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Development of internet of things-based petroleum pipeline topology leak monitoring and detection system using sensors

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Abstract

Transportation of crude oil by pipelines is the safest mode of oil transportation. In Nigeria, over 90% of oil transported by federally regulated pipelines arrives safely every year. The flow starts from oil fields to flow stations to refineries and export tankers and finally, from refineries to depots. Notably, the transportation of oil by pipeline suffers challenges. The challenges range from natural disasters to attacks and activities carried out by vandals. These activities pose a serious threat to Flora and Fauna and have caused devastating effects on the environment, with remarkable destruction of vegetation cover, water bodies, and arable land. In this study, an Internet of Things (IoT)-Based Petroleum Pipeline Topology Leak Detection and Monitoring System (IoT-BPTLDMS) that is capable of monitoring, detecting, and reporting pipeline topology leakage and reports same to the control room before it graduates to spillage has been developed. This was done by strategically mounting pressure-change detecting sensors along the pipelines which are capable of detecting leakages through changes in fluid pressure and results transmitted with the aid of a Long-Range Wireless Area Network (LoRaWAN) module. The transmitted data captures the date, time, event, and geo-location of the leak site. This data is received in a computer and an Android phone. A prototype was used to study the setup's workings. The prototype controller was programmed using C++ with the Arduino Integrated Development Environment (IDE). The Android Application was assembled with Basic4Andriod. The captured result shows consistency with the area of leakage against the geo-location reported. This shows that this method would be effective in checking and detecting petroleum pipeline leakage, and as such, can solve the problem of quick response to pipeline vandalisation and oil spillage in Nigeria or generally.

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1. Introduction

The importance of crude oil to every economy is a "burning issue" and has always taken the lead in several country's economic fora. In many developing countries like Nigeria where crude oil is the major source of national revenue generation, the price of crude oil determines the yearly appropriation bill as their budget is prepared based on how much the price of a barrel of crude oil is pegged at, by the organisation of oil-producing countries (OPEC)[1, 2].

The global practice for transportation of crude oil and its by-products such as dual purpose kerosene (DPK), automotive gas oil (AGO) and premium motor spirit (PMS) [3] from oil fields

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to production plants is through pipeline transportation [4], this is because, for many decades, pipelines have proven to be a reliable and safe means of fluid transportation [5]. The safety of oil and gas products transportation through pipelines was affirmed in a research conducted by *Cramer et al*. [6]. In their review, they assessed deaths emerging from mishaps per ton-mile of transported oil and gas products to be 87 percent for trucks, 4 percent for ships, and 2.7 percent for rail, contrasted with utilising pipelines.

An oil pipeline is a pipe usually with a large diameter that transports crude oil from the oil drilling fields to the refineries and other facilities. In Nigeria, oil giants such as Nigerian National Petroleum Corporation (NNPC), Shell British Petroleum, Mobil, Texaco, Chevron, AGIP and more, own large expanse of pipelines topologies that transport crude oil and gas from the various oil fields in the creeks to substations and other oil infrastructure.

Oil pipelines are constructed using alloy and steel materials. Because these materials are subjected to harsh environmental conditions all through their lifetime during operation, they tend to develop some classic defects that will graduate into leakages if not discovered in good time. These defects may range from wear and tear of the materials as a result of "force of majeure"; that is, natural environmental conditions such as fatigue cracks, age [5], stress corrosion, hydrogen indexing, and materials manufacturing defects, to man-made activities (vandalization), which can be classified as external influences.

For many decades, petroleum-producing nations have taken concerted steps in combating petroleum products-related crimes. In Nigeria for instance, despite these efforts by the national security and joint task forces set up by successive governments to combat the menace, there has not been a permanent solution to this problem. The menace has turned the beautiful mangrove swamp landscape of the oil-rich Niger Delta region into a battle zone [6]. Pipelines are deliberately vandalised by perpetrators using heavy explosives materials. Security agents deployed to safeguard oil installations are being killed by criminals, oil workers are often abducted and huge ransoms are paid by oil companies to secure their release.

The transportation of crude oil is a sensitive business that has critical, time-consuming, and challenging operations. As a rule of thumb, the medium of transport (pipeline) requires frequent maintenance and monitoring of both its external and internal conditions. This maintenance and monitoring are very expensive and form part of national planning policies in several economies in the world. The reason for continued maintenance and monitoring is to prevent disaster and huge losses that may occur because pipeline leakages can cause colossal damage to aquatic lives in water and the vegetation cover of our environment which has an over-bearing influence in our daily lives [7, 8].

With specific reference to the very nature of a pipeline, there exists a complication in the underlying internal and external processes. As indicated in the preceding paragraph, there also exists, a colossal negative corollary of not knowing, what is exactly or approximately going on inside the pipeline. For this reason, the aim of energy companies to intensify the efficiency and safety of gas pipelines has been pushing the metallurgical companies to manufacture high-quality pipes [9] that can withstand high temperatures and pressures produced by hydrocarbon products and ensure safety.

In contemporary times, there are several methods used in monitoring pipeline conditions. These methods have evolved from manual and analog systems to modern smart intelligent systems and sensors, which have capabilities for capturing data right from inside the pipelines, cataloging, storing, and transmitting the same to remote web servers. These methods can be broadly categorised, drawing parameters from their operational sites and characteristics usage conditions, as (1) continuous and (2) non-continuous techniques [10]. Technologies such as helicopter (laser, infrared camera, and leak sniffer) monitoring, smart pigging, and tracking dogs, are classified as non-continuous. Continuous can further be classified into external (direct) and internal (inferential) [11]. Systems such as fiber optics sensing, acoustic emission systems, liquid sensing, vapour sensing, sensor hoses, and video monitoring are classified as external monitoring. Accelerometer, vapour sampling, infrared thermography, ground penetration, florescence, electromechanical impedance, and capacitive sensing are classified as external pipeline monitoring systems [4], while technologies such as pressure point analysis (rarefaction wave monitoring), mass balance method, negative pressure, digital signal, dynamic modeling, state estimators, statistical systems, real-time transient model (RTTM) based systems, ultrasonic, intelligent pigging, extended real-time transient model (E-RTTM) based systems are classified as internal monitoring technologies [12]. Others such as magnetic flux leakage [13], eddy current testing [14]; ultrasonic testing [15] and electrostatic acoustic transducers [16] are also common internal pipe wall diagnostic technologies [17].

We can also categorise the techniques into destructive and non-destructive [18]. Techniques such as hydrostatic testing, pigs, etc. [17], are classified as destructive techniques while techniques such as computed tomography (CT) scanner [19], magnetic flux leakage testing [13], eddy current testing [20], electromagnetic acoustic transducers [16], etc., are termed non-destructive techniques [21]. Other non-destructive techniques are wireless underground sensor networks (WUSNs), wireless sensor networks (WSNs), [22, 23], and non-linear wireless sensor networks [24]. Remote sensing systems that employ a multiplicity of machine learning and deep learning algorithms [25] have provided exceptional prospects for timely oil spill monitoring and detection, which has proven to be stress-free, swift, and inexpensive. These algorithms acquire data from remote systems and use the data to extract valuable features that can suggest the presence of an oil spill. A classic example is the Polarimetric Synthetic Aperture Radar (PolSAR) which has shown data with distinctive capabilities and revealing features for large-scale oil spill detection.

Bui et al. [26] and Sarker [27] have also listed a couple of machine learning algorithms that can be deployed in several fields, including prediction, monitoring, and detection of oil spills. Some of the algorithms are Random Forest (RF), Stochastic gradient descent (SGD), Adaptive Boosting (AdaBoost), Rule-based classification algorithms, Naïve Bayesian algorithm, Linear discriminant analysis, K-means, Gaussian mixture model, Hidden Markov model, and Principal components analysis [27]. Others include Support vector machines, [28] K-Nearest Neighbours (KNN) algorithm, Self-Organizing Maps (SOM), Convolutional Neural Networks (CNN) and Decision trees [29].

The solution to this apparent eternal problem is the Internet of Things (IoT), a phenomenon that can make "things" think and act rationally with little or no human interference [30]. It has been applied in different fields of study and has recorded successful implementation results in pipeline monitoring [31], smart city development [32], transportation [33], health [34], and e-Learning platforms [35]. IoT connects devices and cloud databases for the purpose of sharing data and devices. While data travels through different IoT gateways, it can be sniffed [36, 37] by cyberpunks and made vulnerable to attacks and misuse by unauthorised persons.

2. Literature review

In consideration of what pipelines are and the economic value of the content they transport from oil fields to production plants, there is an eminent need and every reason for them to be monitored, safeguarded, and protected. Currently, what Nigeria is doing in the oil and gas transportation sector is inspection of pipelines and not pipeline monitoring; We make this avowal because pipeline inspection requires periodic checks to measure for changes or aberrations to the expected results, while pipeline monitoring involves constantly or persistently taking a look at the pipeline with the goal of responding quickly to adjustments that might happen either inside or outside the pipeline. These alterations may be caused by factors such as corrosion, vandalism, etc., [38].

In Nigeria, pipelines are assets and the government put in huge manpower to monitor and secure them. If this manpower is converted and quantified in monetary terms, it is worth billions of naira. In developed nations, a myriad of techniques have been deployed to monitor pipelines. These techniques combine two components: the component that is responsible for actually detecting the leakage which can be implemented using different sensor technologies and the component that is responsible for communicating the detection which can be implemented using GPS, GPRS, SMS, Bluetooth, Infrared, Wifi with very high quality of service (QoS) [39, 40], LoRaWAN, etc.

2.1. Review of related works

Oh *et al* [41] developed a method to monitor and discover the development and progression of faults, using a magnetostrictive guided wave technique. To confirm the efficiency of their method, signals from genuine pipeline joins that have classic defects were acquired and manipulated using the phase matching and deduction program. In contrast with the regular piezoelectric framework, their technique shows a higher skill for checking and finding defects in pipelines.

Acosta *et al*. [42] developed an energy-efficient link-level routing algorithm that offers end-to-end dependability in multi-hop wireless sensor networks with a linear structure. Their algorithm employs implicit acknowledgment to offer dependability and connectivity with low delay, low energy consumption and fault tolerance in linear wireless sensor networks. They modelled and analysed their energy consumption and latency and their system was tested and validated using real hardware. When compared to other research that adopts the explicit knowledge technique and routing protocols, it was revealed that their algorithm is energy efficient and has low latency with explicit confirmations, maintaining the same characteristics in terms of reliability and connectivity.

Lawand *et al*. [43] developed a system that addresses the problem of sensing and computing corrosivity of existing unprotected application locations. Their system consists of a sensing array made of an assembly of tinny strips of pipeline steel and a circuit that offers a visual sensor reading to the operator. They proposed a passive sensor based on cordless energy transmission that does not need a continuous power supply. Their circuit design was authenticated using laboratory experimentations and classic simulations. However, their system did not clearly show a specific method of conveying signals generated by the sensors and how the signals are routed to the base station.

Okorodudu *et al*. [44] presented a monitoring system for petroleum pipeline spillage discovery. Their system consists of a wiring sensor that offers an uninterrupted electrical pathway to break the signal path and trigger an alarm at the base station to alert the monitoring teams in the event of a break in the system configuration. The guards of monitoring represent the crossing conditions, these conditions are timer-based as they send signals with any detection of intrusion. They developed an unnoticeable wiring sensor, shielded with resin that can be assimilated into the existing pipeline system. Their research was devoted to increasing efficiency in petroleum pipeline monitoring, government revenue, and agricultural earnings as well as reclaiming the ecosystem and lessening the consequence of spillages on human lives. However, their work did not cover leakages caused by corrosion, and manufacturing defects of the pipe. It did not also cover leak localization and geo-location of incidents. So, if there is leakage caused by the above-mentioned two ways, their system cannot sense such leakage.

Monir *et al*. [45] understudied the efficiency of equal distance placement scheme, based on the Ideal power model and Tmote power models, for Wireless Sensor Networks (WSNs) lifetime maximization in gas pipeline monitoring systems. They used the result of their study to develop an architectural model of WSN implementation. Their model can be used for spotting leakages and/or other types of damages in gas/oil pipelines as well as lifetime maximization of the operating nodes. Their model failed in the area of sensor power efficiency and how the sensor communicates with the gateway for signal evacuation.

Ajao *et al*. [46] proposed an anti-theft oil pipeline vandalization system based on IoT. They made use of ATmega328, a GSM module, and a GPS module in building their prototype. Their prototype was tested in a 10m length pipeline with a configuration threshold ranging from 28 to 210. Their system is capable of sending the distance, specific geographic location, longitude, and latitude of the area where the vandalism is taking place via SMS to the base station. The limitation of their system is that they used the SMS method of signalling, and SMS signals are not the best option in areas where local careers (MTN, GLO, 9Mobile, Airtel) do not have coverage.

Tomiwa *et al*. [47] reviewed the various methods deployed by vandals to illegally take crude oil from the Nigerian oil and gas pipeline infrastructures. They also highlighted the current measures deployed by the Nigerian government and oil companies to monitor pipeline infrastructures across the country. They went further to state the deficiencies that were concurrent with the approaches and suggested how IoT could be efficiently deployed to solve the problem. They developed a four-tier architecture for an intelligent pipeline monitoring system based on IoT. They also suggested the deployment of motion, pressure, vibration, flow rate and temperature sensors as well as cameras and GPS to monitor pipeline infrastructures. However, they did not show clearly, how to determine the geo-location and size of the leakage. We take special note that this work is an innovation, just like [48, 49] which will add to the body of knowledge.

3. Materials and method

3.1. Materials

The hardware design consists of different components (ESP8266 and LoRaWAN) linked via electric circuitry, a power supply unit, an electric pump, piping topology, sensors, valves, a tank, etc., which are discussed below:

i. Pressure sensor: The pressure sensor is used to monitor the pressure differentials along the piping topology. Each of the sensors in the system is designated to constantly monitor the pressure along a particular section of the piping topology.

ii. 12V DC submersible fluid pump: This submersible pump combines mechanical and electrical actions to move crude oil from the oil rig through the piping topology to the reservoir. It is called submersible because water needs to enter its body before it can function optimally. It has a flow rate of 840L/Hour.

iii. Power Supply Unit: The power supply unit supplies 12 volts to the power adaptor. It gives 12v to the pump and 5v to the control or base station where data is processed.

iv. Expressif 8266 (ESP8266) module: The ESP8266 module permits an embedded controller to link to 2.4 GHz Wi-Fi via IEEE 802.11bgn. It possesses the capabilities to work with ESP-AT firmware to deliver Wi-Fi connectivity to peripheral host MCUs. It can also be used as a standalone computer by implementing a Real-Time Operating System (RTOS)-based Software Development Kit (SDK). It possesses a complete TCP/IP stack and offers data processing capabilities, reads capabilities and General-Purpose Inputs Outputs (GPIOs) control abilities. In this work, the ESP8266 Microcontroller is used to capture the geo-location of the leak and also create a WiFi Hotspot to connect users to monitor the piping topology. It is also responsible for processing the data generated by the sensor.

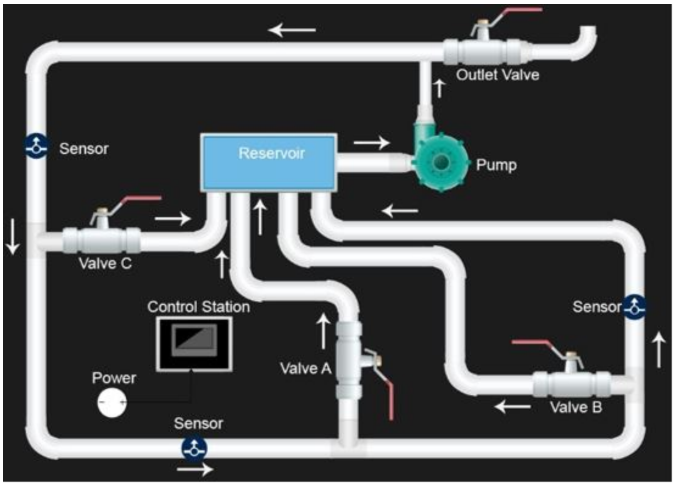

Figure 1. Hardware design and implementation layout of the system.

v. Valves: The valves are used to simulate leakage. If a particular valve is open, the flow pressure of that section of the pipe where the valve is drops. Once the pressure drops, the sensor picks up the new pressure and triggers an alarm.

vi. Tank/reservoir: Tanks or reservoirs are used for storing crude oil at flow stations and refineries tank farms. The tank in this project is made of rubber. In the design, it was used to collect crude oil from the pump and the spilt crude oil from the piping topology. Figure 1 shows the logical design of the hardware.

3.2. Requirement Analysis

Figure 2 describes the current operations and processes undertaken by oil companies in detail. A represents the oil wells (rigs) where crude oil is drilled, either onshore or offshore. The crude oil is drilled as a mixture of water and several other compounds and pumped to flow stations. B represents the flow station. In flow stations, separation of the crude is done and water is removed from it, leaving pure crude oil and then, pumped into tanks. C represents tank farms owned and managed by different companies. For example, Forcados Terminal is managed by Shell BP, while Chevron manages Excravos Terminal. From the tank farm, crude oil is either pumped to D (floating tank) for export or pumped to E (refinery) for refining. From E, the by-products of crude oil are pumped to the depot for distribution nationwide.

Initially, crude oil theft was done when PMS, AGO and DPK were being pumped from point E to point F, but in recent times, given the sophistication of technology, crude oil theft begins even from points B, C, D, E up to F. The major theft in recent times happens between points C to D, that is, where crude oil is pumped to export terminals.

The proposed system is an IoT-Based prototype system that is capable of sensing pressure differentials along the pipeline

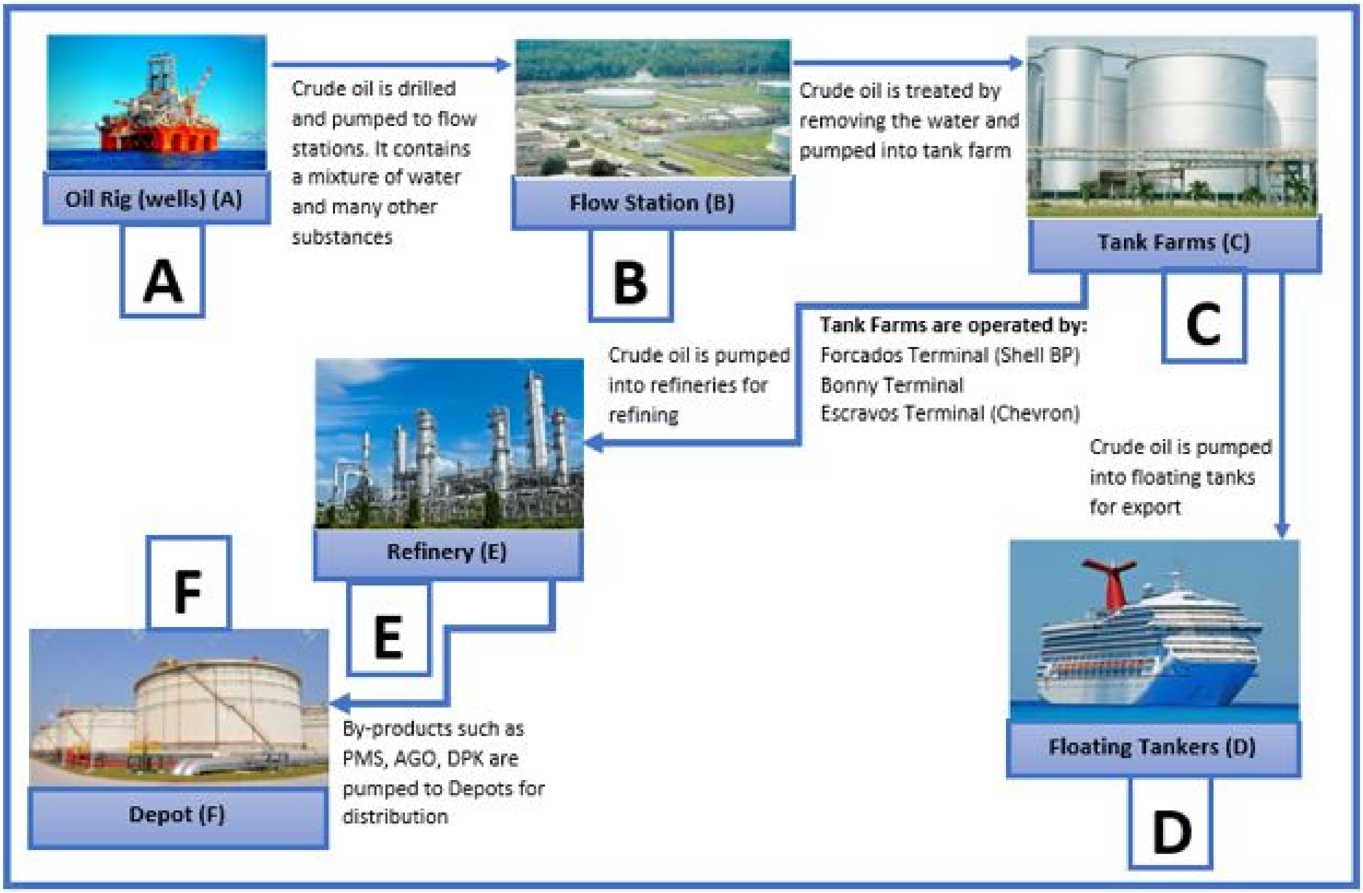

Figure 2. Current operations in crude oil drilling, transport refining and export.

topology and send a signal to the base station. The system has two components: the hardware (prototype) and an Android Application Software. The hardware comprises of a submersible pump, piping system, three pressure sensors, three valves simulated to represent leakage, a reservoir and a control/or base station. The sensors are positioned along piping topology with each sensor dedicated to monitor a particular section of the piping topology labelled A, B and C. Once the system is powered, the pump starts pumping crude oil from the drilling rig. The software which is designed with BASIC for Android communicates with the hardware to accomplish the goal of the proposed system.

3.3. Methodology

In developing this system, we deployed the modified prototyping methodology in both the hardware and the Android application. We call it modified prototyping because we merged the planning and analysis phases of the prototyping methodology to achieve speed, reduce time and cost as well as an efficient result. The design phase and implementation phase were handled independently.

The design of the system is simple and robust. In the system, once the sensors perceive a pressure differential in the pipeline topology, it triggers an alarm and sends the exact location of the leak to the control room so that the emergency response team can get to the leak site before it results in oil spillage. The design consists of three pressure sensors labelled sensor 1, 2 and 3, a 12V DC fluid pump, ESP8266 WiFi LoRaWAN module, a 12V power supply unit, LM1117 linear voltage regulator, four valves labelled Valves A, B, C and discharge valve) and a reservoir (tank).

When the hardware is powered, it establishes a connection with the Android Application and creates a WiFi called Pipeline. The user then connects to that WiFi to monitor the flow pressure. Once this is achieved, the fan (which represents the pump) on the GUI of the Android Application automatically begins to run (i.e. the pump begins to pump crude oil from the oil well). As the crude oil flows from the oil well through the pipe to the tank/reservoir, the sensors planted at designated portions of the piping topology begin to monitor the pressure generated by the pump and the flow of the crude oil. The artifact has three valves each placed on designated portion of the pipping topology and linked to each of the three sensor. These valves are used to simulate leakages.

Assuming the three valves remain closed (i.e. no leakage or diversion of the oil), the oil moves straight to the tank with a uniform pressure. Otherwise, if any of the valves are open (to simulate a leak), the oil is diverted to a different location. Once this happens, the sensor immediately senses a pressure differential (reduction in pressure) and then, communicates the readings of the sensor to the control for computation. The control swiftly triggers an alarm. The sensor records the time, date, event and geo-location of the event and posts the recorded data to a database.

In this research, it is worthy to note that the system is a prototype and as such, it cannot show all the details as implemented in industrial scenarios. In industrial implementation, the pump and the monitoring system do not share the same power source. The pump is powered separately and the monitoring system uses a dedicated and efficient power source. However, because we are trying to mimic the operational and behavioral characteristics of the oil pipeline topology monitoring system, we have decided to share the power source to cut cost.

3.4. Mathematical models for estimating leak size and depth

We adopted Bernoulli's equation to estimate the leak's size. Our reasoning was founded on the pressure of the leaking fluid and the pressure differentials throughout the leak site.

$$\Delta P - \frac{P}{2}v^2,$$

where ΔP is the leak-induced pressure drop, ρ represents the density of fluid, v represents the fluid's velocity as it escapes via the leak. The following relationship can then be used to determine the leak area or size:

$$Q - Av,$$

where Q represents the flow rate through the leak, A denotes the area of the leak, v embodies the fluid's velocity through the leak (determined using Bernoulli's equation).
Computing the value of A:

$$A - \frac{Q}{v}.$$

The conservation of mass and flow equations for the pipeline can be used to get the flow rate Q from the pressure sensor data.

4. Results and discussion

In this study, we have developed a petroleum pipeline leak monitoring and detection system, using sensors. The system is capable of sensing leaks using the sensing layer, evacuating the signals using the communication layer (LoRaWAN module and WiFi), computing the signal using the computation or processing layer (ESP8266 microcontroller) and reporting to the control room using the application layer (Android application). We shall present results based on the following four contributions to knowledge which we christened as objectives:

i. To fabricate a prototype and integrate it into an IoT-based system that can detect pressure differential arising from a drop in the fluid flow rate as a result of pipeline leakage using pipes, ESP8266 chips, sensors, a submersible pump etc.
ii. To develop a novel algorithm for end-to-end leak monitoring that performs sensing, transmission and processing of the data from sensors.
iii. To validate results received from the prototype by developing an Android Application which is capable of communicating with the prototype wirelessly.
iv. To analyse the data that is generated by the sensors for insights such as attack type, attack spots, attack frequency, attack date and time and probably forecast future attacks.

4.1. Objective No. 1: To fabricate a prototype and integrate it into an IoT-based system that can detect pressure differential arising from a drop in the fluid flow rate as a result of pipeline leakage using pipes, ESP8266 chips, sensors, a submersible pump etc.

Figure 6 shows the coupled artefact or fabricated prototype of the Petroleum Pipeline Topology Leak Monitoring and Detection System, which can communicate with an Android application to monitor the pipeline. The prototype features a piping network with three valves: A, B, and C, each mounted on a particular section of the piping network. Each section of the piping topology has a pressure sensor, coloured orange, that monitors that section of the pipe, such that whenever any of the valves is opened, the sensor attached to the section of the valve will sense a drop in pressure of the flow on the section of the pipe and trigger an alarm. It also contains a reservoir, which serves as the oil well and, for this design, as a tank for the purpose of collecting the oil back to a central place during testing operations. The black box, which has an antenna, houses the ESP8266 microcontroller, GPS module, and other components of the prototype. Finally, the prototype also has a 5V submersible pump and an outlet valve.

4.2. Objective No. 2: To develop a novel algorithm for end-to-end leak monitoring that performs sensing, transmission and processing of the data from sensors.

We developed a cross-correlation-based algorithm which we used to detect, and estimate the size and depth of the leak and localise the leak with high precision within seconds. From our experiment, the system has a detection speed of 0.192427 seconds and can detect leaks with 0.03cm in diameter.

Figure 3 shows a pictorial representation of the petroleum flow from a source to a sink. We used the representation to explain the paragraph that follows. In normal flow situations, the pressure between a source and sink remains constant under normal circumstances. But when there is leakage between the source and sink, (for example, the one labeled split/hit signal as shown in Figure 3) the volume of flow from the source drops, necessitating the creation of a vacuum in the pipeline. The fluid that had already flown across the split/hit signal location (that is, point B) will also return to the split/hit signal position, where it will spill to the outer environment. This also creates a vacuum in that section of the pipeline. The vacuums created by the reduction in the volume from both ends force the pressure to drop, creating a pressure differential below the pressure threshold. The pressure differential is what the system senses and then trigger alarm to notify users of the leakage.

To calculate the cross-correlation of two matrices, compute and sum the element-by-element products for every offset of the

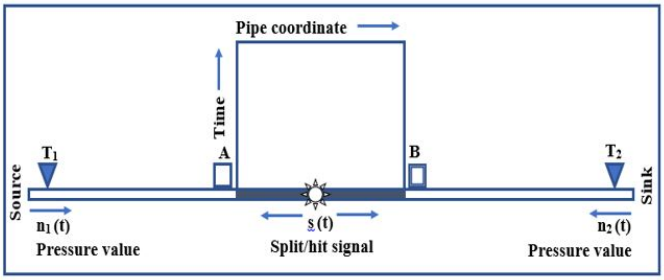

Figure 3. Pictorial representation of the algorithmic flow.

second matrix relative to the first. The two dimensional cross-correlation of an $m \times n$ matrix, X and a $p \times r$ matrix, H is a cross-correlation matrix CCM, of size $m + p - 1$ by $n + r - 1$. The elements of the matrix as postulated by [50] are given by the equation below:

$$CCM(k,l) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} X(m,n)\bar{H}(m-k, n-1) \ldots$$

Where
CCM is the sum of the products of two matrices X and H. Where H is multiplied by X in the inner loop summation $n = 0$ to $N - 1$ while the outer loop is from $m = 0$ to $M - 1$ and CCM is the Cross Correlation Matrix.
where

$$-(P-1) \leq k \leq M-1, -(R-1) \leq l \leq N-1$$

where a bar over H symbolises complex conjugate.
The output matrix, has negative and positive row and column indexes rated as follows: A negative row index corresponds to an upward shift of the rows of H. A negative column index corresponds to a left ward shift of the columns of H. A positive row index corresponds to a downward shift of the rows of H. A positive column index corresponds to a rightward shift of the columns of H. $CCM(k,l)$ calculates the Cross Correlation amid two-dimensional signals (arrays of arrays), where all values are real numbers.

In capturing the geo-location, the time and then detecting the leakage, we implement them in the algorithm as three random variables $q = (q_1, \ldots, q_m)T$, $p = (p_1, \ldots, p_n)T$ and $s = (s_1, \ldots, s_0)T)$, with each containing random elements whose expected values and variance exist, as postulated by [51, 52] as $R^T_{QPS} = (Eqps)^T$ and has dimensions $m \times n \times o$ representing the three random variables. where q denote Pressure, p is Geo-location, and s represent Time.
We can further express the representation above component-wise as follows:

$$R_{qps} = \begin{bmatrix} E[q_1 p_1 s_1] & E[q_1 p_1 s_2] & E[q_1 p_1 s_3] & \cdots E[q_1 p_1 s_0] \\ E[q_2 p_1 s_1] & E[q_2 p_1 s_2] & E[q_2 p_1 s_3] & \cdots E[q_2 p_1 s_0] \\ E[q_3 p_1 s_1] & E[q_3 p_1 s_2] & E[q_3 p_1 s_3] & \cdots E[q_3 p_1 s_0] \\ \vdots & \vdots & \vdots & \ddots \\ E[q_m p_1 s_1] & E[q_m p_1 s_2] & E[q_3 p_1 s_m] & \cdots E[q_m p_1 s_0] \end{bmatrix} \quad (1)$$

Algorithm 1 Sensor-Based Coverage and Pressure Differential Analysis

Require: Coverage Area C, Benchmark Pressure Differential BP
Ensure: Alarm Trigger Status

Start
Determine total coverage area C
Calculate the number of sensors P using:
$$P = \left\lceil \frac{C}{5} \right\rceil$$
Set P as the number of sensors required
for $i = 1$ to P **do**
  Read dataset from the i-th sensor
  Store the retrieved sensor data in a database
  Apply signal filtration (e.g., Kalman filter) to remove noise and outliers
  Extract pressure signals from the filtered dataset
  Analyze pressure signal levels and compare with reference values
  Calculate pressure differential ΔP as:
  $$\Delta P = P_{\text{current}} - P_{\text{previous}}$$
  if $\Delta P < BP$ **then**
    Trigger alarm indicating abnormal pressure differential
  else
    Proceed to the next sensor
  end if
end for
Stop

One thing worthy of note is that the random vectors q, p and s used in this equation do not necessarily need to possess the same dimensions. Another worthy thing to note is that any of them might be a scalar vector. The algorithm can be summarised in the following steps:

4.3. Objective No. 3: To validate the results received from the prototype by developing an Android Application that is capable of communicating with the prototype wirelessly

4.3.1. Data acquisition module

The Andriod application developed in this research has a module that acquires the data generated by the sensor, processed by the $ESP8266$, and transmitted by LoRaWAN. Users can download the datasets by clicking on the Export Data button in the Application GUI shown in Figure 4a. Once the user clicks the export data button, the file will be downloaded into the download folder. the data can then be analysed for non-obvious trends or insights, using any data analysis tool

4.3.2. Data set

One of the results from this research is a comprehensive dataset generated by the three sensors planted on the pipelines. See Figure 4a. The dataset can be downloaded as a db.csv file. It is a record of the alarm triggers. it is a record of the entire monitory activities of the system, including the alarm trig-

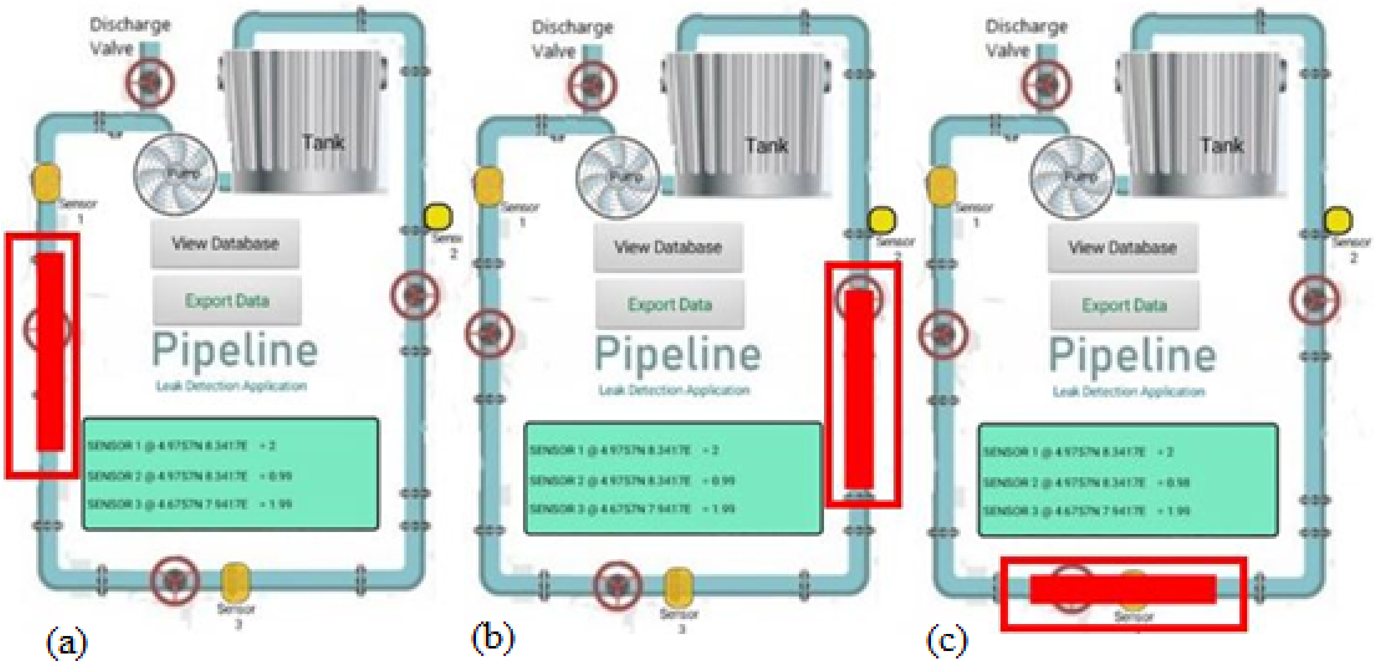

Figure 4. (a) Android application showing leak detection by sensor 1 (b) Android application showing leak detection by sensor 2 (c) Android application showing leak detection by sensors 3.

gers. The dataset can be used that can be used by data scientists in conjunction with sophisticated machine learning and deep learning algorithms to predict petroleum pipeline topology leakage. The dataset shows date, event time stamp and geo-locations as captured by the application.

4.3.3. Leak detection

The basic objective of this research is to monitor and detect leakages in the pipeline topology. In this section, we shall discuss the results in three categories: Leak captured by sensor 1, leak captured by sensor 2, and leak captured by sensor 3. As shown in Figure 4a, 4b and 4c respectively.

Figure 4a shows the point where the system has triggered the alarm because sensor 1 has sensed a pressure differential on the portion of the pipeline topology designed for it to monitor. The alarm comes with a red flagging signal (marked by a red rectangle) which blicks continuously as the alarm keeps blowing. A cursory glance at the light-green rectangle reveal that the system has captured data from sensor 1. Similarly, Figure 4b presents the point where the system has triggered an alarm because sensor number 2 has detected a change in pressure on the area of the pipeline topology designated for it to monitor. Finally, Figure 4c equally displays the point where the system has triggered an alarm because sensor number 3 has sensed a pressure differential on the section of the pipeline topology designated for it to monitor. However, if there is no event, the system keeps running and the portion of the figure marked with a light-green rectangle will be empty, showing that no data has been captured.

4.3.4. Application database

Figure 5 show a screenshot of the Android Application database with readings of the geolocation of the event, date, time and the type of event that occurred.

4.4. Objective No. 4: To analyse the data generated by the sensors for insights such as attack type, attack spots, attack frequency, attack date and time and probably forecast future attacks

.

4.4.1. Data transformation

The data generated by the sensors and transformed as shown in the Data availability section. The first five columns of the data show the original data downloaded from the Android Application while the other nine columns show the transformed data. The data items that were transformed are as follows:

i. Serial number: A cursory glance at the original data downloaded from the Android Application reveals that the serial numbering system is in a reverse order, that is, from larger numbers to smaller number, that is, from serial number 708 to serial number 1. In transforming the data, we reversed the numbering system to reflect the standard numbering system which is from smaller number to bigger numbers, (from serial number 1 to serial number 708).

ii. Geo-location: The second data item that was transformed is the geo-location. The original geo-location captured by the sensor is displayed in coordinates as shown below: 3.2857N, 6.7487E, 4.9757N 8.3417E, and 4.6757N 7.9417E.

DATABASE READINGS

8	03/18/2021	21:16:39	Pressure	3.2857N 6.7487E
7	03/18/2021	21:16:38	Pressure	3.2857N 6.7487E
6	03/18/2021	21:16:38	Pressure	3.2857N 6.7487E
5	03/18/2021	21:16:37	Pressure	3.2857N 6.7487E
4	03/18/2021	21:16:37	Pressure	3.2857N 6.7487E
3	03/18/2021	21:16:36	Pressure	3.2857N 6.7487E
2	03/18/2021	21:16:36	Pressure	3.2857N 6.7487E
1	03/18/2021	21:16:35	Pressure	3.2857N 6.7487E

Figure 5. Android Application database showing captured data readings 1.

The format in which the data is captured by the sensor is raw and cannot be presented graphically. So, in transforming the data, we defined each octet of the data to represent one sensor. 3.2857N, 6.7487E is defined as 3.2, and it represents sensor 1. Similarly, 4.9757N 8.3417E is defined as 4.9, and it represents sensor 2, while 4.6757N 7.9417E is defined as 4.6, and it represents sensor 3. The coordinates were also split into longitude and latitude using the following Microsoft Excel functions: =RIGHT (E2, SEARCH ("\, $E2$, 1) − 1) for longitude and =LEFT (E2, SEARCH ("", $E2$, 1) − 1) latitude.

iii. Time: The third aspect of data transformation is the computation of the difference in time (S). As seen in raw data generated by the sensors, time is captured in three octets: hour, minutes and seconds (12:16:35). In this case we defined time by picking the hour and seconds and then, we converted the colon (:) to a dot (.) so that the new data can be handled in plotting graphs. For instance, in defining the first record or data entry in Appendix B, we converted 12:16:35 to 12.35. In the same vein, in dealing with the second record or data entry, we converted 12:16:36 to 12.36. So, for each data item, we considered the first octet which is in hours and the last octet which is in seconds. In computing the time difference, we used the Microsoft Excel function $= ABS((C3-C2)) * 1000$ to compute a successive subtraction of current time (S1) from initial time (S0).

Figure 6. Prototype of the system showing actual coupling of the artifact.

Figure 7 show graphical representations of the processed data generated by the sensors. It is a pressure versus time graph as well as pressure, time and duration graph. As depicted in the graph, the higher the pressure, the longer the blue line facing downwards. The interpretation is that when the line is long, the size of the leak is large and when the line is short, the size of the leak is small. The graph also illustrates pressure, time and the duration the system ran without detecting any leak. The portion of the graph marked by a red rectangle shows the duration the system operated without detecting any leak.

5. Conclusion

In this research, we present a solution (pipeline topology leakage monitoring and detection system using sensors) to the ostensible interminable challenges in the Nigerian oil and gas sector. The system has a user-friendly platform for monitoring pipeline topology leakages remotely. The research observes that sensors and actuators, combined with high-tech ICT tools can be used to develop a very robust security architecture for pipeline topology leakage monitoring and detection.

From the experiment, the system has a detection speed of 0.192427 seconds. It can also detect leakages with 0.03cm diameter, and the ability to integrate with Mobile Android Application which contains a data acquisition software module.

The pipeline topology leakage monitoring system may be seen as a threat to the political class and Military hierarchy in Nigeria, who have taken undue advantage of the vulnerable security and other weaknesses of the pipeline monitoring system for their selfish, inordinate and imperial ambitions and have continually defrauded Nigeria of billions of dollars. Far be it from Nigerians to watch the collapse of their only source of revenue generation when we have a lasting solution starring us in the face.

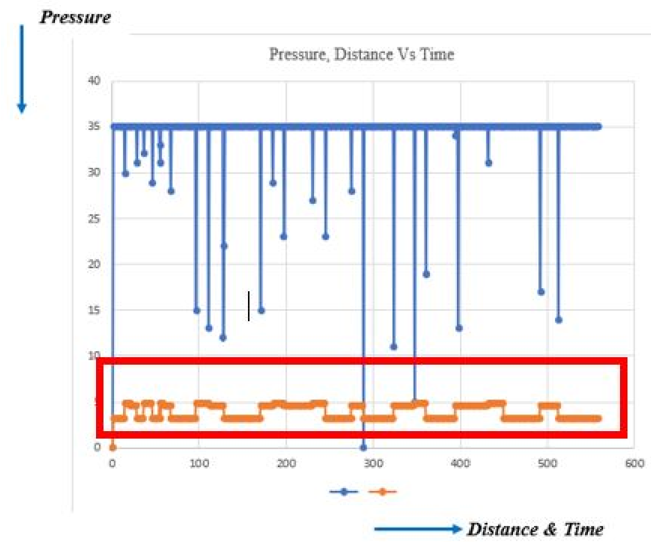

Figure 7. Pressure-time graph and Pressure, duration and time graph.

Data Availability

The dataset used in this study is available in the link provided below: https://drive.google.com/file/d/1Jeguq_K7sGZywJDOP-EVPjywLKpUj29I/view?usp=drive_link.

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