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DESIGN AND FABRICATION OF A SMART PIPE INSPECTION ROBOT FOR PIPELINE MONITORING

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ABSTRACT—

Pipelines are widely used to transport water necessary to detect leaks, cracks, corrosion, and other damages that may affect their performance. Traditional inspection methods are often time-consuming, costly, and unsafe because they require manual checking in confined spaces. This project, Design and Fabrication of a Smart Pipe Inspection Robot for Pipeline Monitoring, presents a simple and cost-effective robotic system for inspecting pipelines safely and efficiently. The robot is designed to move inside pipelines and is equipped with a camera, LED lights, and sensors to monitor the internal condition of the pipe. It captures real-time images and videos and transmits them wirelessly to the operator for continuous monitoring. The robot also measures the distance travelled inside the pipeline, allowing the operator to identify the exact location of any detected fault, such as cracks, leaks, corrosion, or blockages. This helps reduce the time required for maintenance and repairs. The proposed robot is lightweight, easy to operate, and suitable for water supply, sewage, oil, gas, and industrial pipelines. By reducing manual inspection and providing accurate fault detection with location information, the system improves worker safety, lowers maintenance costs, and increases the reliability and efficiency of pipeline monitoring.

Keywords— Pipe inspection robot, pipeline monitoring, ESP32-CAM, four-wheel drive, wireless video, distance sensor, robotic inspection.

1. INTRODUCTION

Pipelines form an important part of water-supply, drainage, sewage, oil, gas, and industrial process infrastructure. Since many pipelines are installed underground, inside buildings, or within industrial equipment, their internal condition cannot be judged through ordinary external observation. Corrosion, cracks, scale, sediment deposits, joint damage, and blockages may develop over time. If these defects remain unnoticed, they can cause leakage, contamination, reduced flow, service interruption, and increased maintenance cost.

Internal inspection is particularly difficult in small-diameter or inaccessible pipes. Manual inspection is possible only where the pipe is sufficiently large and safe for entry. Tethered cameras provide visual access but may be restricted by cable length, friction, and the difficulty of negotiating bends. Commercial robotic crawlers can provide advanced inspection capability, but their cost and complexity may limit their use in small institutions and educational projects.

A compact in-pipe robot can reduce the need for direct human entry by carrying a camera and sensors into the pipeline. Low-cost embedded electronics make it possible to combine mobility, imaging, and wireless communication in a single platform. The present work develops a four-wheel robot with an ESP32-CAM module and a distance-sensing arrangement. The objective is to provide a simple system that moves through a pipe of suitable diameter and transmits a live view of the pipe interior to an operator.

1.1 Problem Statement and Objectives

The principal problem addressed is the difficulty of examining the internal surface of a pipeline using methods that are safe, economical, and suitable for small-scale applications. The project aims to design and fabricate a battery-operated robot that can move inside a pipeline, transmit live camera images over Wi-Fi, and provide distance information to help identify the robot's position along the inspected section.

- Design a compact chassis and four-wheel mechanism suitable for the selected pipe diameter.
- Select DC geared motors and a motor driver to provide controlled movement.
- Integrate an ESP32-CAM module for real-time visual monitoring over Wi-Fi.
- Provide a distance-sensing arrangement to indicate the distance travelled inside the pipeline.
- Integrate rechargeable batteries and the required electrical connections.
- Fabricate, assemble, and prepare the prototype for movement, camera, sensing, and power-system evaluation.

1.2 Scope of the Work

The work focuses on a small-scale, light-duty inspection platform for laboratory test pipes and straight or gently curved pipelines of suitable diameter. It covers the mechanical frame, wheel and motor arrangement, motor-control electronics, wireless camera monitoring, distance sensing, and rechargeable power supply. The prototype is not intended for high-pressure, high-temperature, or explosive-atmosphere pipelines. Its camera-based approach is intended to reveal visible surface conditions; it does not measure wall thickness or identify hidden internal flaws.

2. LITERATURE REVIEW

Pipeline inspection methods include visual examination, CCTV systems, acoustic techniques, ultrasonic testing, electromagnetic methods, and instrumented pipeline pigs. Liu and Kleiner [3] reviewed inspection technologies for assessing water-pipe condition and highlighted that different techniques provide different types of information. Camera-based inspection is useful because it gives a direct visual record of the pipe interior, while specialised non-destructive testing methods are required for defects that are not visible at the surface.

In-pipe robots have been developed with different locomotion arrangements. Roh and Choi [1] described a differential-drive in-pipe robot for urban gas pipelines, demonstrating the relevance of wheeled motion and steering within pipes. Hirose et al. [2] investigated inspection vehicles for different pipe diameters, illustrating the importance of vehicle size, traction, and mechanical adaptation. Kim et al. [4] presented FAMPER, an autonomous mobile robot for pipeline exploration, while Ismail et al. [5] reviewed in-pipe inspection robot development and locomotion mechanisms.

Common locomotion types include wheeled, tracked, wall-pressed, screw-drive, inchworm, legged, and flow-driven systems. Wheeled mechanisms are comparatively simple and can provide useful speed and controllability. Tracked systems may provide improved traction on rough surfaces but generally require more components. Wall-pressed mechanisms are useful when a robot must maintain contact with the pipe wall across a range of diameters, although their mechanical arrangements are more complex.

Wireless camera-based inspection removes the need for a long video cable and allows the operator to view the pipe interior on a phone or computer. Wi-Fi is convenient because it is widely supported, but its practical range may be reduced by the pipe material and geometry. The ESP32-CAM combines a microcontroller, Wi-Fi communication, and a camera interface in a compact module [6]. It is therefore suitable for low-cost monitoring prototypes, provided that its power demand and limited available input/output pins are considered.

Distance measurement and obstacle sensing can be performed using ultrasonic, infrared, time-of-flight, or camera-based methods. Ultrasonic sensors estimate distance from the travel time of an emitted sound pulse and its returning echo. They are inexpensive and can operate in darkness, although readings may be affected by surface angle, material, and sensor range [7]. The project report identifies a distance-sensing arrangement mounted at a wheel to indicate the distance travelled by the robot. The exact sensor implementation and calibration should be confirmed against the final hardware.

2.1 Research Gap

The reviewed approaches indicate a need for a compact and affordable platform that combines in-pipe movement, live wireless video, and distance information using readily available components. Manual inspection is limited by access and safety; tethered systems are affected by cable handling; and commercial robotic systems may be costly or complex for educational-scale use. The present project addresses this gap through a four-wheel drive arrangement, ESP32-CAM-based Wi-Fi monitoring, a distance-sensing arrangement, and rechargeable power.

3. PROPOSED SYSTEM AND METHODOLOGY

The proposed robot is organised into six functional sections: (i) mechanical structure, (ii) drive system, (iii) power supply, (iv) motor-control electronics, (v) camera and wireless communication, and (vi) distance sensing. The chassis supports the four motors, wheels, batteries, motor driver, ESP32-CAM module, and sensor. The camera is positioned toward the front of the robot to capture the pipe interior in the direction of travel.

3.1 System Architecture

The rechargeable battery pack supplies electrical energy to the drive and monitoring sections. The motor driver receives control signals and supplies the required current to the DC geared motors. The motors rotate the four wheels to move the robot forward, backward, or through differential steering. The ESP32-CAM captures images and transmits the video stream through Wi-Fi. The operator accesses the stream using a suitable mobile phone or computer. The distance-sensing arrangement provides information about the distance travelled or the position of the robot along the pipe.

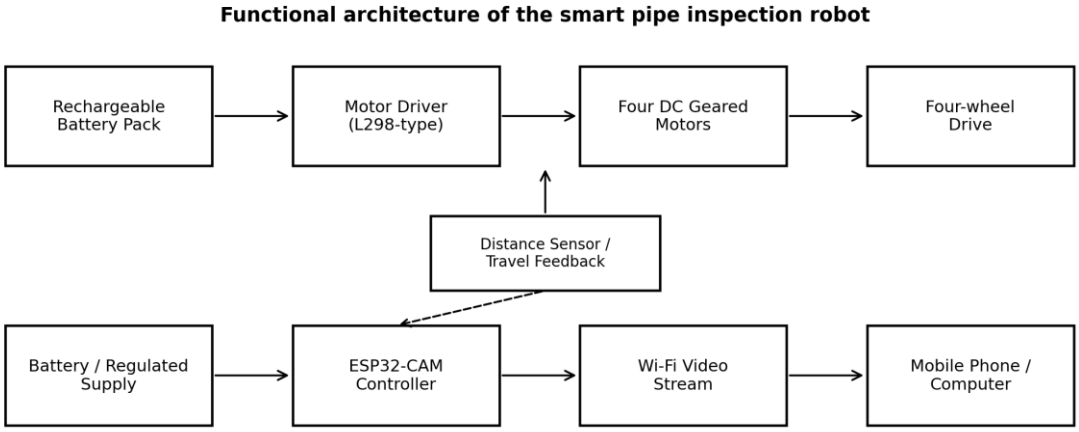


Fig. 1. Functional block diagram of the proposed smart pipe inspection robot.

The architecture separates the drive path from the visual-monitoring path. The battery supplies the motor driver and, through suitable regulation, the ESP32-CAM and sensing electronics. The operator receives the camera stream over Wi-Fi, while the distance-sensing arrangement is intended to support travel-distance recording.

3.2 Mechanical Design

The mechanical assembly consists of a compact frame and four wheels arranged as two wheels on each side. Each wheel is driven by an individual DC geared motor. The four-wheel arrangement allows all wheels to contribute to traction and supports the robot on the pipe surface. The frame dimensions must remain smaller than the internal diameter of the selected pipe, with sufficient clearance for movement over joints and minor surface irregularities. The layout should also provide adequate space for the batteries and electronic modules.

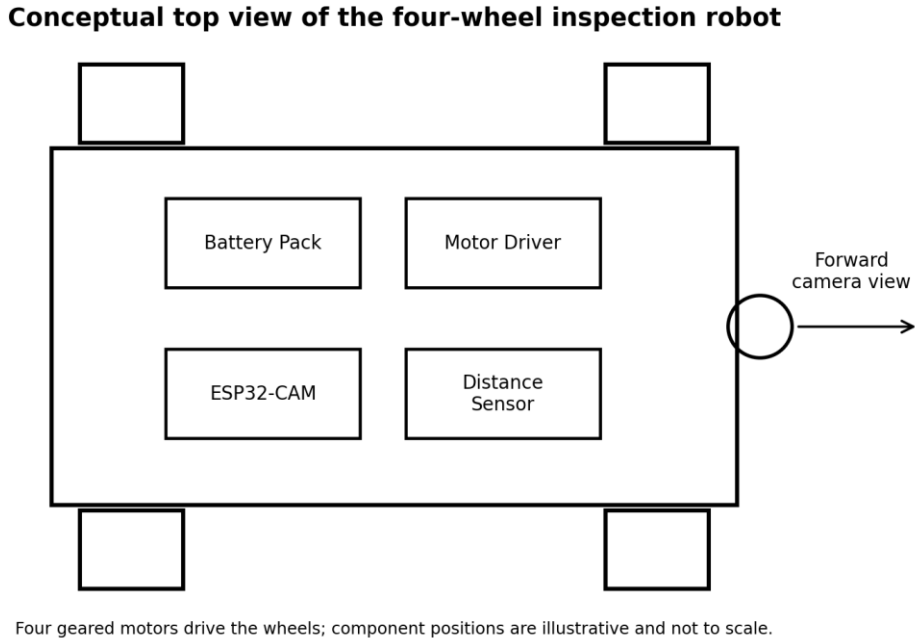


Fig. 2. Conceptual top-view arrangement of the robot components (not to scale).

The wheels are mounted on the motor shafts and aligned so that they rotate freely without unwanted rubbing against the chassis. Steering is achieved through differential or skid steering. When the left and right wheel groups rotate in the same direction, the robot moves forward or backward. When the two sides rotate at different speeds or in opposite directions, the robot turns. The selected motor speed in the project report is 100 rpm; the final motor torque and operating speed should be validated using the actual robot mass, wheel diameter, and pipe conditions.

3.3 Drive and Control System

DC geared motors are used because the gearbox reduces rotational speed and increases the torque available at the wheel. A dual H-bridge motor driver, identified in the report as an L298N-type module, is considered for controlling motor direction and speed. The two motors on the left side may be grouped on one driver channel and the two motors on the right side on the other channel, subject to the current rating of the driver and the motors. Direction is selected by the driver input logic, while speed can be adjusted using pulse-width modulation (PWM).
The basic movement logic is summarised as follows:

Left-side motors	**Right-side motors**	**Robot movement**
Forward	Forward	Forward
Reverse	Reverse	Backward
Reverse / stop	Forward	Turn left
Forward	Reverse / stop	Turn right
Stop	Stop	Stationary

3.4 Camera and Wireless Monitoring

The ESP32-CAM module is used as the visual monitoring unit. Its camera captures the internal surface of the pipe, and the ESP32 microcontroller processes and transmits the image stream over Wi-Fi. The operator views the stream through a web browser on a mobile phone or computer. The camera should face forward along the pipe axis. Since the interior of a pipeline may be dark, suitable lighting is required for clear images. A stable regulated supply is also important because video streaming can increase current consumption and may cause resets if the supply voltage falls.

3.5 Distance Sensing and Power Supply

A distance-sensing arrangement is included to provide information about the robot's travel inside the pipeline. The project report describes the sensor as being mounted near a wheel so that the distance travelled can be estimated and the location of an observed defect can be recorded. For a wheel-based measurement system, the distance estimate depends on the wheel circumference and the number of measured wheel rotations. The final implementation should document the sensor type, pulse count or measurement principle, calibration procedure, and any correction for wheel slip. These details are necessary before a numerical position accuracy can be claimed.
The robot uses three rechargeable lithium-ion batteries. The report notes that the pack voltage depends on the electrical connection: three cells in series

provide a higher nominal voltage, whereas a parallel arrangement increases capacity while retaining the cell voltage. The actual configuration must be confirmed on the prototype. The motor driver is supplied from the battery pack, while a regulated supply is required for the ESP32-CAM and sensing electronics. A fuse, main switch, suitable charging and protection arrangement, insulated wiring, and a common ground are recommended for safe operation.

3.6 Fabrication and Assembly

The fabrication methodology follows a sequence of design, procurement, frame preparation, motor and wheel mounting, electronics installation, programming, and testing. First, the frame dimensions are selected based on the pipe diameter and component dimensions. The frame is then cut and assembled, after which the four geared motors and wheels are fixed in position. The batteries, motor driver, voltage regulation components, ESP32-CAM, and distance sensor are mounted on the chassis. Wiring is completed with the battery disconnected, and the direction of each motor is checked before full integration.

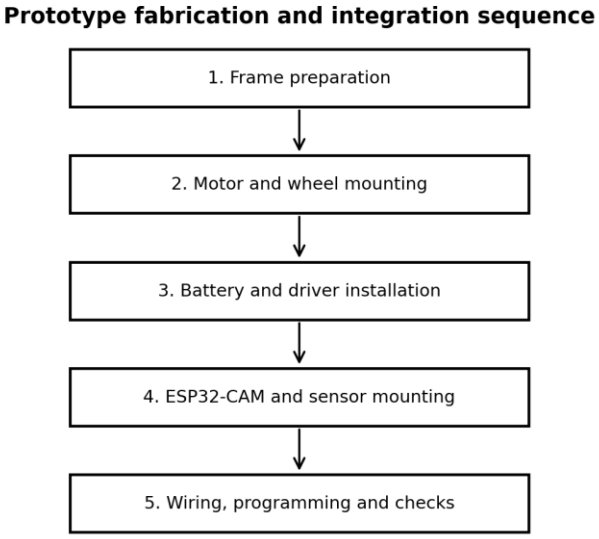


Fig. 3. Main stages in fabrication and integration of the prototype.

The ESP32-CAM is programmed using the Arduino development environment and an external USB-to-serial adapter, as the module does not provide a conventional built-in USB programming interface. After uploading the program, the camera stream, motor operation, and distance-sensing function are checked individually. The complete assembly is then inspected for loose connections, exposed conductors, interference between wiring and rotating wheels, and adequate clearance within the test pipe.

4. COMPONENTS AND DESIGN CONSIDERATIONS

The principal components and their reported specifications are summarised in Table 1. The values below are transcribed from the project report; where a detailed rating is not specified, it is identified as not stated rather than assumed.

Component	Quantity	Reported specification / role
DC geared motor	4	100 rpm
Wheels	4	Plastic
ESP32-CAM	1	5 V supply; Wi-Fi camera module
Distance sensor	1	RKI Encoder (as stated in report)
Motor driver	1	L298-type dual H-bridge (report also lists “L2989”)
Rechargeable batteries	3	Lithium-ion cells
Chassis / frame	1	Supports mechanical and electronic parts

The principal design considerations are pipe diameter, overall robot size, frame stiffness, total mass, wheel traction, motor torque, battery capacity, electrical current demand, and wireless communication quality. The robot must fit inside the selected pipe without excessive clearance that could reduce wheel contact. The centre of gravity should be kept low and balanced, and the batteries should be secured against movement. The camera and sensor should be protected from accidental contact with the pipe wall.

Motor selection should be based on the required tractive force, wheel radius, robot mass, rolling resistance, and any slope to be negotiated. The available motor torque at the wheel must be sufficient to overcome these loads with a suitable design margin. Similarly, battery operating time depends on the usable battery capacity and the combined current drawn by the motors, camera, controller, and sensor. Since the report does not provide complete measured component currents, actual battery capacity, or confirmed cell arrangement, a reliable runtime calculation cannot be reported.

5. RESULTS AND DISCUSSION

The project report records the fabrication and integration of the robot and identifies the ESP32-CAM live-video function and distance-sensing function

as completed project objectives. It also describes the intended evaluation procedure for the complete system. However, the report explicitly leaves the observation tables blank and states that measured values are to be entered after testing. Consequently, the present paper reports the documented implementation status and qualitative system functions only. It does not assign numerical values to speed, travelled distance, sensor error, Wi-Fi range, video frame rate, or battery operating time.

5.1 Functional Evaluation Framework

A complete experimental evaluation should include the following tests:

- Movement test: operate the robot on a suitable test surface and inside the test pipe; record forward and reverse motion, turning response, and any wheel slip.
- Four-wheel mechanism test: check wheel alignment, free rotation, traction, and the ability of all four wheels to contribute to movement.
- Camera test: verify image clarity, field of view, and visibility of the pipe interior under the available lighting.
- Wi-Fi test: record connection stability, video availability, and the maximum usable communication distance under the test conditions.
- Distance-sensing test: compare the sensor or encoder indication with a measured reference distance and calculate the error.
- Battery test: record battery voltage before and after operation, current draw, and the duration of continuous operation.

For repeatability, each test should state the pipe material and internal diameter, test length, surface condition, battery configuration, lighting, wireless environment, and measurement instruments. Multiple trials should be performed under the same conditions. Mean values and variation may then be calculated from the recorded observations. The results should be added to the paper before submission to a journal or conference.

5.2 Discussion

The integrated arrangement combines a simple mechanical drive with low-cost wireless monitoring. The four-wheel configuration is expected to provide support and traction on the pipe surface, while differential steering avoids the need for a separate steering linkage. The ESP32-CAM offers a compact means of viewing the internal pipe surface remotely. The distance-sensing arrangement is intended to support location marking so that an operator can relate a visible defect to the robot's travel distance.

The practical performance of the system will depend on factors that require experimental verification. Wi-Fi signals may be attenuated by metal pipe walls and by the length and geometry of the pipeline. Image quality depends on camera orientation, illumination, and the stability of the power supply. Wheel slip can introduce error into travel-distance estimates. Battery runtime depends on the load and the battery configuration. These factors should be quantified through controlled tests rather than inferred from component specifications alone.

5.3 Limitations

- The system is intended for a limited range of pipe diameters and straight or gently curved sections.
- Wi-Fi communication may be unreliable over longer distances or inside metal and buried pipelines.
- Camera-based inspection reveals visible surface conditions but cannot measure hidden flaws or wall-thickness loss.
- Low-cost distance sensors or wheel-based distance measurement may be affected by surface conditions, alignment, and wheel slip.
- Battery operating time and quantitative performance have not been established in the project report.
- The prototype is not designed for hazardous, high-pressure, high-temperature, or explosive-atmosphere service.

6. CONCLUSION AND FUTURE SCOPE

A compact smart pipe inspection robot has been designed and fabricated using a four-wheel drive mechanism, four DC geared motors, an ESP32-CAM module, a distance-sensing arrangement, and rechargeable batteries. The system is intended to move inside a pipeline of suitable diameter and provide remote visual monitoring through a Wi-Fi video stream. The mechanical, electrical, and electronic sections are integrated on a common chassis. The project addresses the need for a simple and economical inspection platform for small-scale and educational applications.

The report records completion of prototype fabrication and integration and identifies the camera monitoring and distance-sensing functions as completed. Since the report does not include measured test observations, quantitative performance claims are intentionally withheld. Experimental validation of movement, video quality, communication range, distance accuracy, and battery endurance is required before the system can be considered for practical field deployment.

6.1 Future Scope

Future work may add controlled LED lighting, calibrated encoder or time-of-flight distance measurement, automatic obstacle response, and adjustable wheels for different pipe diameters. Improved communication, video recording, image processing, and a sealed waterproof enclosure may extend the system's usefulness. Each improvement should be validated through repeatable laboratory tests and field trials.

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