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A Systematic Review of Existing Crude Oil Pipeline Monitoring Technologies

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ABSTRACT

Crude oil pipelines are major assets/facilities dominating the oil and gas midstream sector. Pipelines have been acclaimed to be one of the safest means of transporting oil and gas products, however, they are prone to failures. These failures may arise as a result of manufacturing defects, environmental conditions, material degradation, third party interference or sabotage and vandalism. When these failures occur, the attendant consequences are usually damaging to human health, terrestrial and aquatic population, the environment, operators' reputation and properties. Also, there are cost implications associated with pipeline failures. This cost implication could come directly in form of loss of products, equipment downtime, and clean-up cost. Indirectly, other associated cost of pipeline failures includes fines and lawsuits. There are several techniques in existence, proposed and currently being researched on for pipeline leak detection, integrity monitoring and prevention of failures on crude oil pipelines. These technologies can be broadly categorised into: Online monitoring technique, periodic inspection, Artificial Neural Network etc. This paper will be reviewing in detail the existing technologies in crude oil pipeline monitoring. It will also discuss proposed systems and systems current being researched on. In discussing these technologies, a detailed comparism of the various systems' strong points will be looked at. These strong points looked at variables such as the systems' reliability, sensitivity, response time and cost effectiveness.

Keywords: Assets, Environmental conditions, Degradation, Third party interference, Sabotage.

1. INTRODUCTION

Crude oil also known as petroleum is a liquid substance found within the earth [6]. Crude oil comprises of hydrocarbons, organic compounds and certain amount of metals. The primary component of crude oil is hydrocarbon. Crude oil is a complex combination of predominantly aliphatic, alicyclic and aromatic hydrocarbons [5]. However, hydrocarbon composition of crude oil can vary from between 50% - 97% depending on the type of crude oil and how it is extracted [6]. Nitrogen, Oxygen and Sulphur are the major organic components making up of about 6%-10% of the component of crude oil. Copper, Nickel, Vanadium and Iron makes up for about 1% of the total component of crude oil.

Crude oil is formed through the compression and heating of organic materials over a long period of time. They are formed from the remain of prehistoric algae and zooplankton decay at the bottom of an ocean or lake. In the process of crude oil formation, organic materials combine with mud, get heated to very high temperature in the earth crust with high temperature arising from the pressure of heavy layers of sediments. The organic material mixed with mud goes through a process of diagenesis changing its chemical composition firstly into waxy compound known as kerogen. With increased temperature and pressure, the compound changes into a liquid form through a process known as catagenesis [6].

Crude oil is extracted through a process of drilling. The process of drilling starts with identifying of land by geologists with potential of oil flowing beneath. Identifying this land could be done through satellite imagery, gravity meters and magnetometers. After identifying a steady flow, the process of well formation and casing is done. Perforating gun with explosive charges, tubes and packers are used for the extraction process. Christmas trees are also placed in a suitable location and used by oil workers to control the flow of crude oil from the well [6].Typical distribution of crude oil from point of extraction to final destination is presented in [2]. Firstly, flowlines convey the crude oil from well location to flow stations. The output of the flow station is fed into small manifold using delivery lines. If fed into the main manifold, pipelines are used. The crude oil is then sent to export terminal or refineries through trunkline [2]. Figure 1 shows a diagrammatic representation of the typical crude oil distribution network.

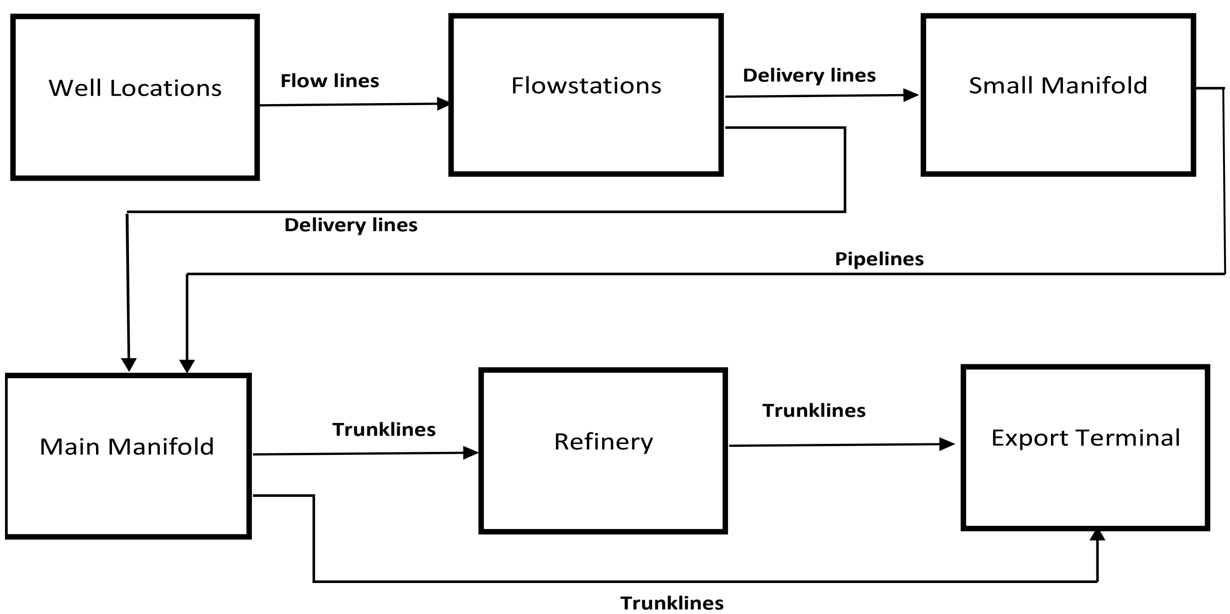

Figure 1: Crude oil Distribution Network.

The trunk line can be seen as one of most critical components of the distribution network. This is due to the fact that third party interference and major attacks by vandals are carried out on the trunkline. Attacks on the trunkline can lead to shut down of production from wells feeding the trunkline. Also, trunklines are the most expensive to build and most lucrative for oil thieves due to the volume oil flow per time [2]. There are various technologies being applied to monitor these pipelines which among others include: overflights, use of community personnel, and security-based surveillance [9]. Alternatively, wired systems such as fibre optics, Supervisory Control and Data Acquisition System (SCADA) and more recently, Wireless Sensor Network and Internet of Things (IoT) are also being explored in crude oil pipeline monitoring and detection [2].

2. CRUDE OIL PIPELINE LEAKS

A leak in crude oil pipeline can be defined as an unintended crack, hole or porosity in an enveloping wall or joint of a pipeline. Leaks allow the escape of fluid or gas from a closed medium into the surrounding or environment. Leak can result from either operational failure of pipelines, third party interference either by way of sabotage, crude or line theft or accidental third party damage. Occasionally, certain leaks are described as mystery spills as there is no established cause of the leakage. Figure 2 shows the chart of recorded spills from Shell Petroleum Development Company (SPDC) operated pipelines in the Niger Delta. Leaks are undesirable. With increasing public awareness and concern for the environment, recent pipeline leak incidents have shown that the cost to a company can be far more than the downtime and clean up expenses. As shown in figure 2, a greater number of leaks result from sabotage. From 2007 to 2011, Nigeria lost more than USD 11 billion to crude-oil theft and pipeline vandalization [2]. The total amount being lost by Nigeria annually has been estimated at approximately USD 6 billion [2]. As more stringent statutory regulations are introduced in the developed countries, as such, cost effective and reliable leak detection systems are in demand. Leak detection entails the identification of the likelihood or actual escape or loss of containment of fluid or gas from an enclosed pipeline. The basic function of leak detection is to localize and measure the size of leaks in a sealed product or system [1].

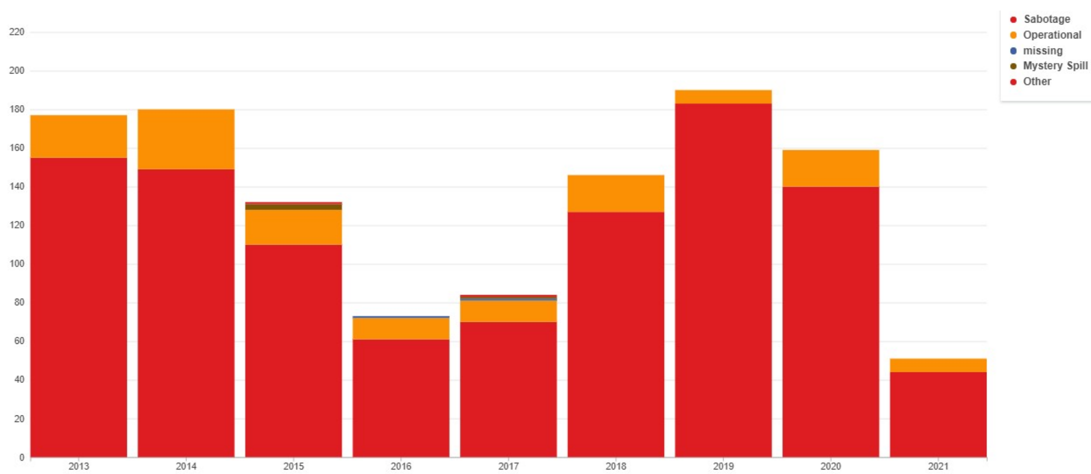

Figure 2: Chart of recorded leaks in SPDC operated pipelines as at June 2021. Source: Shell Oil Spill Data

Pipeline leak detection forms an important component of pipeline leak management. It allows operators to respond in a timely manner to leaks hence prevent further escalation of spill incidents. Various technologies are available to detect leak from pipelines. These detection techniques are based on the nature of the fluid in the pipeline and the size of the leak. The techniques range from basic material balance techniques to much more complicated systems [15].

3. CLASSIFICATION OF PIPELINE MONITORING TECHNIQUES

There are various classification of pipeline monitoring techniques in the literature. In [8], Pipeline Monitoring Technique is broadly classified into Monitoring and Inspection Techniques. In [4] and [16], leak detection systems were broadly classified into Hardware and Software based systems. [8] considered Biological, Technical and non-technical leak detection systems as another classification. Also, in the literature, another classification into optical and non optical methods is presented in [12]. Another classification is the grouping of pipeline monitoring techniques into automated, semi-automated or manual detection methods [4].

[8] considered another useful classification where continuous online monitoring and periodic based monitoring were highlighted. In [8], a graphical representation of Hardware, Biological and Software techniques was presented. Hardware base methods use hardware sensors to directly detect the occurrence of a leak and assist the localization [8]. Hardware techniques were further broken down into Visual and Acoustic methods. Software based methods use computer software packages to constantly monitor data of pressure, temperature, and flow rate for detecting leaks in a pipeline [8]. Software techniques was broken down into flow pressure change and mass or volume change. Biological methods use experienced personnel or trained dogs to detect and locate a leak by visual inspection, odour or sound. The experienced personnel walk along a pipeline looking for unusual patterns or smelling substance that could be released from the pipeline. They also listen to noises generated from the escape of product from the pipeline. This method is largely dependent on the experience of the individual whether a leak developed before or after the inspection [15]. Detail of these classification is presented in figure 3.

Table 1: Classification of Pipeline monitoring techniques.

Author(s)	**Classification**	**Description**
Sachedina, K. and A. Mohany (2018)	i. Monitoring and Inspection Techniques. ii. Biological, Technical and Non-Technical methods. iii. Continuous Online Monitoring and Periodic based monitoring.	i. Very broad classification comprising of active and passive methods of leak detection. ii. Use of trained personnel to patrol the pipe to observe changes in the pipeline corridor. iii. a. Constantly monitors and detects pipeline failure once they occur. iii. b. Periodically used to accurately detect failures before they occur. Periodic because it can interfere with the normal operation of the pipeline
Zhang, J (1997); Geiger, G (2006); Scott, S.B.A (2003)	Software and Hardware based systems	Relies on special external sensors or uses internal measurement of flow parameters such as pressure, temperature or flow rates.
Sivathanu, Y. (2003)	Optical and non-optical systems	Involves visually evaluating the condition of the pipe using nonvisual sensors and software to detect leaks
Murvay, P.S and I. Silea (1996)	Automated, semi-automated and manual detection methods	This looks at the degree of human intervention required for operation.

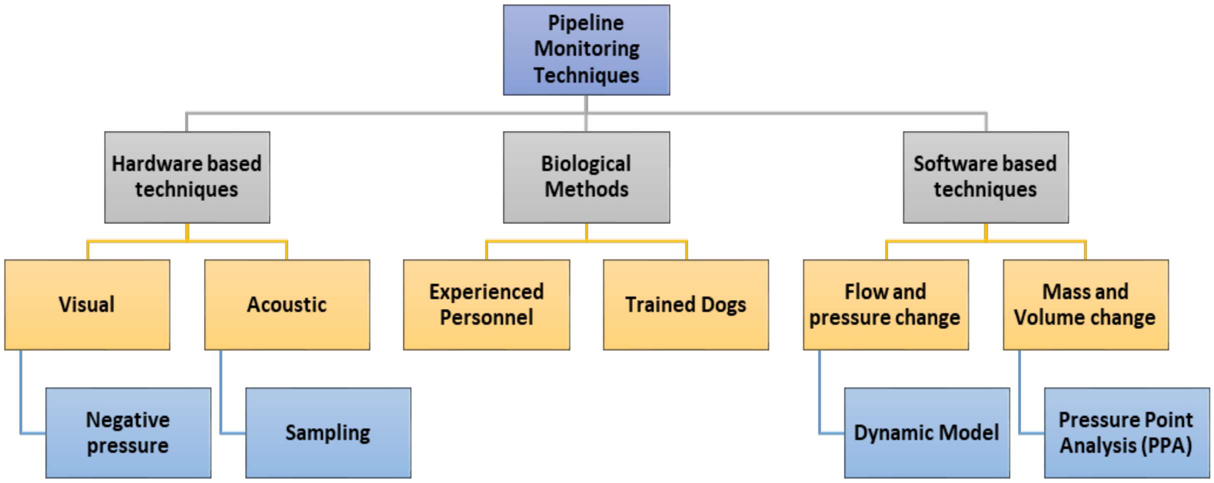

Figure 3: Classification of Pipeline monitoring techniques. Adapted from Yong Bai, Qiang Bai (2016)

4. REVIEW OF SELECTED CRUDE OIL PIPELINE DETECTION TECHNOLOGIES.

4.1 Atmos Pipe Technology

Atmos Pipe is a statistical pipeline leak detection system. It incorporates advanced pattern recognition functions. Atmos pipe was developed at Shell using advanced statistical techniques to analyse the flow and pressure measurements of a pipeline. Changes in flow rate and flow pressure is studied and registered. Through the process of understanding the pattern change, leak alarms are generated when an abnormal pattern or a unique pattern of flow and pressure variation exists.

Atmos pipe utilizes the statistical concept of Optimum Sequential Analysis Technique (Sequential Probability Ratio Test) to detect variation in the flow behaviour of inlet and outlet flow and pressure. It is based on the concept that pressure and flow will always vary after a leak occur. It is established that leak could cause a decrease in pressure and also introduce some changes in the inlet and outlet flowrate. Atmos Pipe utilizes advanced online learning algorithm to learn and adapt to changes in the pattern of pressure and flow rate. The major disadvantage of this system is that it is a reactive system rather than a proactive leak detection system. Leak has to occur before detection.

4.2 Remotely Piloted Aerial Patrol Drones

Unmanned Aerial Vehicles (UAVS) are now evolving as highly effective tools for tackling the requirements of oil and gas pipeline monitoring in a specific environmental. UAVs are aircraft deployed either with or without human operators' control. They provide video information over a location. The constituent of the UAV include: ground control station, payloads, data link and support equipment [2]. Application of UAVs include but not limited to:

i. Aerial reconnaissance where it is used to acquire aerial video of remote locations where there is potential risk to the pilot of manned aircraft.
ii. Research: UAVs can be used to obtain necessary data from remote and most often risk prone areas for the purpose of using the acquired data for scientific research.
iii. Logistics and transport: There are certain variety of UAVs that can be used to carry and deliver a variety of payloads. The suspension of the payloads at the bottom of the helicopter makes it immune to any aerodynamic drag [2].

4.3 Fiber Optic Pipeline Encroachment Detection

In this approach of pipeline leak detection and monitoring, fibre optic cables are installed externally along the pipeline right of way. These fibre optics has sensor capabilities and can act as distributed or point sensors. To extensively detect physical or chemical properties of crude oil spillage. It utilizes variation in the temperature of hydrocarbon fluid engross into the coating cable. Distributed Optical fibre sensor provides environmental measurement based on three classes of scattering. These scattering measurement include: Raman, Rayleigh and Brillouin scattering [4a]. Raman scattering capability of distributed fibre optics cable can measure temperature. Rayleigh utilises elastic scattering. This means it is not affected by frequency variation. Brillouin scattering can measure both strain and temperature. The general principle of the operation of optical fibre is that they are sensitive to stress applied on the fibre. Changes in the fibre light transmission may be detected and located by using Optical Time Domain Reflectometry (OTDR).

Fiber optic technology may be another solution offering real-time monitoring and low operating costs. Light signals are periodically sent through the specialized fiber (which is sensitive to changes in stress and vibration), and reflected light is recorded back at the source. When heavy equipment is within the right of way, it compresses the soil and creates vibrations which change the dynamic of the light and reflect those changes back to the source. Using a custom designed optical time domain reflectometer, which can measure the reflected light and accurately interpret the signal, the system objective was to identify a target and determine its status as hazardous or benign. If the signal is determined to be hazardous, an alarm is triggered. Since the velocity of the light is known, the equipment will be able to pinpoint the precise location and notify the operator for a response.

4.4 Acoustic Impact Detection Systems

Acoustic emission is a phenomenon whereby transient elastic waves is been generated through a rapid release of energy form a localised source within a material [4a]. Acoustic detection is based on the principle of noise and vibration. These noise and vibration are generated as a result of sudden drop in pressure. Detection of crude oil leak is achieved with the use of sensors that are sensitive to elastic waves in the frequency range of up to 1 MHz from high pressure perforated point. Time lag between the acoustic signals sensed by two sensors is used to pinpoint the leak location on the pipeline. Acoustic impact detection systems are in two broad categories. These are active and passive methods. Active method detects leak by listening to the reflected echoes of sound pulses emitted from the pipeline. On the other hand, passive method, detects leaks by listening to changes in sound generated by pressure waves in the pipeline.

The Gas Technology Institute (GTI) is currently conducting research on acoustic impact detection for providing real time monitoring against third party damage. The system is comprised of multiple acoustic sensors, power supplies and remote transmitting devices which are placed along the pipeline at fixed intervals. When a piece of equipment, such as the shovel of a backhoe, strikes the pipeline, the sound generated travels through the gas stream and the pipe to the nearest acoustic sensor in both directions. The sensor's electronics filters and analyses the sound to determine if an alarm is warranted. If the sound meets the alarm criteria, a radio alert is transmitted to operations personnel or the monitoring service. The acoustic sensors transmitting the alert will identify the location of the strike to facilitate rapid intervention.

4.5 Satellite Detection of Encroachment Events

The concept of identifying and detecting crude oil leak from space using satellite imagery is also being explored, Satellite monitoring system photographs the crude oil pipeline corridor as it passes over a given Right of Way (RoW). The image from the photographic operations is constantly being compared to computerised change detection analysis software. If an encroachment is detected, within the RoW, the image is further analysed using a database of heavy duty equipment or backhoe signatures. With this comparison, the system is able to identify a piece of heavy duty equipment or backhoe on the RoW and pinpoint its location using GPS technology and contact the operation center for on the ground investigation.

5. KEY ATTRIBUTES OF LEAK DETECTION TECHNOLOGIES

Each leak detection method has its advantages and disadvantages. The performance of the different methods is determined by some key attributes which among others include:

a. Leak sensitivity: Can small leaks be detected?
b. Location estimate capability: Is location estimate given?
c. Operational change: Can the method work if pipeline experiences operational changes e.g. throughput change, pigging?
d. Availability: Can the method monitor a pipeline continuously i.e. 24 hours a day?
e. False alarm rate: Frequency of leak alarms generated during leak-free operations.
f. Maintenance requirement: Level of technical expertise required to maintain the system.
g. Cost: Capital expenditure (CAPEX) and ongoing operating costs (OPEX).

6. SUMMARY OF REVIEWED PIPELINE TECHNOLOGIES

Table 1 presents the summary of the pipeline monitoring and Leak detection technologies reviewed. The table looks at the method vis a vis the principle of operation, their strength and weaknesses. This is done to give the pipeline operators a bases for the selection of most suitable technology for implementation.

Table 2: Summary of leak detection technologies

Methods	Principle of operation	Strengths	Weaknesses
Atmos pipe	Utilizes statistical concept of Optimum Sequential Analysis Technique (Sequential Probability Ratio Test) to detect variation in the flow behaviour of inlet and outlet flow and pressure	Minimal false alarm generated. Ability to detect small leak. Reduced localization error and detection time.	It is a reactive system that only works after an actual leak has occurred.
Remotely Piloted Aerial Patrol Drones	Acquires aerial video of remote locations where there is potential risk to the pilot of manned aircraft	Reduces risk of exposure to operators.	It is not cost friendly to maintain.
Fiber Optic	Detect leaks through the identification of temperature changes in the optical property of the cable induced by the presence of leakage.	Insensitive to electromagnetic noise and the optical fibre can act both as sensor and data transmission medium.	The cost of implementation is high, not durable and not applicable for pipelines protected by cathodic protection systems.
Acoustic Impact	Detect leaks by picking up intrinsic signals escaping from a perforated pipeline. Acoustic detection is based on the principle of noise and vibration. These noise and vibration are generated due to of sudden drop in pressure.	Easy to install and suitable for early detection, portable and cost-effective	Sensitive to random and environmental noise, prone to false alarms and not suitable for small leaks.
Satellite Detection	Identifies and detects crude oil leak from space using satellite imagery.	Identifies leak more accurately and capable of pin-pointing leak location	High cost of operating.

7. RECENT ADVANCES IN LEAK DETECTION SYSTEM AND FURTHER WORK

Most of the methods already discussed are constantly evolving with the view of improving the sensitivity, accuracy and reliability of the methods. Updating existing systems with faster and more accurate sensors, modern servers, algorithms can overcome the shortcomings of out-of-date systems [7]. This section discusses some of the most recent work current being done in the area of crude oil pipeline monitoring and encroachment detection.

a. Context-Aware Crude Oil Pipeline Monitoring and Encroachment Detection System

The authors are currently carrying out a research on the implementation of a monitoring system in the area of context awareness. The system in principle uses the concept of Internet of Things, Wireless Sensor Network and Cloud Computing. Two important context that are applicable to pipeline Right of Way are being used to detect and monitor threat to crude oil pipeline. These contexts are motion and vibration. It is worthy of note that for a physical external damage or sabotage or third-party interference to occur on the pipeline, human presence must be the involved. Also, the activity of ground penetration in the form of manual or mechanical excavation generates some level of vibration hence the use of motion and vibration context for the monitoring and detection of crude oil pipeline.

b. Artificial Neural Network (ANN)

In the works of [10] on Leak detection in liquefied gas pipelines by Artificial Neural Networks, the concept of ANN was explored to detect and monitor leaks on crude oil pipelines. ANN are computing systems that utilizes the concept of biological neural networks. These systems have the capacity to learn tasks through data training. They generate outputs on their own base on the learnings from the training data set. [10] system works based on training from examples of pipeline data. These data include flow, pressure and temperature etc from systems with or without leaks. The system will process and analyse the data, creating criteria which can be used on other systems in real time to determine whether or not the system parameters are indicative of a leak. ANNs have been developed that are based on process variables routinely measured during pipeline operation, which allow these systems to be used with basic hardware and incorporated into existing systems without the need for physical intrusion on the piping. While ANNs are sensitive to the training received and noise levels of the sensor signals, developed models have shown promising results. Some literatures have reported the ability of ANN-based systems to detect leaks as small as 1% of the flow rate without false alarms [10]. These systems also reported good accuracy under transient conditions and for the location of leaks which were 5 % or more of the flow rate [8].

c. Resilient IoT-based Monitoring System for Crude Oil Pipelines

In the work of [9], they proposed a hierarchical and distributed network architecture for the implementation of the pipeline monitoring system. This kind of architecture prevents Single Point of Failure (SPOF) usually associated with centralised systems. Their goal was to allow for a scalable network without substantially affecting performance metrics such as accuracy of the leakage detection and localisation, latency, cost, and energy consumption. The proposed network architecture is based on a 3-tier architecture. Layer 1, consists of the sensors connecting to other sensors, one or multiple gateways. Geographically close sensors will share information to take advantage of the spatial correlation of data allowing distributed detection and localisation. In Layer 2, they took advantage of the fog paradigm to reduce latency and energy consumption for more complex computations in the gateways. Layer 3 is implemented for long-term storage and historical analysis of data and services. In terms of communication, they made use of LoRaWAN for both the short and long-range communications. We also proposed the use of a cellular network as a backhaul as they are more widely deployed. Their work introduces Placement and Distributed Estimation for Leakage Detection and Localisation on Oil Pipelines, which is divided into two parts: a) Node placement, distributed detection and localisation b) Distributed data and service management. They consider as a tradeoff the accuracy of leakage detection and localisation, the cost, the fault-tolerance, the scalability, and the efficiency of the system in terms of data storage, packets transmitted and energy consumption [10].

d. Integrated Oil Pipeline Monitoring and Incident Mitigation Systems

In the works of Johnson Eze et al., a specification for pipeline surveillance based on integrated system architecture was proposed. The architecture utilizes a Multi-Agent System (MAS) for the realization of an Integrated Oil Pipeline Monitoring and Incident Mitigation System (IOPMIMS) that can effectively monitor and provide actionable information for pipelines. The basic concept of IOPMIMS is to use MAS to integrate heterogenous Wireless Monitoring Sensor Network (WMSN) for pipeline surveillance. The WMSN architecture has the capability to acquire signals from various sensors such as seismic, motion and cameras sensors. The system carries out aggregation of data at the substation, the MAS at the base station collates information from other devises such as GPS, wireless camera equipped drones, pipeline flow meters and pressure sensors for threat and leakage detection. Upon detection of threat or leakage in the pipeline system, decision is taken by the system and actionable information, or alerts are sent to security personnel or pipeline operators [3].

8. SUMMARY

Crude oil pipelines are major assets in the oil and gas midstream sector. It has been acclaimed as the safest means of transporting oil and gas products. However, crude oil pipelines are prone to failures either in the form of equipment failure or third-party interference in various forms. When these failures occur, the attendant consequences are usually damaging to human health, terrestrial and aquatic population, the environment, operator's equipment, and reputation. The fact that some countries depend on the sales of crude oil as a means of revenue, also underscores the loss incurred as a result of pipeline failure. This paper has looked at some technologies used in monitoring crude oil pipeline. It has also looked at some work currently being research for the purpose of crude oil pipeline monitoring and encroachment detection. Various classification of pipeline monitoring techniques was studied. This classification according to various authors include Monitoring and Inspection techniques, Hardware and Software based techniques, Biological, Technical, and non-technical techniques, optical and non-optical methods, automated, semi-automated and manual methods, continuous online monitoring, and periodic monitoring among others.

Some popular techniques such as Atmos pipe technology, remotely piloted aerial patrol drones, fiber optic pipeline encroachment detection, acoustic impact detection system, satellite detection of encroachment events were reviewed. This paper also took a dive into the key attributes of a leak detection system. The work highlighted leak sensitivity, location estimation capability, operational change, false alarm rate, maintenance requirement and cost capital expenditure as some of the important attributes of a leak detection system. Recent advances in leak detection were also x-rayed. This paper highlighted the work currently being research in context-aware crude oil pipeline monitoring and encroachment detection. It was noted that this system incorporates the principle of Internet of Things, Wireless Sensor Network and Cloud computing in solving the problem of crude oil leak. This paper also looked that works by other authors in Artificial Neural Network, Resilient IoT Monitoring system for crude oil pipelines and Integrated oil Pipeline Monitoring and Incident Mitigation Systems.

9. CONCLUSION

Robust solution to the protection of crude oil pipelines lies in active research. Unarguably several research works have proposed various systems for the monitoring of crude oil pipeline. However, there is need to see the results of such research translating to reduction in the count of spill incidents. Current field solutions that implement some of the aforementioned techniques do not provide the desire result to meet operator's expectation. Current research work by the authors in the area of context aware system promises to provide the intended result. The system utilizes two important context relating to crude oil incident. These contexts are motion and vibration context. Context sensors are used to detect potential threat to the crude oil pipeline. The detected context are transmitted to the cloud using a third party cloud-based platform as a service.

The sensed context is interpreted by a context manager which in turns transmit it to the user interface.
The system also incorporates Global Position System map in locating the précised location of the threat. The system also has the ability to initiate calls, send text message or email to responders when threat is detected.

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