Design and Experimental Evaluation of an IoT-Based Smart Drainage Monitoring and Blockage Detection System

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Abstract

This paper presents an Internet of Things based smart drainage monitoring and blockage detection system developed to improve urban water management. The proposed system integrates microcontroller based sensor modules equipped with laser based water level sensors and methane gas sensors to enable real time detection of drain blockages and gas emissions. Each module operates using solar power and includes a servo motor driven self cleaning mechanism for autonomous maintenance. Data from distributed nodes are transmitted through the Message Queuing Telemetry Transport (MQTT) protocol to a centralized Node RED dashboard for remote monitoring and analysis. Experimental validation using a three meter physical prototype demonstrated high accuracy in anomaly detection and the results confirm that the system offers a scalable, energy efficient, and sustainable framework for developing intelligent drainage infrastructure in modern urban environments.

Keywords: Internet of Things, Smart drainage system, Blockage detection, Water level monitoring, Urban water management, Sustainable infrastructure

1 Introduction

Urban drainage systems play a critical role in maintaining public hygiene, preventing urban flooding, and ensuring effective stormwater management. However, with the rapid pace of urbanization and industrial development, these systems are increasingly burdened by a range of challenges such as solid waste accumulation, sedimentation, and structural degradation. Blockages in drainage networks not only disrupt water flow but also lead to frequent incidents of waterlogging, property damage, and vector- borne diseases. These issues are particularly acute in densely populated metropolitan areas, where inadequate maintenance and aging infrastructure exacerbate the risk of flooding during heavy rainfall events. As illustrated in Figure 1, real world drainage systems often experience waste accumulation and restricted accessibility, emphasizing the need for an intelligent, automated monitoring framework.

Fig. 1 Real-world drainage scenario

Traditional drainage maintenance methods rely heavily on periodic manual inspections and reactive interventions. While these approaches provide short-term relief, they are often inefficient, labour intensive, and incapable of offering real-time insights into system performance. Consequently, critical anomalies such as partial blockages or gas buildup—may go undetected until a major failure occurs. Moreover, clogged drains frequently emit hazardous gases such as methane and hydrogen sulfide, posing severe health and safety risks to maintenance personnel and nearby residents. These limitations underscore the urgent need for a more intelligent, automated, and data driven approach to urban drainage management.

Recent advancements in the Internet of Things (IoT), wireless sensor networks, and embedded systems have enabled the development of smart infrastructure capable of continuous monitoring and adaptive control. IoT based solutions offer the potential for real time data acquisition, remote visualization, and predictive maintenance through low power, networked sensor nodes. Several studies have explored the use of water level sensors, gas sensors, and communication protocols such as Message Queuing Telemetry Transport (MQTT) to create intelligent environmental monitoring systems. However, many of these implementations are either constrained by high power consumption limited scalability, or lack of autonomous cleaning mechanisms, which restrict their practical deployment in outdoor drainage environments.

To address these limitations, this work proposes a fully automated, IoT enabled smart drainage monitoring and blockage detection system that integrates sensing, communication, and self maintenance capabilities into a unified framework. The system employs ESP32 microcontrollers interfaced with VL53L0X LiDAR sensors for high precision water level and blockage detection and MQ4 gas sensors for methane monitoring. The design emphasizes energy efficiency through solar-powered operation and robustness via a servo motor–based self-cleaning mechanism, enabling reliable long term performance in harsh environmental conditions. The use of the MQTT proto- col ensures low latency, bidirectional communication between sensor nodes and the centralized monitoring platform, facilitating real time visualization, data logging, and alert generation.

Experimental validation was conducted on a three-meter prototype system to evaluate the accuracy, latency, and stability of the proposed design. The results demon- strate effective detection of abnormal water level variations, prompt identification of gas emissions, and autonomous cleaning operations without human intervention. These findings highlight the system's potential as a scalable, resilient, and cost effective solu- tion for modern urban drainage infrastructure. By enabling continuous monitoring and predictive maintenance, the proposed framework contributes to the broader vision of smart and sustainable cities.

2 Related Works

Efficient urban drainage management is essential for preventing flooding, ensuring public hygiene, and maintaining sustainable urban infrastructure. Conventional inspection practices such as manual observation, CCTV surveys, and reactive maintenance are labour intensive and inadequate for continuous performance assessment. Consequently, a global shift toward smart, IoT driven drainage systems has emerged across recent research.

The transition from traditional systems to smart, data driven infrastructure has been comprehensively reviewed in [1] and [2], which identified fragmented communication standards, insufficient data integration, and high operational costs as key barriers to adoption.

These reviews emphasize the need for real time sensing, low latency communication, and adaptive control within urban drainage networks. Further, Ramovha *et al.* [3] highlighted the potential of artificial-intelligence based modeling in storm water management, stressing that combining physical sensors with data driven prediction can significantly enhance system responsiveness and water quality outcomes.

Reliable blockage detection is central to proactive maintenance. A real time IoT system using ultrasonic sensors and cloud analytics to detect blockages in sanitary sewers was proposed in [4], demonstrating that threshold based analysis of water level variations can identify partial obstructions early. Complementary to this, a reflected wave technique for continuous sewer blockage detection which is an innovative non intrusive approach using pressure waves to locate obstructions was presented in [5]. Both studies confirm that effective blockage detection depends on robust sensing and frequent data sampling, motivating the use of LiDAR based distance sensors for higher precision.

Gas detection is another critical aspect, as toxic gases such as methane (CH_4) and hydrogen sulfide (H_2S) are common in enclosed drains. Pacheco *et al.* [6] deployed multiple commercial H_2S sensors in Berlin sewers and proposed a detailed sensor management protocol for calibration and rotation to maintain long term accuracy, highlighting the importance of automated gas monitoring for worker safety. Similarly, Salem *et al.* [7] developed an industrial cloud-based wastewater IoT platform integrating gas and chemical sensors with remote visualization, demonstrating the viability of large-scale monitoring through cloud computing.

The success of smart drainage frameworks relies heavily on communication reliability and energy efficiency. A rigorous performance analysis of LoRaWAN under varied spreading factors, power levels, and gateway distances was presented in [8], offering guidelines to minimize latency while maintaining low power consumption. A practical deployment study in [9] validated these theoretical findings, showing that LoRaWAN can achieve stable connectivity across complex urban terrains. Moreover, Garlisi *et al.* [10] demonstrated data driven clustering techniques for LoRa traffic behavior, aiding network optimization in large drainage networks. Solar powered LoRaWAN nodes have also been demonstrated as feasible solutions for real-time water-quality and stormwater monitoring [11, 12].

Cloud integration and data platforms play a vital role in enabling scalable, real-time supervision. Salem *et al.* [7] emphasized the benefits of industrial cloud dash- boards for wastewater monitoring, while Boulouard *et al.* [13] presented a nationwide AIoT framework integrating LoRaWAN and 5G for flood prevention. The open- source dashboard proposed by Pires *et al.* [14] achieves low-latency visualization and long-term stability, making it an ideal match for the real-time monitoring pipeline envisioned in this study.

Sustained outdoor operation further requires energy autonomy and antifouling capability.

The long-term evaluation conducted by Naloufi *et al.* [15] revealed that biofouling and drift remain major issues for low cost sensors in rivers, suggesting that self-cleaning mechanisms can extend operational life. Similarly, the solar-powered LoRa prototypes presented in [11, 12] confirm sustainable operation under intermit- tent sunlight. Collectively, these studies underline the importance of designing energy aware, self maintaining sensor nodes capable of long term operation in harsh drainage environments.

While these studies demonstrate the feasibility of IoT based smart drainage monitoring, most focus on isolated subsystems such as blockage detection, gas sensing, or communication reliability. However, the integration of these elements into a unified, energy autonomous, real time monitoring framework for urban drainage systems remains underexplored. The present study aims to address this gap by proposing a fully integrated IoT-based architecture capable of continuous, intelligent drainage monitoring with enhanced system reliability and scalability.

3 Methodology

The proposed system functions as an integrated and autonomous IoT platform for real time monitoring of urban drainage networks. It combines water level sensing, methane gas detection, blockage identification, and self cleaning capabilities within a compact, solar assisted unit. The architecture integrates sensing, processing, communication, and power modules coordinated by an ESP32-S3 microcontroller. Sensor data are continuously acquired, transmitted through the MQTT protocol, and visualized through a Node-RED dashboard for remote supervision. The system was designed for robustness, scalability, and long-term outdoor operation.

A physical prototype was constructed to simulate real drainage conditions, as shown in Figure 2. The 3 meter long, 30 cm high model was built using modular PVC foam sections joined with corrosion resistant fittings to ensure watertight sealing. Three sides were opaque to reduce light interference, while one transparent glass side enabled visual observation and calibration. The sensor and control unit comprising the ESP32-S3 board, LiDAR sensors, and power components was mounted above the drain for protection and vertical clearance. This modular setup allowed easy transport and maintenance during field simulation.

Fig. 2 System prototype developed for experimental validation.

At the system core, the ESP32-S3 DevKit served as both processing and communication hub, chosen for its dual core 32-bit architecture, 8 MB flash memory, and integrated Wi-Fi/Bluetooth connectivity. Two VL53L0X LiDAR sensors were used for Time of Flight (ToF) distance measurement. One mounted vertically for water- level detection and another horizontally for blockage identification. A TCA9548A I^2C multiplexer enabled parallel sensor communication, while AMS1117 voltage regulators ensured 3.3 V/5 V signal compatibility.

A 1000 mAh lithium ion battery with a TP4056 charging module provided power autonomy. The charging system, connected to a solar panel tilted at 45°, enabled continuous operation under daylight. A blocking diode prevented reverse current flow, and protection circuitry ensured safe charging. Continuous endurance testing validated the design's stability and self-sufficiency for off grid environments.

All electronics were integrated on a custom PCB, as shown in Figure 3, serving as the central interface for sensing and power control. The assembly was enclosed in a waterproof polycarbonate housing with heat vents and silicone seals for environ- mental resilience. A self cleaning mechanism powered by an SG90 servo motor was mounted above the vertical LiDAR sensor to prevent optical fouling. The silicone wiper, triggered automatically every 30 minutes or manually through MQTT, maintained measurement accuracy over prolonged use. The overall system block diagram is shown in Figure 4.

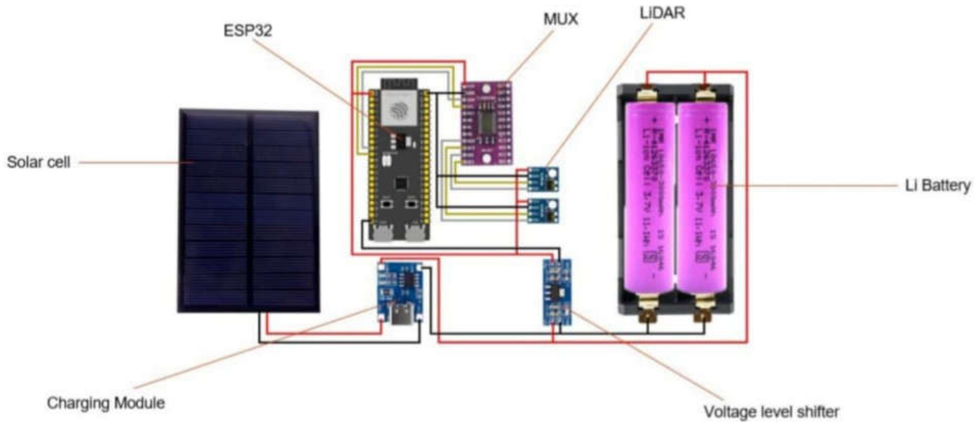

Fig. 3 Custom PCB design for sensor and power integration.

The system's sensing modules were configured for three primary operations: block- age detection, gas detection, and water level monitoring. Blockage detection combined horizontal LiDAR scanning with comparative level analysis between nodes to identify flow restriction events. Gas detection employed MQ4 sensors operating in both digital and analog modes for threshold based and continuous methane monitoring. Water level detection relied on the vertical LiDAR sensor to measure surface distance, with a 10 cm threshold for overflow alerts. Firmware development was performed using the Arduino IDE with an event driven programming model. The LiDAR and gas sensors interfaced through I^2C, while the servo motor was controlled using pulse width modulation (PWM). Wireless data trans- mission was achieved over Wi-Fi through MQTT, and all live readings such as water level, gas concentration, blockage status, and power level were visualized in real time through the Node-RED dashboard. The dashboard also enabled remote control of the cleaning mechanism and system resets.

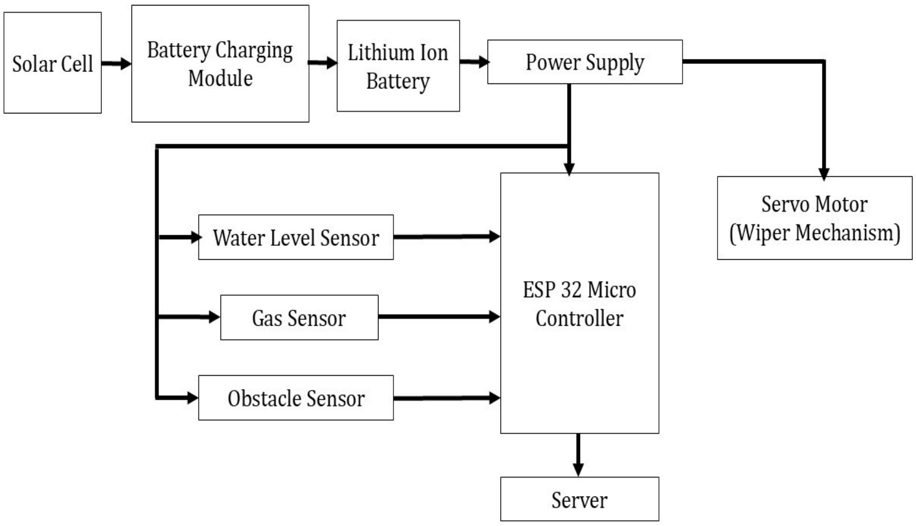

Fig. 4 Overall system block diagram.

Overall, the proposed system presents a compact, energy efficient, and modular design integrating sensing, communication, and power autonomy. The combination of LiDAR and gas sensing with MQTT based real time analytics ensures continuous, low-maintenance operation suitable for smart drainage applications.

4 Experimental Results

The system was evaluated using three monitoring nodes—Node 1, Node 2, and Node 3 and these are installed along the prototype drain. Blockage detection was verified by introducing materials such as sponge, plastic, and cardboard to simulate debris. As shown in Figure 5, the algorithm accurately detected obstructions at Node 1, identifying flow restriction when water levels rose upstream while remaining constant downstream. Alerts were triggered only if the condition persisted for over 10 seconds, effectively minimizing false detections.

Gas detection was validated using MQ4 sensors operating in dual mode. As shown in Figure 6, artificial methane exposure resulted in immediate alert generation through the Node-RED interface, activating both audible and voice warnings. The analog read- ings exhibited smooth transitions corresponding to concentration changes, confirming stable tracking and redundancy between analog and digital channels.

Water level sensing performance, illustrated in Figure 7, showed excellent precision during multiple water addition and drainage cycles. The LiDAR sensors maintained accuracy within ±5 mm of manual readings and generated MQTT alerts upon exceed- ing the 10 cm threshold. Measurements remained consistent even under varying light and humidity conditions, validating their robustness for outdoor operation.

Fig. 5 Obstacle (blockage) detection at Node 1.

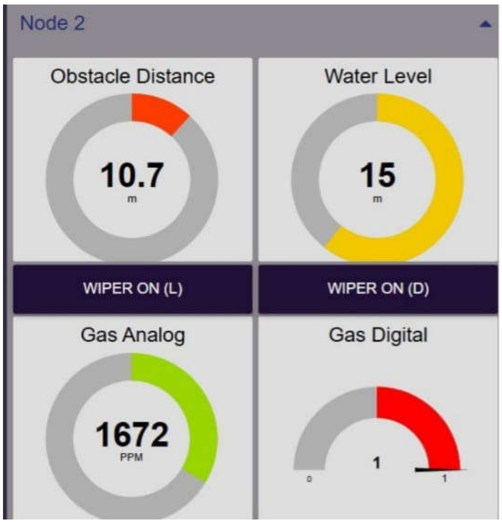

Fig. 6 Methane gas detection at Node 2.

Data transmission over Wi-Fi via MQTT remained stable, with zero packet loss and dashboard update latency within 0.5–1 seconds. This low latency communication ensured timely alerts for critical events while maintaining scalability for additional sensor nodes. The overall system dashboard is shown in Figure 8. The energy subsystem which is shown in Figure 9, maintained reliable performance throughout testing. The 1000 mAh battery sustained operation across day night cycles, while the solar panel replenished the charge within 4–5 hours of sunlight. Even under partial cloud cover, voltage levels remained above 3.7 V, enabling continuous off grid operation for over 30 hours.

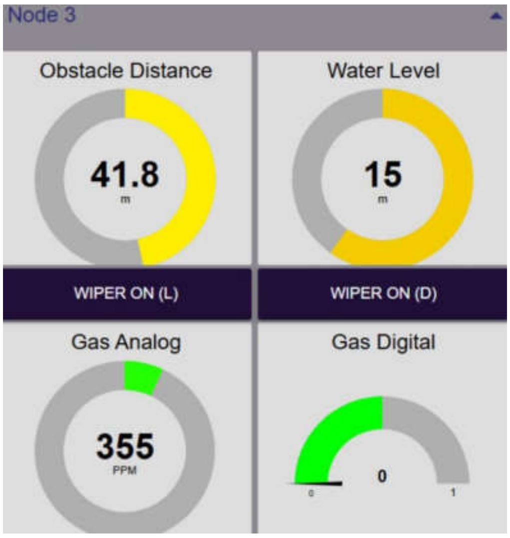

Fig. 7 Water-level detection at Node 3.

Fig. 8 System dashboard for real-time visualization.

The self cleaning wiper, shown in Figure 10, proved highly effective in restoring sensor accuracy after fogging or droplet accumulation. The SG90 servo motor showed no mechanical wear over extended testing, validating its durability and ensuring minimal manual maintenance.

Continuous data logging was implemented for all monitored parameters, including water level, gas concentration, blockage status, and battery voltage. Each record was time-stamped and stored in InfluxDB for further analysis. As shown in Figure 11, the data logs confirmed reliable system behavior and accurate trend correlation between drainage flow, gas concentration, and power performance.

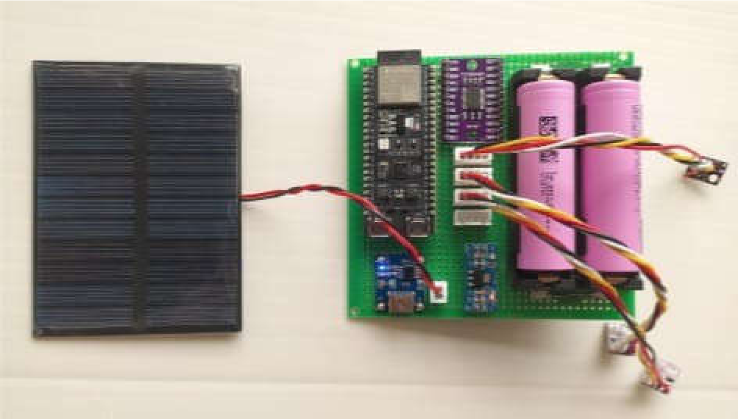

Fig. 9 Charging unit with solar input and TP4056 module.

Fig. 10 Self-driven wiper mechanism for LiDAR lens cleaning.

Overall, the experimental evaluation verified the system's ability to detect block- ages, monitor methane concentration, and measure water levels with high precision and responsiveness. The energy module ensured sustained autonomy, and the self cleaning feature maintained consistent sensor accuracy. Minor limitations were observed under murky water conditions and shaded solar environments, which can be mitigated through hybrid energy sources or enhanced optical calibration. The compact, low cost, and scalable design demonstrates strong potential for deployment in smart drainage and flood management systems.

Date	Time	Sensor Type	Node1	Node2	Node3
02-03-2025	21:31:02	Obstacle Distance	56	60	46
02-03-2025	21:31:02	Water Level	200	200	7
02-03-2025	21:31:02	Gas Analog	39	11	0
02-03-2025	21:31:02	Gas Digital	0	0	0

Date	Time	Sensor Type	Node1	Node2	Node3
02-03-2025	21:31:02	Obstacle Distance	56	60	46
02-03-2025	21:31:02	Water Level	200	200	7
02-03-2025	21:31:02	Gas Analog	41	11	0
02-03-2025	21:31:02	Gas Digital	0	0	0

Date	Time	Sensor Type	Node1	Node2	Node3
02-03-2025	21:31:02	Obstacle Distance	56	60	46
02-03-2025	21:31:02	Water Level	200	200	7
02-03-2025	21:31:02	Gas Analog	41	11	0
02-03-2025	21:31:02	Gas Digital	0	0	0

Date	Time	Sensor Type	Node1	Node2	Node3
02-03-2025	21:31:02	Obstacle Distance	57	60	46
02-03-2025	21:31:02	Water Level	200	200	8
02-03-2025	21:31:02	Gas Analog	41	13	0
02-03-2025	21:31:02	Gas Digital	0	0	0

Date	Time	Sensor Type	Node1	Node2	Node3
02-03-2025	21:31:02	Obstacle Distance	56	60	46
02-03-2025	21:31:02	Water Level	200	200	7
02-03-2025	21:31:02	Gas Analog	39	11	0
02-03-2025	21:31:02	Gas Digital	0	0	0

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02-03-2025	21:31:02	Gas Analog	39	11	0
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02-03-2025	21:31:02	Gas Analog	41	13	0
02-03-2025	21:31:02	Gas Digital	0	0	0

Fig. 11 Sample of recorded data log.

5 Conclusion and Future Scope

The proposed system presents a compact and autonomous IoT based framework for real time drainage monitoring and blockage detection using LiDAR and gas sensing technologies. The prototype effectively detects water level rise, blockages, and methane gas accumulation while maintaining energy autonomy through solar power and long term reliability via a self cleaning mechanism. Experimental validation confirmed high accuracy, low latency communication using MQTT, and uninterrupted performance, demonstrating the system's suitability for deployment in resource constrained or disaster prone regions.

Future enhancements can focus on integrating AI-driven predictive analytics to enable proactive maintenance based on learned drainage patterns. Expanding communication options to include GSM or LoRaWAN would enhance scalability in remote areas, while mobile app integration could support real time user notifications and geotagged reporting. The addition of sensors for turbidity, flow rate, and pH would enrich environmental assessment, and coupling with GIS-based cloud analytics could facilitate large scale visualization and flood prediction. With its modular and scalable architecture, the system provides a strong foundation for next generation smart urban drainage infrastructure.

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