FUPRE Journal

of

Scientific and Industrial Research

ISSN: 2579-1184(Print) ISSN: 2578-1129 (Online)

http://fupre.edu.ng/journal

Monitoring of Crude Oil Pipeline Using Long-Range Network

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ARTICLE INFO

Received: 21/05/2025
Accepted: 24/07/2025

Keywords

IoT,
Leak Detection,
LoRa Network,
Pipline Monitoring,
Pressure Sensing,
Remote Monitoring,
Long-Range Communication

ABSTRACT

This study presents a crude oil pipeline monitoring system using Long Range (LoRa) networks in Internet of Things (IoT)-based technology. Pipeline leakages, caused by aging pipes, rusting, and vandalism, remain a major challenge in crude oil distribution. While existing IoT-based solutions use short-range technologies like Bluetooth, WiFi, and ZigBee for real-time monitoring, they struggle with long-distance communication in remote areas with poor network coverage. This study applies LoRa technology to transmit leakage data over long distances to a remote monitoring point. An experimental testbed was designed to simulate pipeline scenarios, using pressure readings to detect leaks. Results showed that in 9 seconds, leak pressure at point 1 (P1) near the supply rose from 0 Psi to 11.74 Psi, while pressures at P2 (0.325m from P1) and P3 (0.55m from P2) increased to 10.48 Psi and 9.79 Psi, respectively. This indicates that leak pressures build up more near the supply source, and increasing the leak opening results in higher pressure loss. The findings highlight the effectiveness of LoRa-based IoT systems for real-time, long-range pipeline monitoring and early leak detection.

1. INTRODUCTION

In modern society, the safety and security of pipelines are considered one of the most crucial requirements, especially with advancements in digital information, automatic process control, system technology, and the increasing rate of criminal activities. Surveillance and wireless communication can be applied to effectively monitor daily activities to improve pipeline security and avert the consequences of pipeline vandalization.

The process of monitoring pipelines is very hectic, requiring extensive man-hour labor and intensive work. It involves traveling miles in difficult terrains to inspect these pipelines. Without technological advancements, manual pipeline monitoring presents many challenges due to the burdens experienced by pipeline managers and security personnel, whose primary purpose is to guard pipelines against vandals. Nigeria's Oil and Gas industry accounts for about 35% of the country's Gross Domestic Product (GDP), with an average of over 2 million barrels exported per day. Petroleum export revenue represents over 90% of Nigeria's total export revenue (OPEC, 2017). However, the unscrupulous operations of vandals, such as crude oil thieves and militant invasions, pose the biggest threat to the security of crude oil pipelines, resulting in a decline in Nigeria's crude oil export rate from 2 million

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barrels per day to 1.5 million barrels per day (Kachikwu, 2016).

Long Range (LoRa) communication is a vast modulation of spread spectrum technique that has been discovered from Chirp Spread Spectrum (CSS) technology. LoRa is an emerging Low Power Wide Area Network (LPWAN) technology that is particularly useful for transmitting data over long distances. Devices based on LoRa and other technologies, such as wireless radio frequency, are all wireless platforms with low power that support Internet-of-Things (IoT) platforms. LoRa devices have revolutionized IoT by enabling data communication over a long range while using little power. When connected to a non-cellular long-range Wide Area Network (WAN), LoRa devices accommodate a vast range of IoT applications by transmitting packets of data with important information.

This study aims to develop a crude oil pipeline monitoring system using a long-range wireless network. The specific objectives include evaluating existing crude oil pipeline monitoring systems, designing a system capable of remote monitoring using a long-range network, building a prototype of the system, and evaluating its performance. Most short-range wireless systems suffer from challenges such as non-distinctiveness, noisy input, and non-universality. The inclusion of a long-range network in pipeline monitoring offers several advantages. It helps to overcome the limitations of short-range transmission, increases accuracy by combining multiple detection methods, and reduces errors resulting from sensor noise. Additionally, using more than one sensor minimizes the risk of inaccuracies, and the potential for fraud, such as cloning or tampering, is significantly reduced.

Crude oil is one of the most valuable natural resources available to man today. Despite its usefulness, crude oil spillage has become a significant menace. When spillage occurs in pipelines, it has serious negative socio-economic impacts, including water pollution, soil pollution, ecosystem degradation, health hazards, and revenue loss. Spillage can result from vandalization or the natural breakdown of pipelines due to aging, corrosion, wear and tear, extreme weather conditions, and other environmental factors (Johnson et al., 2022), leading to pressure drops.

Over the years, crude methods have been employed for leak detection, involving maintenance personnel who periodically monitor the pipelines (Febaide and Uzedhe, 2021). This method has significant lapses due to direct human involvement, leading to slow response times in the event of leakage. Hence, there is a need for remote pipeline monitoring to enable real-time data collection on pipeline conditions and prevent leakages. This study focuses on developing a pipeline monitoring system that utilises a long-range network to obtain pipeline pressure parameters and detect leakage through pressure loss. By leveraging IoT and LoRa technology, this system aims to improve pipeline surveillance, reduce environmental hazards, and enhance the efficiency of crude oil transportation.

Pipelines remain a primary means of transporting large volumes of fluids over long distances, making leak detection critical due to economic losses and environmental hazards (Ostfeld et al., 2008). Various studies have explored different technologies for pipeline monitoring, focusing on automation, real-time detection, and IoT integration.

1.1 Automated Pipeline Monitoring Systems

Several researchers have developed automated systems for pipeline monitoring. Ofualagba and Ejofodomi (2020) designed an oil and gas pipeline vandalism detection system using geophones, Arduino Mega boards, and GSM/GPRS modules to detect seismic activities like digging and drilling. However, this system relies on a GSM network, which may be unreliable in remote areas. Shoewu et al. (2013) proposed a microcontroller-based alarm system using pressure and PIR motion sensors. While effective in detecting vandalism, it lacks real-time remote monitoring capabilities. Similarly, Ononiwu et al. (2014) developed an acoustic-based intrusion detection system, but signal delays over long distances remain a challenge.

1.2 IoT-Based Pipeline Monitoring

Anyanwu et al. (2018) developed an IoT-based crude oil pipeline monitoring system capable of transmitting real-time data every 20 seconds. However, its reliance on stable internet connectivity poses a limitation. Obodoeze et al. (2014) proposed an electronic surveillance system using PIR sensors and video monitoring, but its inability to differentiate between humans and animals leads to false alarms. Igbajar and Barikpoa (2015) introduced a GSM-based monitoring system with an alarm and SMS alerts, yet its lack of internet connectivity restricts remote access.

1.3 Wireless Sensor Networks and LPWAN Applications

Recent advancements in wireless sensor networks (WSNs) have improved pipeline monitoring. BenSaleh et al. (2013) utilized acoustic sensor nodes for underwater pipeline monitoring, though challenges like high propagation delay and limited battery life persist. Maglaras and Katsaros (2012) highlighted the role of WSNs in detecting leaks, dependent on fluid type and pipeline location. Raza et al. (2017) and Ahlers et al. (2016) explored Low-Power Wide-Area Networks (LPWANs) for IoT applications, emphasizing their cost-effectiveness and long-range capabilities. Chavala et al. (2022) evaluated LoRa-based sensor nodes for oil pipeline monitoring, demonstrating their efficiency in long-distance communication with low power consumption.

1.4 Hybrid and Multi-Sensor Approaches

Several studies have integrated multiple technologies to enhance monitoring. Rajesh et al. (2021) proposed a hybrid system combining Zigbee and LoRa for real-time oil pipeline surveillance, while Ayeni and Ayogu (2020) suggested an IoT-based system incorporating SCADA for real-time detection and control. Aliyu et al. (2017) implemented a multi-sensor system using motion, vibration, and sound detection to monitor pipelines, but reliance on GSM networks may hinder effectiveness in areas with poor connectivity.

1.5 LoRa Technology for Pipeline Monitoring

LoRa technology has gained attention for its long-range, low-power transmission capabilities. Petajajarvi (2015) assessed LoRa coverage, demonstrating effective communication over 30 km in water and 15 km on land. Bor et al. (2016) studied the scalability of LoRa networks in smart cities, while Ernesto et al. (2020) applied LoRa sensors for air quality and gas leakage detection, highlighting its potential for pipeline monitoring.

Despite advancements in pipeline monitoring, challenges such as network instability, high power consumption, and detection inefficiencies remain. This study proposes an IoT-enabled crude oil pipeline monitoring system leveraging LoRa technology for continuous data transmission to a web-based interface while providing SMS alerts in case of pressure drops. By integrating IoT with LPWAN, this system aims to enhance real-time monitoring, improve efficiency, and reduce the risks of vandalism and leaks.

2. MATERIALS AND METHOD

2.1 Materials

The design and implementation of this work involved the use of some basic sets of electronic components;

i. Diode,
ii. Capacitors,
iii. Voltage Regulator,
iv. Resistor,
v. Crystal Oscillator,
vi. Bipolar Junction Transistor (BJT),

vii. Flow pressure sensor,
viii. Atmega328pu Microcontroller,
ix. LONG RANGE network module,
x. Liquid crystal display module,
xi. Optocoupler
xii. RTC timer DS1307

2.2 Method

This study develops a crude oil pipeline monitoring system using a Long Range (LoRa) network. The system comprises several key units as depicted in Figure 3.1.

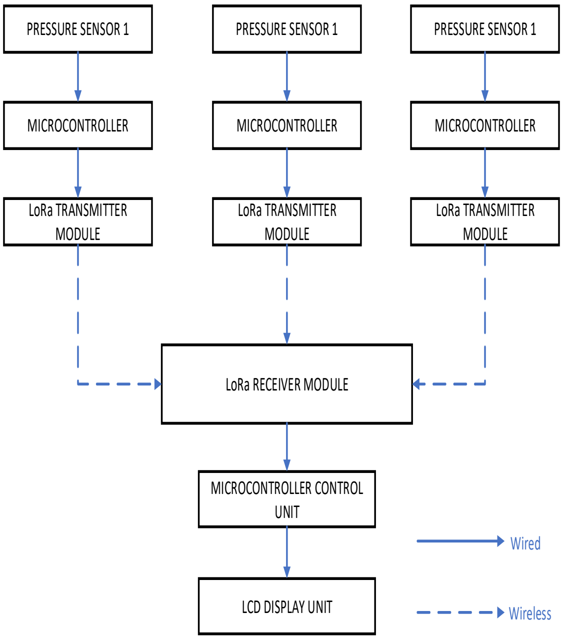

Figure 1: Block diagram of the pipeline monitoring system

3.2.1 Power supply unit

The system is powered by a 12V battery, which supplies voltage to different components. A DC-DC converter regulates the voltage to 3.3V for the LoRa network modules and 5V for the microcontroller. The power system includes ripple filter capacitors and an LM317T adjustable voltage regulator to ensure stable operation.

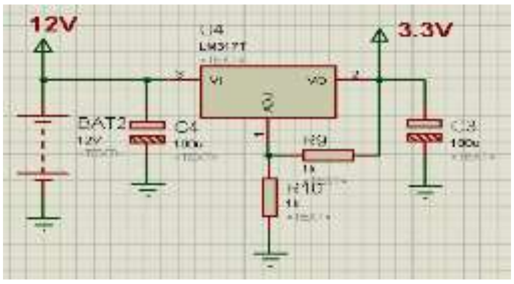

Figure 2: Power supply unit for the pressure sensor and LORA network module

2.2.2 Pressure sensing unit

The pressure sensing unit consists of YF-S401-3/4 inch flow pressure sensors, which detect pressure variations in the pipeline. These sensors operate within a pressure range of 0–200 psi and transmit readings to the microcontroller. Pressure changes indicate potential pipeline leaks or failures, prompting real-time alerts.

2.2.3 Processing and Control Unit

The ATMEGA328 microcontroller processes incoming sensor data and transmits relevant signals to the communication unit. It has 28 pins, 6 analog inputs, 13 digital I/O pins, and operates at 20 MHz with 512 Bytes of EEPROM and SRAM. The microcontroller converts analog pressure signals into digital data for efficient transmission.

2.2.4 Display Unit

A 16×2 Liquid Crystal Display (LCD) is integrated into the system to provide real-time monitoring. It operates on 5V power and uses data pins DB0–DB7 for interfacing with the microcontroller. The display updates system status, including pipeline pressure and detected anomalies.

3.2.5 Communication Unit

The LoRa-based communication unit employs SX1278 LoRa modules operating at 433 MHz, capable of transmitting data up to 10 km. Pressure sensors are strategically positioned along the pipeline, each assigned a unique address. The 8-bit microcontroller schedules data transmission to ensure accurate monitoring. LoRa receivers capture the transmitted data, process it, and display it on the LCD.

2.2.6 Circuit Design

The circuit consists of three pressure sensors, microcontrollers, LoRa transmitters, and a 5V power unit. Pressure sensors are placed at specific intervals along the pipeline and connected via wired cables

Figure 4: 3D view of field pipeline monitoring system using LoRa network

to the microcontroller. When a pressure drop occurs, the system detects it, converts the signal to digital format, and transmits the data wirelessly. The receiver station processes the information and displays real-time alerts.

2.2.7 Software Design

The system software follows a structured algorithm for data acquisition, processing, and transmission. A flowchart outlines core instructions executed by the microcontroller and LoRa network. The program ensures sequential execution of tasks, allowing smooth coordination between sensing, control, and communication units.

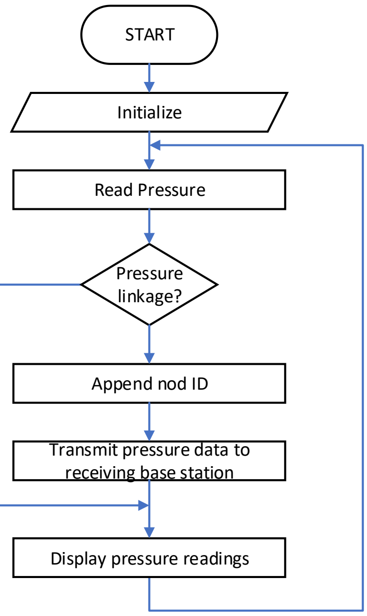

Figure 3: Flow chart of pipeline monitoring system using LoRa network

2.2.8 Mechanical Design

An experimental prototype was designed using AutoCAD 2010. The setup includes a 100-inch-long wooden platform supporting a PVC ½-inch pipeline. The pipeline connects a pump discharge line to a receiving tank, simulating crude oil flow. Three pressure sensors are installed at specific intervals to monitor pressure variations. A control station with an LCD display receives alerts via the LoRa network, allowing authorized personnel to monitor pipeline conditions.

This system enhances pipeline security by enabling remote, real-time monitoring, reducing manual inspections, and improving response times to potential leaks or vandalism.

2.3 implementation, testing, and results

4.1 *Implementation*

4.1.1 Simulation Stage

The program for the ATMEGA328PU microcontroller was written in C and compiled using the Arduino compiler. It was then simulated using Proteus 8.0, a circuit simulation and virtual system modeling software. This simulation allowed for testing the system's logic and functionality before hardware implementation. Proteus includes digital input/output components and circuit design tools, enabling visualization of how the system would function in real-world applications.

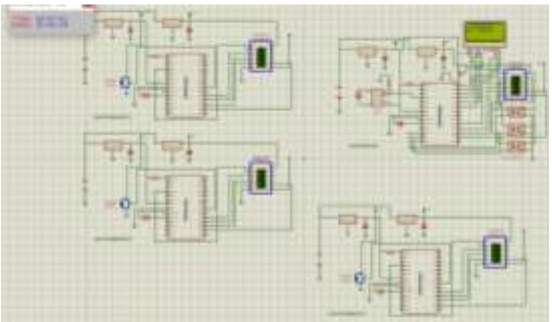

Figure 5: System Simulation on Proteus

3.1.2 Breadboard Testing

After completing the simulation, the design was transferred to a breadboard to identify potential real-life circuit challenges that may not have been apparent during the simulation phase. The breadboarding phase helped refine the design and troubleshoot any electrical connectivity issues before proceeding with the final hardware assembly.

3.1.3 Vero Board Construction

Following successful breadboard testing, the circuit was assembled on a Vero board, which provides a structured layout for electronic components. The Vero board consists of a grid of holes with copper tracks running in one direction. Each component was carefully positioned, and its leads were soldered to the copper tracks using a soldering iron and lead. A continuity test was conducted after soldering to ensure all connections were properly established.

Figure 6: Vero board construction of the system

Figure 7: Setup of the pipeline monitoring system

3.2 Fabricated System

The final system was enclosed in a plastic casing to protect its components. The casing was made of white plastic due to its high resistance to corrosion, lightweight nature, and insulating properties. The enclosure measured 225mm × 150mm × 60mm with a thickness of 3mm. The power supply, microcontroller, and LoRa modules were housed within this enclosure, while the flow pressure sensor was connected externally using a 7-meter-long flexible cable. The power switch and battery pack were positioned on top of the casing for easy access.

The experimental setup included a pipeline platform with three sensors and designated leak simulation points. This system configuration ensured that the sensors could effectively detect pressure variations along the pipeline and transmit data to the receiver module.

The receiver unit was also fabricated and packaged to display real-time pressure data. This unit serves as the monitoring interface, allowing operators to view system status and take appropriate actions.

4.3 Testing

The system was tested in sections before being integrated into a complete monitoring solution.

Power Supply Testing: The power supply unit was tested to verify that it produced the required voltage levels.

Continuity Testing: A multimeter was used to check the connectivity of circuit joints to ensure there were no open circuits.

Flow Pressure Sensor Testing: The pressure sensor was tested using the Arduino IDE serial monitor, which displayed real-time pressure readings in PSI.

System Integration Testing: The entire system was tested using an experimental pipeline setup. The predetermined pressure levels were programmed into the system, and artificial leaks were simulated by opening valves at different points.

4.4 Results and Discussion

4.4.1 Results

Table 4.1: Node 1, 3 days average pressure readings (Psi) against time in (seconds)

T1 (Sec)	1	3s	5s	7s	9s
P1 (PSI)	0	5.46	7.68	9.62	11.74

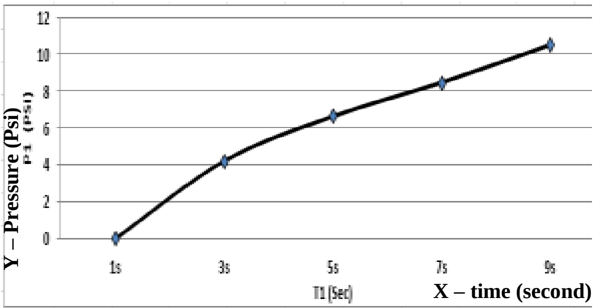

Figure 8: Node 1, pressure readings for leaks against time

Table 4.2 : Node 2, 3 days average pressure readings (Psi) against time in (seconds)

T2 (Sec)	1s	3s	5s	7s	9s
P2 (PSI)	0	4.2	6.62	8.45	10.48

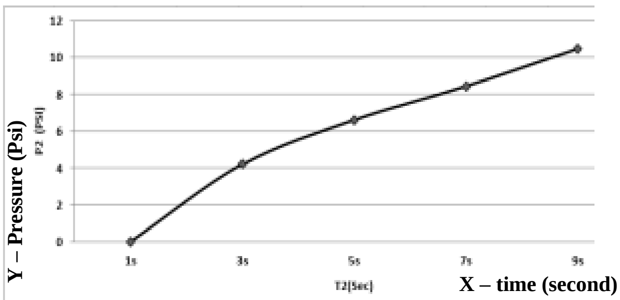

Figure 9: Node 2, pressure readings for leaks against time

Table 4.3: Node 3, 3 days average pressure readings (Psi) against time in (seconds)

T3 (Sec)	1	3s	5s	7s	9s
P3 (PSI)	0	3.63	6.37	7.81	9.79

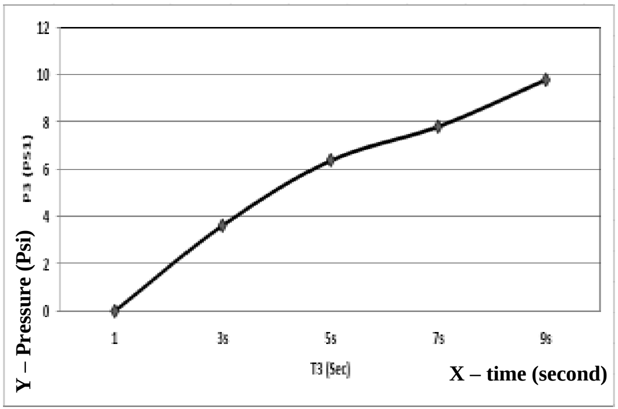

Figure 10: Node 3, pressure readings for leaks against time

4.2 Discussion

The results obtained from the testing phase demonstrate the effectiveness of the pipeline monitoring system in detecting leaks based on pressure variations. The system successfully measured real-time pressure values at different sensor nodes and transmitted the data wirelessly to a remote monitoring station. Observations from the results indicate a strong correlation between pressure drops and leak occurrences, confirming the system's reliability in detecting and reporting pipeline leaks.

At system startup, all pressure readings were 0.00 psi, indicating that the sensors were properly calibrated. When leaks were simulated by opening designated leak taps at different positions along the pipeline, the corresponding sensors detected an immediate drop in pressure. The pressure values were recorded at different time intervals to observe how leaks affected the pipeline pressure over time.

The results showed that the pressure readings varied depending on the sensor's position along the pipeline. The sensor closest to the pump (P1) consistently recorded higher pressure values than the sensors further downstream (P2 and P3). This can be attributed to the pressure distribution along the pipeline, where pressure naturally decreases as the distance from the pump increases. Consequently, leaks at P1 resulted in a greater initial pressure drop compared to P2 and P3, confirming that sensor placement plays a crucial role in leak detection accuracy.

A key observation was that as the leak tap was progressively opened, the pressure loss at each sensor node increased proportionally. This indicates that small leaks may initially cause minor pressure losses, but as the leakage point widens, the pressure drop becomes more significant. This reinforces the importance of early leak detection, as unaddressed leaks can lead to severe pressure losses, increased fluid wastage, and potential pipeline failures.

The pressure data recorded over three days showed a consistent pattern of pressure loss when leaks were introduced. The measurements taken at 3 seconds, 5 seconds, 7 seconds, and 9 seconds after opening the leak taps revealed that the system was able to detect and report pressure drops in real time. This confirms the responsiveness of the pressure sensors and the reliability of the data transmission system.

The LoRa-based wireless communication module effectively transmitted pressure data from the sensor nodes to the base station without significant data loss or transmission delays. This demonstrates that the system is capable of remote pipeline monitoring, allowing operators to receive real-time leak alerts and take immediate corrective actions. The stability of the wireless communication is crucial for large-scale applications, where monitoring pipelines over long distances is necessary.

From the recorded data, it was observed that the leakage pressure reading at P1 was slightly higher than P2, and P2 was slightly higher than P3. This trend confirms that pressure loss occurs progressively along the pipeline, with the most significant pressure drop occurring at the farthest sensor node. Additionally, the pressure values stabilized after each leak simulation, indicating that the system effectively captured pressure fluctuations and returned to a steady state after the leaks were controlled.

In all, the results validate the effectiveness of the developed pipeline monitoring system. The ability to detect pressure losses in real time and transmit the data wirelessly makes this system a reliable tool for pipeline leak detection. The findings highlight the importance of continuous pipeline monitoring, as early detection of leaks can prevent potential environmental hazards, reduce maintenance costs, and improve operational efficiency.

5. CONCLUSION

5.1 Conclusion

This study explored the development of an IoT-based remote pipeline monitoring system utilizing the LoRa network for real-time leak detection. A comprehensive review of existing crude oil pipeline monitoring technologies informed the system's design, leading to the development of a prototype for experimental evaluation. The results demonstrated that pipeline leaks could be effectively detected and localized through pressure loss measurements. Furthermore, the study highlighted the importance of integrating intelligent monitoring capabilities and long-range, unlicensed network connectivity for efficient pipeline surveillance. Given that crude oil pipelines often traverse remote areas with limited or no cellular network coverage, the implementation of a LoRa-based monitoring system offers a practical solution for seamless and continuous leak detection. This innovation has the potential to significantly improve pipeline management by reducing response times, preventing environmental hazards, and minimizing economic losses.

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