering the potentially hazardous areas.

I. INTRODUCTION

Pipeline networks are one of the essential components of modern infrastructure. They serve as the main arteries for transportation of water, petroleum, and other fluids over long distances. The robustness of this type of infrastructure cannot be underestimated; at the same time, pipeline networks are constantly under threat of deterioration due to factors such as stress-related cracking, corrosions, and sediment formation. These problems pose danger and can lead to expensive repairs.

Traditionally, pipeline monitoring was carried out manually by human crews, which has several significant drawbacks, namely the high costs, labor intensity, and inherent dangers of this method. It poses threats not only to the well-being of inspection personnel who have to operate in potentially hazardous environment (constrained space, chemical exposure, etc.) but also leads to inconsistencies in fault identification. As a result, small problems may become much more serious in the process of time.

Thus, to address the challenges faced by traditional inspection methods, this study proposes developing and deploying autonomous inspection robots for use in monitoring pipelines. Based on the use of optical sensors combined with various types of navigational capabilities, the system will allow inspecting pipelines from the inside and delivering accurate images of their interior in real time. In essence, it will replace potentially dangerous manual inspections by allowing human operators to assess the condition of the pipe from outside using automated equipment.

The main goal of the research is to ensure that the technology is affordable and accessible for both small and large organizations, including academic research institutions. Therefore, special attention will be paid to modular and scalable designs in order to achieve optimal performance-to-cost ratio.

II. LITERATURE REVIEW

The rapid advancement of the Internet of Things (IoT) and embedded systems has significantly improved modern security and access control solutions. Researchers have developed various smart security systems that enable remote monitoring and control of entry points in homes and offices. These systems aim to enhance safety and convenience by reducing human dependency and enabling real-time decision-making. However, many traditional systems are limited to password-based or RFID-based access, which can be vulnerable to security breaches and unauthorized access. Several studies have focused on biometric authentication methods such as fingerprint recognition, iris scanning, and facial recognition for secure access control. Among these, facial recognition has gained significant attention due to its Pipeline inspection has been an important area of research due.

to the growing dependence on pipeline networks in industries such as water supply, oil and gas, and manufacturing. Traditional inspection methods mainly involve manual monitoring or the use of bulky and expensive equipment. While these methods are widely used, they are often time-consuming, unsafe, and lack real-time feedback. The contactless nature of modern robotic systems provides a safer alternative by reducing direct human involvement in hazardous environments, making them more suitable for contemporary industrial applications.

Robotic pipeline inspection systems have gained attention due to their ability to navigate confined spaces and perform inspection tasks efficiently. These systems typically use wheeled or crawler-based mechanisms to move inside pipelines and capture visual data. While they improve accessibility and reduce risk, many existing solutions are costly and complex, limiting their usability in small-scale applications.

Camera-based inspection systems have further enhanced pipeline monitoring by enabling real-time video streaming and visual analysis of internal conditions. Modules integrated with embedded platforms such as Raspberry Pi allow continuous monitoring and recording. However, factors such as lighting conditions, camera resolution, and focus limitations can affect image clarity and reduce the accuracy of defect detection, especially in long or poorly illuminated pipelines.

In addition, the use of sensors such as ultrasonic sensors has been explored for detecting obstacles, measuring distances, and assisting navigation within pipelines. These sensors contribute to automation by enabling the system to respond to environmental conditions. Despite these advancements, many existing systems focus only on inspection or monitoring and lack proper integration of navigation, sensing, and real-time data transmission.

Ease of use and system simplicity are also important considerations in practical applications. Many advanced inspection systems require skilled operation and complex setup procedures, which reduce their accessibility. A system that is cost-effective,

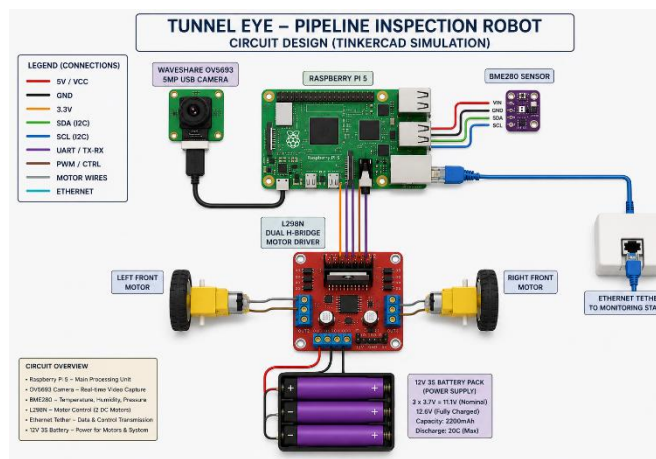
and user-friendly can significantly improve adoption in small industries and municipal applications.

Although significant progress has been made in pipeline inspection technologies, there is still a need for a unified solution that combines robotic navigation, real-time monitoring, sensor integration, and ease of operation into a single platform. The proposed system addresses these limitations by providing a cost-effective and integrated pipeline inspection robot that enhances safety, improves efficiency, and enables reliable defect detection with minimal human intervention.

I. SYSTEM DESIGN

The proposed “Tunnel Eye” robotic inspection system uses a modular architecture for real-time pipeline inspection in industrial environments. The robot performs live visual monitoring, AI-based crack detection, environmental sensing, leak analysis, and stable communication inside refinery pipelines.

The system integrates embedded processing hardware, inspection cameras, sensing modules, locomotion mechanisms, tethered communication, and regulated power management into a compact platform. Its modular design improves reliability, maintenance flexibility, scalability, and future system upgrades while ensuring stable operation in confined industrial environments.



A. Control System

Raspberry Pi 5 Processing Unit

The control subsystem uses the Raspberry Pi 5 with 2GB RAM as the central processing platform for image processing, sensor-data acquisition, communication handling, and locomotion control. The ARM Cortex-A76 quad-core processor supports simultaneous execution of OpenCV-based image analysis, real-time video streaming, and telemetry monitoring. Python-based backend processing and AI-assisted defect analysis are executed directly on the Raspberry Pi for edge-level inspection capability.

The processing unit is integrated with the Official Raspberry Pi 5 Active Cooler to maintain stable operating temperature during continuous inspection and AI-processing tasks. The active cooling mechanism minimizes thermal throttling and improves computational stability during long-duration operation.

B. Visual Inspection Unit

The visual inspection subsystem uses the WaveShare OV5693 5MP USB camera with M12 optics for

capturing 1080p video at 30 FPS. The camera continuously records internal pipeline surfaces for identifying cracks, rust, corrosion, leakage traces, and structural deformation. The USB interface provides stable high-speed communication with the Raspberry Pi 5 and supports OpenCV-based real-time image processing. Low-light performance and high image clarity improve inspection visibility inside confined refinery pipelines.

C. Sensor System

The BME280 sensor monitors temperature, humidity, and atmospheric pressure inside refinery pipelines. The sensor uses I2C communication for stable real-time data transfer to the Raspberry Pi. Environmental monitoring helps identify abnormal internal conditions that may contribute to corrosion, moisture accumulation, and structural degradation.

D. Locomotion System

N37 12V 160RPM Metal Gear Motor

The locomotion subsystem uses N37 12V 160RPM metal gear motors with D-type shafts for stable movement inside refinery pipelines. The geared motor design improves torque generation, traction stability, and low-speed control required for accurate inspection. A four-wheel drive configuration improves balance and reduces vibration during robot movement.

L298N Motor Driver Module

The L298N dual H-bridge motor driver controls directional movement and PWM-based speed regulation of the N37 motors. The module enables forward, reverse, left, and right movement while protecting the Raspberry Pi from motor-generated electrical noise.

E. Communication System

Ethernet Tether Serial Communication

The communication subsystem uses Ethernet cable-based tether serial communication for transferring live video streams, telemetry values, sensor readings, and locomotion-control commands between the robot and the monitoring station. The tether architecture eliminates wireless signal attenuation and

electromagnetic interference inside metallic industrial environments. The Ethernet communication system provides stable low-latency connectivity over operational distances up to 50 meters and supports uninterrupted industrial inspections.

F. Power System

12V DC 3S 18650 Battery Supply

The robotic platform operates using a regulated 12V DC power system for supplying stable electrical power to the Raspberry Pi, camera module, sensors, motor driver, and locomotion motors. Voltage regulation and electrical-noise filtering improve subsystem stability and ensure reliable operation during continuous inspection tasks.

G. Software System

The software subsystem combines a React.js-based monitoring dashboard with a Python-Flask backend for robotic control and inspection-data processing. The frontend interface includes modules such as Dashboard.js, LiveFeed.js, SensorGauge.js, ControlPad.js, Sidebar.js, and ServoControl.js for real-time monitoring and operator interaction.

The backend software integrates OpenCV libraries for image preprocessing and Ultralytics YOLO frameworks using the rust_detector.pt model for AI-assisted crack and rust detection. The software architecture enables real-time video analysis, telemetry synchronization, and inspection-data visualization during robotic operation.

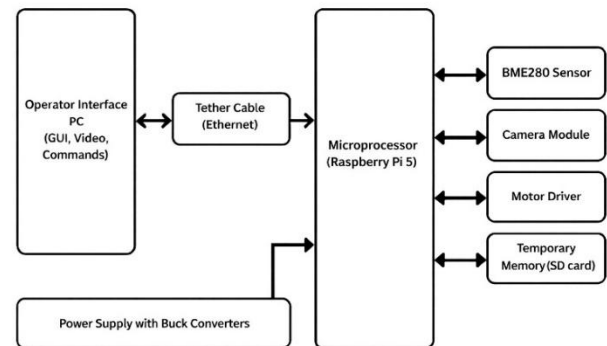
H. Operational Workflow

The workflow of the proposed “Tunnel Eye” robotic inspection system begins with initialization of the Raspberry Pi 5 processing unit, Waveshare OV5693 USB camera, BME280 environmental sensor, pressure sensor, motor driver module, and Ethernet tether communication interface. After successful hardware initialization, the robot enters inspection mode and begins moving inside the refinery pipeline using the four-wheel drive locomotion mechanism powered by N37 12V 160RPM metal gear motors. During robot movement, the Waveshare OV5693 5MP USB camera continuously captures real-time video of the internal pipeline surface.

The captured image frames are transferred to the Raspberry Pi 5, where OpenCV-based preprocessing operations such as grayscale

conversion, contrast enhancement, edge enhancement, and noise reduction are performed. The processed images are then analyzed using YOLO-assisted AI models for identifying cracks, rust accumulation, corrosion patches, leakage traces, and abnormal surface conditions. Simultaneously the BME280 sensor continuously monitors temperature, humidity, and atmospheric pressure inside the pipeline, while the pressure sensor measures internal pressure variation for identifying abnormal flow conditions and structural instability. The collected sensor readings are processed and synchronized with the inspection data during operation.

All inspection data including live video streams, telemetry information, AI-assisted defect alerts, and locomotion-control commands are transmitted through Ethernet tether serial communication to the external monitoring station. The operator monitors the complete inspection process using the React-based dashboard interface, which provides real-time video visualization, telemetry monitoring, and remote robotic control. The coordinated interaction between embedded processing, **AI-assisted image analysis, environmental sensing, locomotion control, and tether communication enables reliable refinery pipeline inspection in confined industrial environments.**



II. Methodology

The proposed robotic inspection system integrates autonomous data acquisition, edge-computing-based defect detection, and a high-throughput tethered telemetry network. The operational workflow is structured into five core phases: hardware initialization, digital image preprocessing, AI-driven anomaly detection, multi-sensor environmental telemetry, and real-time operator visualization.

The enhanced visual frames are inputted into a lightweight, edge-optimized YOLO (You Only Look Once) object detection model deployed directly on then Raspberry Pi 5.

Data Acquisition

The system acquires real-time inspection data using the Waveshare OV5693 5MP USB camera, BME280 environmental sensor, and industrial pressure sensor. The OV5693 camera continuously captures high-definition video frames of the internal pipeline surface while the robot moves through the refinery pipeline using the four-wheel drive locomotion mechanism.

A. Data Processing and Decision Making

The Raspberry Pi 5 processes the captured image frames using OpenCV-based preprocessing operations including grayscale conversion, contrast enhancement, edge sharpening, and noise reduction. These preprocessing operations improve structural visibility and enhance crack-detection accuracy during inspection. After preprocessing, the processed image frames are analyzed using YOLO-assisted AI models integrated through the rust_detector.pt framework. The AI model identifies structural abnormalities such as cracks, rust accumulation, corrosion patches, leakage traces, and abnormal surface textures from the captured inspection data.

Based on the inspection results:

- If structural abnormalities are detected, the system highlights the suspected defect regions and transmits the inspection feedback to the monitoring interface.
- If no abnormalities are detected, the system continues continuous real-time monitoring and inspection operations.

The integrated AI-assisted analysis improves inspection reliability while reducing dependency on continuous manual observation. Communication and Data Transmission.

B. Communication and Data Transmission

The system uses Ethernet tether serial communication for transferring inspection data between the robotic platform and the external monitoring station. The tether continuously transmits live video streams, telemetry values, sensor readings, AI-assisted inspection feedback, and locomotion-control commands in real time.

The Ethernet tether architecture provides stable low-latency communication inside metallic refinery pipelines where wireless communication systems experience signal attenuation and electromagnetic interference. Continuous communication improves

operational reliability and enables uninterrupted inspection monitoring during long-distance industrial operation. The communication subsystem supports operational distances up to 50 meters while maintaining stable inspection-data synchronization and reliable operator control.

C. Monitoring and User Interface System

The The system incorporates a React.js-based monitoring dashboard for real-time inspection visualization and robotic control. The dashboard interface continuously displays live video feeds, telemetry information, sensor values, and AI-assisted defect-analysis results during robot operation.

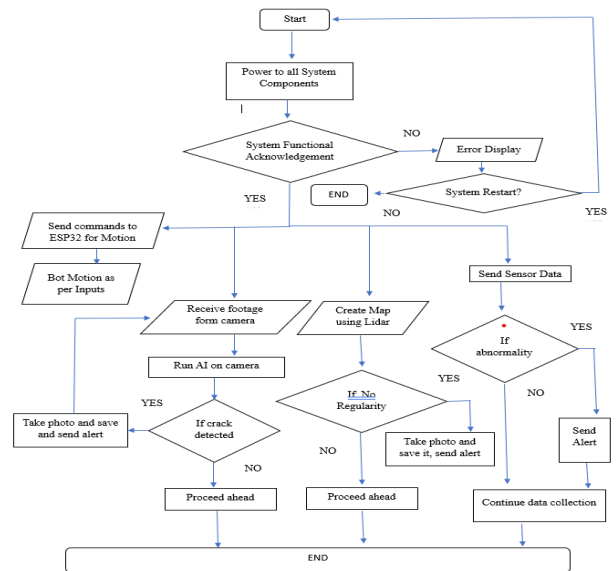


Fig. 3. Flowchart

V.RESULTS

A.Visual Inspection System Performance

The visual inspection subsystem demonstrated stable real-time monitoring performance during experimental testing inside a simulated refinery pipeline environment. The Wave share OV5693 5MP USB camera successfully captured continuous 1080p video streams at 30 FPS while the robot moved through curved and confined pipeline sections. The camera provided clear visualization of artificial crack markings, rust accumulation, corrosion patches, and surface abnormalities under normal inspection lighting conditions..

B. AI-Assisted Defect Detection Performance

The AI-assisted inspection subsystem demonstrated satisfactory structural-anomaly detection capability during testing. The YOLO-integrated rust_detector.pt model successfully identified crack-like patterns, rust regions, corrosion traces, and abnormal surface textures from the captured pipeline image frames.

The AI-processing subsystem operated continuously on the Raspberry Pi 5 without major processing interruption during inspection. Detection performance improved under stable illumination and controlled robot speed conditions. Surface reflections, uneven lighting, and excessive dust accumulation occasionally affected detection consistency, indicating the possibility of further optimization for industrial deployment conditions.

C. Communication and Remote-Control Performance

The Ethernet tether serial communication subsystem demonstrated reliable low-latency communication throughout the inspection process. Live video streams, telemetry data, sensor readings, AI-assisted inspection feedback, and locomotion-control commands were transmitted continuously between the robotic platform and the external monitoring station without major communication interruption.

The tether architecture eliminated wireless signal attenuation and electromagnetic interference commonly observed inside metallic industrial environments. Stable communication performance was maintained over operational distances approaching 50 meters. The React-based monitoring dashboard successfully displayed real-time inspection information, live video feeds, and telemetry values while enabling

remote operator control of the robotic platform. Access Control System Performance.

D. Environmental and Pressure Monitoring Performance

The BME280 environmental sensor continuously measured temperature, humidity, and atmospheric pressure conditions during inspection trials. The sensor demonstrated stable response characteristics and reliable real-time telemetry transfer to the Raspberry Pi through I2C communication.

The pressure-monitoring subsystem successfully detected pressure fluctuations introduced during simulated abnormal flow conditions. Sudden pressure variation was identified as a possible indicator of leakage or unstable internal pipeline conditions. Real-time environmental and pressure monitoring improved inspection awareness by correlating structural observations with surrounding operating conditions inside the pipeline.

E. Overall System Performance

The complete “Tunnel Eye” robotic inspection platform demonstrated successful integration of embedded processing, AI-assisted image analysis, environmental monitoring, pressure sensing, tether communication, and stable locomotion into a compact refinery pipeline inspection system.

The Raspberry Pi 5 processing subsystem maintained stable operation during simultaneous execution of image processing, telemetry monitoring, AI-assisted defect analysis, and communication handling tasks. The Official Raspberry Pi 5 Active Cooler effectively minimized overheating and prevented thermal throttling during continuous inspection operation.

The overall system demonstrated reliable real-time inspection capability while reducing dependency on manual pipeline inspection procedures. Although the robotic platform performed effectively during testing, factors such as low-light industrial environments, surface contamination, and mechanical vibration may affect inspection accuracy and can be improved further in future system development.

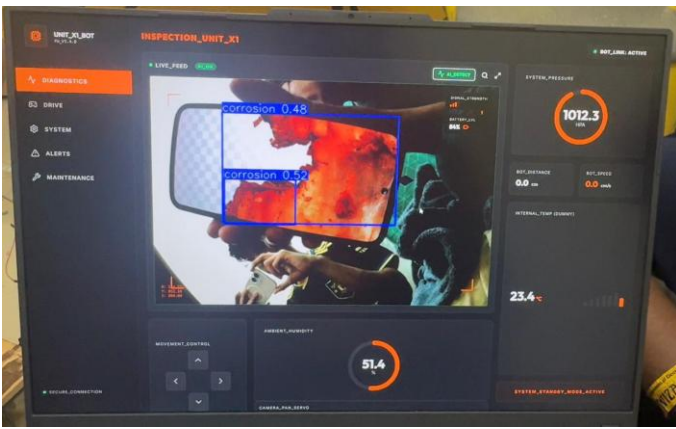


Fig. Operator UI Design and Result



Fig. Tunnel Eye Inspection bot

CONCLUSION

This paper presented the design and implementation of an IoT-based facial authentication system for secure and intelligent door access control. The proposed system integrates facial recognition, real-time monitoring, wireless communication, and automated door control into a single embedded platform.

The experimental results demonstrate that the system is capable of reliably detecting the presence of a person, capturing images, and performing facial recognition for identity verification. The integration of the ESP32-CAM module enables efficient image processing and communication, while the use of Wi-Fi connectivity allows real-time notification and remote access control. The system successfully allows the authorized user to verify visitors and make decisions to grant or deny access, ensuring improved security and convenience.

The proposed solution offers a cost-effective, scalable, and efficient approach to modern security systems, reducing dependency on traditional access

methods such as keys and passwords. The combination of sensing, processing, and communication enhances system performance and user experience. However, certain limitations such as dependency on network connectivity, lighting conditions, and recognition accuracy may affect system performance.

Future improvements can focus on enhancing facial recognition accuracy, improving system security, and integrating additional features such as cloud storage.

In conclusion, the developed system demonstrates the practical implementation of IoT and facial recognition technology for smart security applications and provides a strong foundation for further research in intelligent access control systems

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