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# IoT-Based Pipe Inspection and Cleaning Robot with Wi-Fi/LoRa Dual-Mode Control and Combustible Gas Sensing

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### ABSTRACT—

Sending workers into underground pipes is dangerous, and the robots that could replace them cost more than most small municipal bodies and colleges can spend. We built a low-cost crawler that inspects and cleans a pipe while the operator stays outside. Control normally runs over Wi-Fi through a browser dashboard; when signal strength drops, the robot hands over to a 433 MHz LoRa link driven by a handheld joystick. On board, an ESP32-CAM streams live video, an MQ-2 sensor watches for combustible gas, and a spring-loaded rotating brush clears loose debris. On a test rig of 150, 200 and 250 mm pipes the robot removed 78% of a sand-and-gravel load on average, kept video latency at 320 ms, raised its gas alarm in 7.2 s, and held a LoRa link out to 45 m. A charge lasted 145 min, and the parts came to about INR 16,000. The results suggest that a modest, human-operated robot with a redundant radio link is a practical option where commercial crawlers are out of reach.

**Index Terms**—pipeline inspection, in-pipe robot, Internet of Things, LoRa, ESP32-CAM, MQ-2 gas sensor, dual-mode communication

## I. Introduction

Pipes under a city or inside a plant are easy to forget until something goes wrong. Water mains, sewers, fuel lines and chemical headers all silt up, corrode and sometimes crack, and each of them needs an occasional look from the inside. In many places that look is still taken by a person who climbs into the line with a torch. The air down there can be short of oxygen or carry methane and other combustible gases, the space is cramped, and help is slow to arrive if the worker collapses.

Crawler robots take the person out of the pipe, and several vendors sell them. The catch is price. A single Deep Trekker crawler, for instance, is listed at roughly USD 6,000 to 13,500 depending on configuration [1], and IBAK-class systems are built around the needs of large municipal and industrial operators [2]. A town council with a small drainage budget, or an engineering college that wants a platform to experiment on, will struggle to justify that kind of spending.

A second obstacle is radio. Pipe walls made of metal or concrete absorb and reflect signals, so a robot that is perfectly controllable at the manhole may drift out of reach a few metres downstream. Propagation measurements inside pipelines and underground spaces show signal levels falling with distance and depth [3], [4]. Wu et al. compared Wi-Fi and LoRa links for underground use and found that LoRa copes better with multipath fading, while Wi-Fi delivers higher data rates over shorter distances [5]. Those two findings point to an obvious compromise: use Wi-Fi while it works, because video needs the bandwidth, and keep a LoRa link in reserve so that the operator never loses the robot.

This paper describes a robot built around that idea. It inspects with a camera, checks the air with a combustible-gas sensor, and sweeps loose debris with a rotating brush, all under operator control from outside the pipe. Our contributions are (i) a low-cost platform that combines cleaning, live video and gas sensing on one chassis; (ii) an automatic Wi-Fi-to-LoRa failover scheme that uses hysteresis on received signal strength, together with a joystick backup controller; and (iii) a measured evaluation on a pipe test rig that covers mobility, cleaning, video, gas response, communication and endurance. Section II reviews related work, Section III describes the design, Section IV explains how we tested it, Section V gives the results, and Sections VI and VII close with limitations and conclusions.

## II. Related Work

Low-cost inspection robots built from hobby-grade parts are not new. Villaseñor-Chávez et al. assembled a sewer vehicle from an Arduino Mega 2560, an ESP32-CAM, a laser distance sensor and an optical encoder, steered it over a hybrid Bluetooth and RF link, and mapped its trajectory over as much

as 61 m [6]. Their work shows that open hardware can bring preventive inspection within reach of municipal agencies. It carries no gas sensor or cleaning tool, though, and nothing in the design addresses what happens when the radio link fades inside a metal pipe.

At the other end of the complexity scale, PLIERS sends a swarm of camera-equipped robots into emptied water and sewage pipes. The robots talk to each other over LoRa, report to a server over LoRa and Wi-Fi, and a convolutional neural network grades the severity of the cracks they find [7]. It is a capable design, but the fleet, the trained model and the server infrastructure put it well beyond what a small maintenance team would deploy.

Review articles help place the mechanical choices. Rashid et al. sort in-pipe robots by locomotion type (wheeled, tracked, screw-driven and legged) and discuss where each one struggles [8]. Luna et al., writing about soft robots, note that rigid machines have trouble adapting to changing diameters and tight bends [9]. We chose a rigid four-wheel skid-steer body for simplicity and accepted that bends would be its weak spot, which the results in Section V bear out.

On the sensing side, Hadi built a wheeled robot around an MQ-2 sensor, an LED and buzzer alarm, and a microSD logger to track flammable gas, and reported detection of methane, LPG and propane at 300–400 ppm [10]. That robot has neither a camera nor any cleaning function. Kim et al. tested IoT sensor nodes with edge processing at hydrogen pipeline construction sites and recorded a 100% success rate for Wi-Fi against 97% for LoRa at 50 m [11], which is a useful reminder that the two links complement each other rather than compete.

Remote operation also raises a security question. Hamad et al. review the threats facing IoT-enabled inspection robots and argue for strong authentication, access control and continuous monitoring [12]. In the same spirit, we placed the web dashboard behind a login. Table I compares the systems discussed above with the robot presented here. None of the earlier systems combines cleaning, live video, gas sensing and automatic link failover on a budget that a small institution could meet, and that combination is what we set out to build.

TABLE I

Feature comparison with related robots

| System              | Video | Gas  | Clean  | Backup link | Cost class |
|---------------------|-------|------|--------|-------------|------------|
| BORT [6]            | Yes   | No   | No     | No          | Low        |
| PLIERS [7]          | Yes   | No   | No     | Yes         | High       |
| Hadi [10]           | No    | Yes  | No     | No          | Low        |
| Commercial [1], [2] | Yes   | Rare | Varies | Varies      | High       |
| This work           | Yes   | Yes  | Yes    | Yes         | Low        |

### III. System Design

#### A. Overview

The robot is organized in four layers: a mechanical layer (chassis, drive and brush), an electronics layer (power, motor drivers and sensors), a communication layer (Wi-Fi and LoRa) and a user layer (dashboard and joystick). Keeping the layers separate let us test each on its own before putting the machine together. An Arduino Mega 2560 is the main controller. It drives the motors, reads the gas sensor and handles the LoRa radio, while an ESP32-CAM takes care of the camera and the Wi-Fi web server. Fig. 1 shows the overall arrangement.

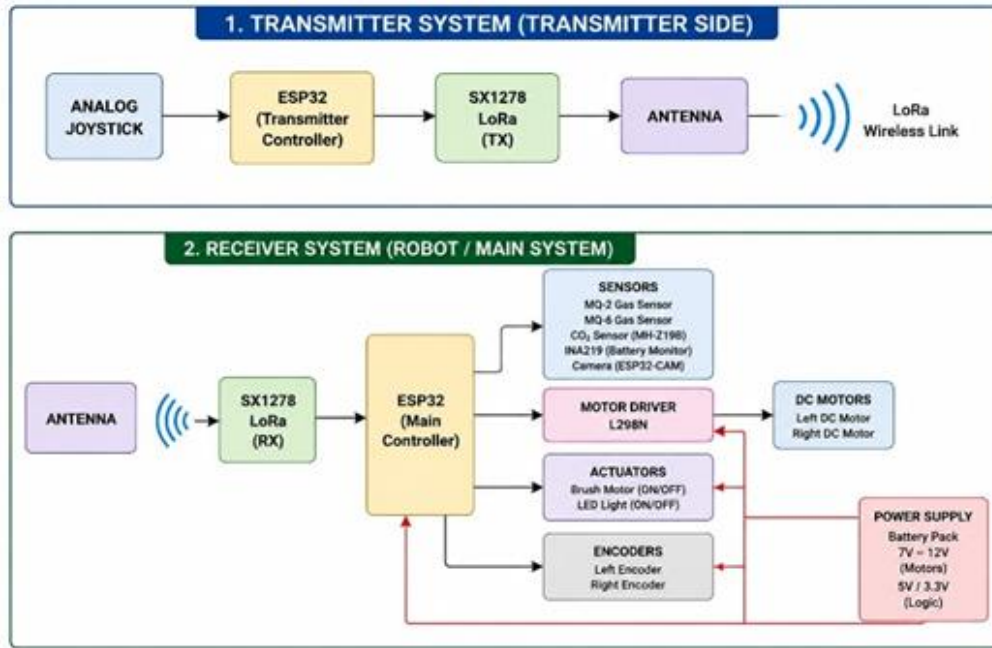


Fig. 1. Block diagram of the proposed pipe inspection and cleaning robot.

#### B. Chassis and Locomotion

The body measures  $280 \times 180 \times 120$  mm and is cut from 2 mm sheet. Four 12 V geared DC motors (200 rpm, 2 kg·cm) are arranged for skid steering, each carrying a 60 mm rubber wheel that is 25 mm wide. Two L298N H-bridge modules set direction and, through PWM, the speed of the left and right pairs. The robot turns by running one side faster than the other, so no steering linkage is needed and the body can stay short. The assembly is shown in Fig. 2.



Fig. 2. Chassis and drive assembly of the prototype.

#### C. Cleaning Mechanism

A cylindrical brush at the front sweeps loose sand, silt and light debris off the pipe surface. It sits on a spring-loaded arm that keeps 5 to 10 N of contact force on the wall, and it is turned by its own 12 V motor through a 2:1 gear stage at about 150 rpm. A 5 V, 10 A relay switches the motor on the operator's command, and a firmware timer cuts the power after 30 s of continuous running so that the motor cannot overheat.

#### D. Video Inspection

The ESP32-CAM sits at the front of the robot and streams  $640 \times 480$  Motion-JPEG video at 10–15 frames per second. The stream is served at a local IP address, so any laptop or phone on the same network can open it in a browser without installing an app. Compression happens on the camera board itself, which keeps that load off the main controller.

#### E. Gas Sensing

An MQ-2 metal-oxide sensor gives an analog voltage that rises with the concentration of combustible gas. The controller digitizes the signal and, after a 20 s warm-up in clean air, records a baseline. When the reading crosses 400 ADC counts, a buzzer and an LED fire on the robot and a warning appears on the dashboard. The sensor responds to a family of combustible gases and vapors and cannot say which one it is detecting, a limitation we return to in Section VI.

#### F. Dual-Mode Communication

In normal operation the operator logs in to a web dashboard served over Wi-Fi, which shows the live video and the gas reading and offers drive and cleaning controls. As a backup, the operator carries a joystick unit with its own SX1278 LoRa transceiver (433 MHz), paired with a second transceiver on the robot. Command packets carry an XOR checksum, and the robot discards any packet that fails the check.

Switching between links is automatic and based on RSSI. If the Wi-Fi signal stays below  $-80$  dBm for three consecutive readings, the robot moves control to LoRa. It returns to Wi-Fi only after the signal has stayed above  $-75$  dBm for three consecutive readings. The 5 dB gap between the two thresholds stops the robot from flipping back and forth when the signal hovers near a limit. As a last line of defense, a failsafe halts the motors and sounds the buzzer if no command arrives for 2 s. The decision logic is outlined in Fig. 3.

#### G. Power and Data Logging

A 12 V lithium-ion pack feeds the motors directly. An LM2596 buck converter supplies the 5 V rail for the Arduino, driver logic, relay and gas sensor, and an AMS1117 regulator gives 3.3 V to the ESP32-CAM and the LoRa module. A voltage divider (10 k $\Omega$  and 2.2 k $\Omega$ ) lets the controller watch the battery and disable the motors at 10.5 V. Once a second, the controller writes sensor readings and events, such as gas warnings and link switches, to a microSD card as a CSV file for later review.

TABLE II

Main design parameters of the prototype

| Item       | Specification                               |
|------------|---------------------------------------------|
| Chassis    | 280 × 180 × 120 mm, 3 mm sheet              |
| Drive      | 4 × 12 V DC geared motors, 200 rpm, 2 kg·cm |
| Wheels     | 60 mm diameter, 25 mm wide, rubber          |
| Brush      | 12 V motor, 2:1 gear, about 150 rpm, 5–10 N |
| Camera     | ESP32-CAM, 640 × 480, 10–15 fps, MJPEG      |
| Gas sensor | MQ-2, alarm at 400 ADC counts               |
| LoRa link  | SX1278 at 433 MHz, XOR checksum             |
| Failover   | $-80$ dBm down / $-75$ dBm up, 3 readings   |
| Battery    | 12 V Li-ion, cutoff at 10.5 V               |

#### H. Operating Procedure

Before the robot enters a pipe it runs a short self-check that confirms the motors respond, the gas sensor is reading, the camera feed is available and the communication link is healthy. The operator then signs in to the dashboard, watches the video and gas values as the robot advances, and switches the brush on when debris appears ahead. If the gas warning comes up, the robot can be pulled back and people kept away from the opening. Every action is started by a person, so the operator always knows why the machine is doing what it is doing. For confined-space work we valued that transparency more than autonomy.

## IV. Experimental Setup

Testing took place on a rig built from 280 mm sections of PVC and mild-steel pipe. Each subsystem was checked alone before the full-system trials.

For mobility, the robot was commanded to cover 3 m of straight pipe, to pass 45° and 90° bends, and to cross a 10 mm obstruction. For cleaning, 50 g of a sand-and-gravel mixture was spread over a 1 m section, the brush ran for 10 s, and the removed fraction was worked out by mass. Video latency was measured from a real event to its appearance on the dashboard, 20 times at a distance of 10 m, while three observers scored image clarity from 1 to 5. Gas response was timed after exposing the sensor to 500 ppm LPG. In the communication tests we lowered the measured RSSI artificially to force link changes, and we found the LoRa range by moving the robot away from the joystick until packets started to drop. Battery life was logged during continuous running at a moderate speed (PWM value of 100).

## V. Results and Discussion

### A. Mobility and Cleaning

Table III lists the mobility outcomes. The robot completed every straight run, handled 45° bends in 19 of 20 attempts, and managed 90° bends in 16 of 20. Each of the four failed 90° attempts ended in a stall that the operator cleared by reversing and trying again. We suspect the length of the body relative to the pipe diameter plays a part, but we did not isolate that factor. With a 1.0 kg load added, the robot kept moving and the current in each motor stayed under 1.8 A.

TABLE III

Mobility test outcomes (200 mm pipe)

| Test              | Trials | Success |
|-------------------|--------|---------|
| Straight run, 3 m | 10     | 100%    |
| 45° bend          | 20     | 95%     |
| 90° bend          | 20     | 80%     |
| 10 mm obstacle    | 10     | 90%     |

Over five trials the brush removed 78% of the debris on average (range 72–84%), above our 70% target. The spring arm held a mean contact force of 7.2 N, inside the intended 5–10 N window. The brush motor ran for the full 30 s without its temperature passing 60 °C. When the brush met a 15 mm obstruction it stalled, the relay limited the current, nothing was damaged, and the operator was alerted.

### B. Video, Gas Sensing and Communication

Table IV gathers the main figures against their targets. Video latency averaged 320 ms (range 280–410 ms), comfortably under the 500 ms limit. The three observers rated clarity at 4.1 out of 5, with a Fleiss' kappa of 0.68, which indicates substantial agreement. The stream stayed reliable up to 12 m inside the 200 mm steel pipe and degraded beyond 15 m; the mean frame-drop rate over five-minute sessions was 3.2%. That 12 m figure is well short of the LoRa range, and it is exactly why the backup link matters: once video is lost, the operator can still steer the robot out with the joystick.

TABLE IV

Measured performance against design targets

| Metric                       | Measured | Target    |
|------------------------------|----------|-----------|
| Debris removal               | 78%      | ≥ 70%     |
| Video latency                | 320 ms   | < 500 ms  |
| Gas alarm time (500 ppm LPG) | 7.2 s    | < 10 s    |
| LoRa range (200 mm pipe)     | 45 m     | ≥ 30 m    |
| Joystick response            | 120 ms   | < 200 ms  |
| Battery life                 | 145 min  | ≥ 120 min |

The gas alarm sounded after 7.2 s on average (range 6.5–8.1 s). The 400-count threshold triggered correctly in all 20 trials, and ten minutes in clean air produced no false alarms. Alcohol vapor also set off the alarm, at about 450 counts. That is a fair reminder of what the MQ-2 is: an indicator that some combustible vapor is present, not an analyzer that names the gas.

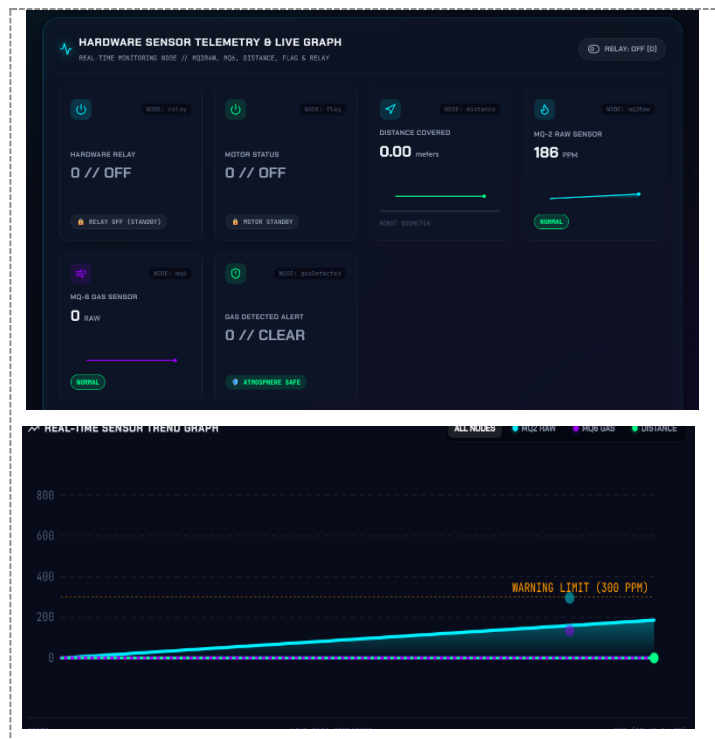


Fig. 5. Web dashboard during a live test, showing the video feed, gas reading and control buttons.

Link switching worked in all 15 trials in each direction. Moving from Wi-Fi to LoRa took 1.8 s on average and moving back took 1.5 s. LoRa reached 45 m on average (range 38–52 m) in the 200 mm pipe, and all 20 deliberately corrupted packets were rejected by the checksum. The joystick-to-motor delay averaged 120 ms. When commands were withheld for 2 s, the failsafe stopped the motors within 2.1 s in all 10 trials.

Table V adds the finer communication, sensing and power outcomes that sit behind the headline numbers.

TABLE V

Detailed communication, sensing and power results

| Test                               | Outcome      |
|------------------------------------|--------------|
| Wi-Fi to LoRa switch               | 15/15, 1.8 s |
| LoRa to Wi-Fi switch               | 15/15, 1.5 s |
| Corrupted packets rejected         | 20/20        |
| Failsafe motor stop                | 10/10, 2.1 s |
| Gas threshold activation           | 20/20        |
| False alarms in clean air (10 min) | 0            |
| Video frame drop                   | 3.2%         |
| Total operating current            | 2.4 A        |
| Low-voltage cutoff                 | 10.48 V      |

### C. Power, Logging and Cost

A full charge lasted 145 min on average (range 138–152 min over three runs). The motors were cut off at  $10.48 \pm 0.05$  V, matching the 10.5 V setting. The 5 V rail stayed between 4.92 and 5.08 V and the 3.3 V rail between 3.22 and 3.38 V, both within  $\pm 5\%$ , and the whole robot drew 2.4 A on average with all functions running. In a 30 min session at 1 Hz the logger saved all 1800 records with no missing fields, and the files were readable on a computer in each of five sessions. The material cost came to about INR 16,000. By comparison, the commercial crawler cited earlier starts at USD 6,000 [1], so the prototype undercuts commercial units by a wide margin, although it also does less.

#### D. Discussion

Two results deserve a closer look. The first is the gap between the video range (12 m) and the LoRa range (45 m). It shows that the dual-link design does real work inside a pipe: for a stretch of more than 30 m the operator has no picture but still has full control, and that stretch is where a Wi-Fi-only robot would simply be lost. The second is the 90° bend figure. An 80% success rate is acceptable for a prototype, but it is the weakest number in the paper. A shorter body, or a pivoting joint between two segments, might raise it; we have not tried either.

The spread inside each test was small. Debris removal had a standard deviation of 4.8 percentage points over five trials, gas response stayed between 6.5 and 8.1 s, and latency between 280 and 410 ms. Each test used only a handful of trials, though, so these ranges are indicative rather than statistical proof. The targets were also set by us, which means that meeting them shows the design is adequate for its intended use. It does not show how the robot would rank against a commercial crawler in a head-to-head trial, and we did not run one.

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### VI. Limitations and Future Work

The results come from a controlled rig, not from a live sewer or process line, so mud, standing water and irregular joints have not yet been tried. The robot is meant for straight or gently curved pipes and is not suited to vertical runs or tight, irregular geometry. The MQ-2 cannot tell methane from LPG or alcohol vapor, and it cannot detect hydrogen sulfide or carbon monoxide specifically, both of which are common in sewers. Video quality depends on lighting and the Wi-Fi link, and the battery limits a mission to a little over two hours. The prototype has no autonomous navigation, obstacle avoidance or automatic defect detection.

Several extensions follow naturally. A convolutional network could flag cracks and corrosion in the video, as PLIERS does for its images [7]. Adding dedicated hydrogen sulfide and carbon monoxide sensors would make the atmosphere readings more useful. Mapping and localization would let the operator know where along the pipe a defect lies, and a cloud service could store inspection histories so that maintenance teams can track how a pipe changes over time.

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### VII. Conclusion

We have presented a pipe inspection and cleaning robot that gives an operator live video, a combustible-gas warning and a debris-clearing brush from outside the pipe, and that keeps control alive when Wi-Fi fades by switching on its own to a LoRa joystick link. In tests on a rig it met every target we set: 78% debris removal, 320 ms video latency, a 7.2 s gas alarm, a 45 m LoRa range and 145 min of running time, for roughly INR 16,000 in parts. These figures suggest that small municipalities, colleges and maintenance teams can obtain much of what a commercial crawler offers without its price, provided they accept human-in-the-loop operation and the limits described above.

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