Smart Pipeline Monitoring System: A Review

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Abstract— **In Africa's most populous nation, Nigeria, Pipelines are the primary way of transporting liquid and gas. Oil and fuel pipeline networks have proven to be the most secure and competitively priced way of transporting petroleum products while meeting increased demand for efficiency and durability. As a consequence of the negative impact of unreliable pipeline systems on society, the demand for a credible pipeline system is increasing by the day. Failure in pipeline systems can result in pollution and explosions, which pose a threat to people, property, and the ecology. Hence, this paper presents an overview of a smart pipeline monitoring system. The review encompasses the various methods of monitoring pipeline systems, ranging from traditional systems to IoT-based systems. From the papers reviewed, it was seen that there exist numerous methods to carry out pipeline monitoring. These approaches and methods produced different degree of accuracy and efficiency when applied in monitoring pipelines, and also depends on the content or material the pipeline carries. The review identifies key features of pipeline monitoring systems to include: real-time capability, predictive capability, scalability and accuracy. This paper reveals the possibility to adopt technology-based monitoring system as opposed to traditional methods.**

Keywords— Internet of Things, Monitoring, Pipeline, Smart, Vandalization.

I. Introduction

Crude oil, natural gas, chemicals, and other vital liquid hydrocarbons are transported primarily via pipelines, which are considered financial assets[1]. In terms of cost and safety, oil and gasoline pipeline infrastructures are among the most reliable and efficient means of shipping crude oil. [2][3]. However, as the use of miles-long pipelines to transport hazardous substances grows in popularity across the world so does the risk of catastrophic pipeline collapse increases. Pipeline failure can be caused by either deliberate (vandalism) or incidental (material failure and corrosion) damage, causing irreversible effects, such as lost income and environmental degradation, especially if the leak is not discovered immediately [4]. To prevent and mitigate these failures, various models of pipeline monitoring systems have been designed over time. In the 90s, an acoustic-based monitoring system was designed for monitoring pipeline systems. This model monitors intrusion into the pipeline right of way through impact detection. Sensor placement in this model was sparse, hence it experienced low sensitivity ratio. Also, the scalability index was low due to sophisticated and expensive filters [5]. Not long afterwards, the monitoring of pipelines using fiber optics cable emerged. In this model, an optical time-domain reflectometer (OTDR) is used to detect variation in light transmission. This variation is then used to detect vibration and pressure changes along the pipeline. This model is more effective for real-time monitoring and intrusion detection rather than leakage. Also, the scalability index is low due to sophistication in signal processing equipment. Hence it is costly to implement on a very large scale.

Another way to monitor pipeline systems is the use of satellite imagery to monitor pipeline areas. Images of the pipeline are taken at regular intervals and analyzed. This model is most applicable in monitoring pipeline networks that extend over a very large area. It is also applicable in monitoring and detecting leakages along pipeline networks. However, it is ineffective for pipeline real-time monitoring. IoT-based monitoring systems have been created as a result of the development of cloud computing, big data, and the Internet of Things (IoT). These systems use wireless sensor networks to monitor pipelines and communicate changes detected to a server. The server is then connected to an interface where actionable insights are derived [5]. By leveraging on any of these systems, high-potential situations are examined and adequately mitigated before leading to accidents. Furthermore, the risk profile of a system is considered when designing a pipeline network and its monitoring system. Assessing the possible consequences of failures, leaks and intruders would prevent significant losses from accidents, which in turn would have a huge impact on the business downside: the cost of lives involved; damage to facilities; environmental cleanup costs; related legal costs; economic losses and so on. In most cases, strict measures are implemented to reduce any risk that is deemed to have a high effect, regardless of the frequency of occurrence.

II. Literature Review

Oil theft and pipeline vandalism have continued uninterrupted in the Niger Delta (south-south area) for a long time, and the country's efforts to stop them have mostly failed. One of the motivations is a civil disorder in this region of the country. Pipeline vandalism is seen by Niger Delta militants and other disgruntled jobless youth as a method of living and expressing their frustrations against a visibly hostile Nigerian state and oil companies [6].

A. Traditional Pipeline Monitoring Approach in Nigeria

The deployment of in-house security employees is the first approach being used to monitor pipelines in Nigeria.

These men are typically unarmed and are employed by active oil corporations to interact with other outside security forces such as vigilante groups in the area. Vigilantes typically stay near the pipelines to protect them from local intruders. These vigilante groups gather information about individuals or organizations that may be plotting to steal oil by destroying pipelines. All security issues are reported to full-time security company vigilantes The federal government of Nigeria uses the Joint Task Force (JTF) to keep tabs on regions where there used to be oil saboteurs. Speed boats are frequently used by the Navy in regions where patrol vehicles cannot go, such as streams and wetlands [7]. The Nigerian government's second strategy for combating pipeline damage and vandalism in the Niger Delta region is to impose an amnesty. The Niger Delta is the country's oil-producing region, and violent riots are in full force. An amnesty program was established in 2009 to reduce the regionally higher level of risk associated with attractive rebels. Ex-combatants are persuaded to forego extremism and become productive members of their diverse communities through empowerment and monetary upgrade packages in this program [8]. Asides from these approaches, the use of an inner sensor to notice strain fluctuations used to be adopted to monitor the nation's pipelines [9]. A remote monitoring system is used to monitor the pressure sensor, which is commonly put within pipes. If the system indicates pressure fluctuations, the leak is presumed to have occurred. Authorities remotely close the pipeline's nearest valve, and security men and engineers are dispatched to intercede [9].

Additionally, one of the primary issues with present pipeline monitoring methods is corruption. According to Mele Kyari, CEO of NNPC Group, there is a trade-off between safety officials who must monitor and protect pipelines, community leaders who must locate pipelines, and energy industry employees who must monitor pipelines [10]. Most of the earlier bunker sites were in swamps, streams and remote places [11], making it difficult for security forces to identify bunker activities. Table 1 show some traditional methods used in pipeline monitoring and techniques used.

TABLE I. FEATURES OF TRADITIONAL PIPELINE MONITORING METHOD

Author	Traditional Pipeline Monitoring		
	Real-Time Monitoring	***Data Analysis and Predictive capabilities***	***Scalability***
[7]	✓	✓	✓
[8]	✓	✓	✓
[9]	✓	✓	✓

B. Fibre Optic-Based Pipeline Monitoring System

A proposed system to detect threats to a pipeline includes: a Distributed Acoustic Sensing (DAS) and a Pattern Recognition System (PRS) [12]. DAS collects signals along the pipeline. For the collection of signals; an optical sensor named FINDAS was used. FINDAS has a spatial resolution of 5 meters and a range of 45km using single-mode fibre (SMF). When acquiring data, the system sampled frequency at 1085Hz. The pattern recognition system used Gaussian Mixture Models (GMM) - as a baseline model - to analyse and process received signals. The signal processing occurs in 2 stages. The first stage identifies the activity while the second stage predicts if the activity is a threat. This system takes a step further by applying a speech recognition model (tandem approach) to the signal. This step enhances the feature vector of the baseline system. Results from experimental tests on the system reveal a significant improvement in predicting threats in a system. The results show a 12% reduction in false alarm prediction and 0.5% in predicting exact threats to a system [12].

Another system to notice very small leaks in gasoline pipelines using DAS was also developed [13]. The system used fibre cable applied in a helical shape along the pipeline to detect leakage. Due to the level of sensitivity required, a fibre of pitch 2.5cm was used. The system focused on signals between 0-5Hz to avoid interference with environmental noise. The system was able to detect pinhole leaks in pipelines and reduce leakages in the pipeline to 0.1%. This device, on the other hand, is well-suited for monitoring both short and medium-length pipelines [13]. Both [12] and [13] are based on the method of optical time domain reflectometry (OTDR). In [14], the internal corrosion and leakage in a pipeline were monitored using Optical Frequency-domain Reflectometry (OFDR) which is a technique of DAS - was used to monitor the pipeline. Measures hoop strain on the pipeline's outside via an array of fiber optic sensors spaced evenly apart. A program is generated when the hoop strain is measured in order to pinpoint the precise position and degree of the corrosion or leakage. Results from the monitoring revealed high efficiency and accuracy in detecting leakages and corrosion. However, further work is required to investigate the feasibility of the OFDR technique. Fiber-bragg grating (FBG) sensors and a back-propagation (BP) neural network were used to find pipeline leaks [15]. The FBG sensors are attached to the pipeline and monitor changes in hoop strain. The BP neural network then calculates the location of the leak. Results reflected robustness and preciseness of this approach in locating leaks along a pipeline [15].

It was discussed in [16] how a smart optic fiber monitoring system could be used to detect threats to pipelines. The system was deployed at an unknown location and time to determine the accuracy and performance optic fiber monitoring system. Following deployment, the system had an 80% accuracy rate and a 30 meter precision for real-time threat detection. When the distance between the sensor and the system increased, the signal quality suffered. Similar to this, [16] describes the creation of a long-distance pipeline monitoring system utilizing fiber-optic technology because of its performance over long-distance applications, the system monitor parameters in the pipeline at a distance of 125km without any problems encountered. This method also reduced operational risk and prevented delays in production over a long period. [16] argued that the installation is time and cost-friendly. Machine learning features applied to distribute acoustic sensing of pipelines was reviewed [17]. The feature extraction model is divided into three categories in the review: time-domain features, frequency-domain features, and time-frequency domain features. The review listed 2 stages in building a pattern classification system in machine learning to include; the training stage and classification stage. The review also classified machine models for pipeline monitoring into; generative and discriminative model [17]. Table 2 show some techniques, nature of monitoring, scalability used in pipeline monitoring by some authors.

TABLE II. FEATURES OF FIBER OPTIC-BASED PIPELINE MONITORING METHOD

Author	Fiber Optic Monitoring			
	Real-time monitoring	*Data analysis & Pred. capabilities*	*Scalabi -lity*	*Technique used*
[12]	✓	✓	✓	OTDR
[13]	✓	✓	X	OTDR
[14]	✓	✓	X	OFDR
[15]	✓	✓	✓	OTDR
[16]	✓	✓	✓	OTDR

C. *Iot-Based pipeline Monitoring System*

Pipeline monitoring methods are currently corrective rather than preventive. As a result, locating leaks and arresting vandals is complicated. However, with IoT-based monitoring, stakeholders will move from a reactive to a predictive and proactive monitoring mechanism. [18] Presented the development of a smart wireless sensor network testbed for water pipeline monitoring. The use of WSN improves reliability and accuracy. A functional wireless sensor node System on Chip (SOC) was created. The system employed a pressure-based leak detection Predictive Kalman Filter (LPKF). This system successfully detected leaks in pipelines over long distances by using leak detection and localization techniques. Although the system detected leaks in pipelines, it was not efficient in detecting leaks in real-time situations [18]. A smart multiproduct pipeline leakage monitoring system was implemented using big data, cloud computing, IoT technology, and distributed computing methods [19]. This method had a calculative error of less than 5%. The system identified leakage points in a very short period, to enable fast emergency response time. Regardless, the system lacked systematics data analysis functionality and decision-making in the presence of leakage and emergency [19].

A cognitive internet of things-based smart water monitoring system was developed in [20]. This system oversees a 50-kilometer water transportation pipeline network. The system utilized a TelosB sensor node placed at 100m from each other. These sensor nodes relied on flowrate to detect leakages in the pipeline system. Using the message queue telemetry transport (MQTT) protocol, data gathered from the nodes is sent to a local and cloud server. The transmitted data is then monitored, analysed and interpreted using an Apache spark framework. After analysis, the data is transmitted to a user interface after further breakdown by the Diagnosis Decision Making Module (DDMM). This system enabled end-users to gain insights and learnings from the data collected [20]. In a similar vein, [21] created a wireless sensor network-based pipeline monitoring system. This system included a highly interactive graphical user interface and 105 TelosB nodes spaced 100 meters apart. The placement of the sensor nodes, however, was zigzagged. The monitoring system made use of a four-tier network architectural protocol that featured a network control panel, a basic sink node, communication relay nodes, and data dissemination nodes. The system achieved a 99% packet delivery ratio, good energy efficiency, and high scalability prospects [21]. The sleep-wake pattern with several time synchronization messages in the modified multi-channel protocol stack was partially responsible for the outcomes.

An architecture for the construction of an industrial internet of things-based water pipeline monitoring systems was presented [22] due to difficulties encountered when scaling up pipeline monitoring systems. The proposed architecture consisted of four layers: a data collection and pre-processing layer, a data storage layer, a network layer, and a remote-control center. In the data collection layer, sensors, cameras, and RFID tags were used to gather signals from the pipeline system, and the data storage layer was used to store the data that was collected from the sensors. The data is then sent to a remote control center via the network layer, an intermediary layer [22]. Similar to this, [23] highlighted early successes in leveraging powerful IoT to monitor crude oil pipelines. The pipeline monitoring system was to be implemented using a distributed and hierarchical network design. The approach reduces the single point of failure (SPOF) that has typically been present in pipeline monitoring systems up until this point. In contrast to other systems, its architecture combined three distinct methodologies to find leaks. Methods included the negative pressure wave method (NPWM), gradient-based (GM), and pressure point analysis (PPA) (NPWM) [23]. Also, the architecture used the Ns3 application to model one-phase flow crude oil propagation and leakages [23]. Less complicated and requiring less storage space are the calculation techniques used in the design. An Internet - of - things smart pipeline monitoring system was proposed to have a 4-tier architecture [24]. The device suggested a structure made up of layers for sensory, communication, computing, and application. A combination of sensors: motion, cameras, action, stress, vibration, temperature, GPS and actuators, and radio frequency identification is proposed for the structure's sensory layer (RFID). These sensors would monitor variables like as flow rate, vibration, temperature, pressure, and location and would communicate with one another via a special addressing system. The communication layer, which connects the computing layer and the sensory layer, comes next. Wi-Fi is suggested to be used for short-range communication and 4G/5G for quicker and longer-range communication on the network.

[25] Created a smart real-time, big data, and distributed computing framework for the use of a multiproduct pipeline leakage handling system. For emergency treatment, new computational modules are proposed for locating leaks, estimating leakage quantities, and carrying out shutdown procedures. The technique put forward in this paper demonstrates ways of locating the pipeline leak's source and extent, as well as the addition of capability for carrying out emergency measures in cases where damages or leaks may result in human casualties and property losses. Moreover, [26] created a transient state water pipeline monitoring system based on a clever evolutionary algorithm. The system described in the article was developed using a cognitive water distribution system (WDS) that integrated IoT, big data, and numerous linked devices. By taking into account both the steady-state and transient glide of the water in the pipelines, the gadget was demonstrated to be both environmentally friendly and very accurate in identifying leaks but was unable to provide the precise site of the damage or leak. The level of the water in the pipeline was monitored by an ultrasonic sensor, and the user saw a live feed through an API interface automatically displayed using cloud traffic data. This approach was utilized by [27] to construct an automatic pipeline water leak detection and monitoring system based on cloud platforms and IoT

providing live feed and result in real time to enable the user keep track of the occurrence in the pipeline. Also, this method was successful in detecting the point of leakage in the pipeline. The application of an IoT analytic platform in monitoring petroleum pipeline systems exploited in [28], using the principles of vibration and time delay between pulse arrivals at the sensor point using Arduino and Wi-Fi modules to provide wireless communication. The system was able to identify pipeline activity, and the wireless communication system's performance produced satisfactory data recording results. When deployed in a real-time scenario from anywhere in the world using any internet-enabled device, the technology was also capable of locating damage on a real pipeline [28]. [29] Conducted research on a robust IoT-based monitoring system for crude oil pipelines to detect and mitigate pipeline failure. The technique was cost-efficient, Scalable, and efficient. Regardless the efficiency of the proposed technique, the method using in this paper was not applied in real time [29] .In a work done by [30], the use of IoT for the monitoring of oil pipeline based on Zigbee and Long-Range Architecture approach and the integration of a 2.4 GHz based ZigBee, Lora WAN and Wi-Fi Communication devices was employed in the development of an IoT based long range oil pipeline monitoring architecture system [30]. It was time consuming and had high financial implications. The Objective of monitoring oil pipeline at a long range was successful using 2.4GHz based ZigBee, LoRa and Wi-Fi communication devices [30]. Table III show some techniques, nature of monitoring, scalability used in pipeline monitoring by some authors.

TABLE III. FEATURES OF IOT-BASED MONITORING METHOD

Author	IOT Pipeline Monitoring		
	Real-Time Monitoring	*Data Analysis and Predictive capabilities*	*Scalability*
[18]	✓	✓	✓
[19]	✓	✓	X
[20]	X	✓	X
[21]	✓	X	✓
[22]	X	✓	✓
[23]	X	✓	✓
[24]	X	✓	X
[25]	X	✓	✓
[26]	✓	✓	✓
[27]	✓	✓	✓
[28]	✓	✓	✓
[29]	X	X	✓
[30]	✓	✓	✓
[31]	✓	✓	✓
[32]	✓	X	✓
[33]	✓	✓	✓

The architecture in [31] is made up of three modules: the control unit, the gateway device, and the smart object device. . The sensing layer was the smart object module, which incorporates pressure, temperature, sound, flow, and level sensors. The gateway module represented the network layer and was responsible for smart object to smart object communication and smart object to control centre communication. Communication between the smart objects used short range communication protocols while Communication between the smart object and control centre used long range communication protocol [31]. The control module (centre) is the brain that stores data from the smart objects, processes stored data and provides visualisation to the user. The offshore, midstream, and downstream oil and gas industries all have use cases for this suggested architecture [31]. A tracking and information management system for pipeline using RFID was developed. The system was developed to replace paper-based tracking system [32]. The tracking system uses RFID tags to track location and status of the pipeline, then an android mobile terminal – operated by a personnel and connected to a RFID reader - sends and receives data from the tag [32]. Then a control server aggregates data from all android terminals and uploads to cloud platform. The server was built on java server page and deployed on Ali Cloud platform. During the testing stage, the system RFID reader is able to read data from the tags at a maximum distance of 1m. The system proved resourceful in identifying location and depth of buried pipelines [32]. A cost-effective wireless sensor node was designed and implemented to monitor oil pipeline. The system measured vibration changes in the pipeline to monitor and detect changes/damages in the pipeline [33]. Three nodes were used in the system's design. Each sensor node included a 3-axis ADXL accelerometer, a 32-bit ARM core microcontroller, and a ZigBee RF transceiver. For testing, two of the sink nodes were fastened to an oil pipe made of carbon steel. Where the third node operated as the base station and was wired to a computer. The accelerometer-collected vibration signal.

D. Airborne-Based Pipeline Monitoring System

A method for accessing pipeline conditions through remote sensing and data visualization was developed in [34]. To identify targets and identify security issues, environmental dangers, and unauthorized entry into the pipeline right-of-way, this system uses satellite images and target identification analysis. The satellite-based system continuously records synthetic aperture radar and multispectral spatial pictures of the pipeline area [34]. Collected images are analysed using computerized change detection. If any issue is detected after analysis, higher resolution images can be captured over the particular area where the problem is identified. Accordingly, the system recorded a 93% detection rate as opposed to an 88% detection rate from other airborne systems [34], the system was capable of detecting leaks in underground pipeline systems but further research is needed in the identification of hydrocarbon products from numerous ones available. A system mapping and monitoring pipelines using unmanned aerial vehicles (UAVs) was reviewed [35]. The monitoring of pipeline systems using UAVs requires selecting the right sensor, UAV platform and data processing software. Sensors used to monitor pipelines include Gas IR sensor, active Lidar, radar, laser gas detector, laser fluorescence. Financial constraints, legal and flight restrictions, and lack of miniaturized sensors are challenges facing the adoption of UAVs for pipeline monitoring.

Notwithstanding, [35] maintains that UAV based monitoring system could serve as a better alternative to remote sensing methods because sensors employed can be changed and retrofitted over the lifetime of UAVs**.** Table 4 show some techniques, nature of monitoring, scalability used in pipeline monitoring by some authors.

TABLE IV. FEATURES OF AIRBORNE-BASED PIPELINE MONITORING METHOD

Author	Airborne Pipeline Monitoring		
	Real-Time Monitoring	***Data Analysis and Predictive capabilities***	***Scalability***
[34]	✓	✓	✓
[35]	✓	✓	✓

E. Robot – Based Pipeline Monitoring System

A 4-wheeled robot to monitor water pipeline system was designed in [36]. The robot casing was designed using a water-proof material and for a pipeline of 8-inches. Components used to develop the robots were; a DC power pack, obstacle detecting sensor, flow sensor and a camera. The robot incorporates a raspberry module as the processing unit. The raspberry controls movement and actions of the robot. At the user's end, a control interface was implemented using ESP8266 Node MCU, cloud storage platform and programmed using Arduino interface. The control centre allows users to review data collected during the robot movement [36]. There is needed to equip the system with real-time monitoring capacities and adaptability to different pipe sizes. An autonomous sensor-based robot to detect and rectify fault in pipeline systems was implemented. The sensor-based robot was cost-effective, scalable and customizable to fit various applications [37]. A mobile sensor called High Performance Mobile Sensor (HPMS), a fixed sensor called Multiple Channelled Redundant Array of Independent RFID Tags (McRAIT), and a robot agent called Fully Autonomous Topology-aware Mobile Pipeline Exploration Robot (FAMPER) made up the sensor-based robot [37]. The mobile sensor (HPMS) and the robot agent get location information from the stationary sensors (McRAIT), attached to the pipeline (FAMPER). The fixed sensors are inexpensive and passive RFIDs that are cost and energy efficient. The mobile sensor (HPMS), enclosed in a liquid resistant casing, monitors pipeline health through visual, sonar and pressure sensing. The mobile sensor flows along the content of the pipeline while relying on location tags from the McRAIT [37]. The robot agent (FAMPER) rectifies faults identified by the HPMS. The robot agent relies on a caterpillar wheel for movement inside the pipeline, a processing unit for navigation and control, sensing and actuation devices depending on the application [37]. Other notable work in this are in [38][39][40]. Table 5 show some techniques, nature of monitoring, scalability used in pipeline monitoring by some authors.

TABLE V. FEATURES OF ROBOT-BASED PIPELINE MONITORING METHOD

Author	Robot Pipeline Monitoring		
	Real-Time Monitoring	***Data Analysis and Predictive capabilities***	***Scalability***
[36]	✓	✓	x
[37]	✓	✓	✓

III. CONCLUSION

This review presents an overview of smart pipeline monitoring systems. It also presents the various methodologies that can be adopted in the development of a smart pipeline monitoring system. Currently, IoT-based smart pipeline monitoring systems are the most used methodology when developing pipeline monitoring systems. Followed closely by fiber optic-based monitoring systems which provide near accurate threat detections in pipelines. While, the use of unmanned aerial vehicles and robots to monitor pipelines have not been properly explored as viable alternatives. Furthermore, this review reveals the possibility to adopt recent monitoring methods rather than rely on traditional method which is inefficient and expensive. This review also identifies real-time capability, predictive capability and scalability as key features to consider when selecting and implementing a pipeline monitoring system. Although, cost and accuracy are other key features to consider, very little literature dwells on the cost and accuracy of their monitoring systems. Further work is needed to examine the efficiency of modern pipeline monitoring systems in public domain and industrial use cases

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REFERENCES

[1] K. Rehman, F. Nawaz. "Remote pipeline monitoring using Wireless Sensor Networks," in Conf. Communication, Computing and Digital Systems, Islandbad, Pakistan, 2017.

[2] L. Boaz, S. Kaijage, R. Sinde. "An overview of pipeline leak detection and location systems," in 2nd Pan African Conf. Science, Computing and Telecommunications, Arusha, Tanzania, 2014.

[3] R. Cramer, D. Shaw, R. Tulalian, P. Angelo, M.V. Stuijvenberg, "Detecting and correcting pipeline leaks before they become a big problem," Mar. Technology Society, vol. 49, pp. 31–46, 2015.

[4] L.A. Ajao, E.A. Adedokun, C.P. Nwishieyi, M.A. Adegboye, .J. Agajo, J.G. Kolo, "An Anti-Theft Oil Pipeline Vandalism Detection: Embedded System Development," Eng. Sci. Appl., vol. 2, pp. 55–64, 2018.

[5] K. R. Anupama, N. Kamdar, S.K. Kamalampet, D. Vyas, S. Sahu, S. Shah. "A wireless sensor network based pipeline monitoring system," In Conf. IEEE Signal Processing and Integrated Networks, pp. 412-419.

[6] A.C. Okoli, "Oil pipeline vandalism in the Niger Delta," 2019. Available:https://www.accord.org.za/conflict-trends/oil-pipeline-vandalism-in-the-niger-delta/

[7] Al-Jazeera News. (2014). *Tracking oil theft in Nigeria* [Online]. Available: URL https://www.aljazeera.com/indepth/inpictures/2014/09/pictures-tracking-oil-theft-nig-201498195636567970.html.

[8] C. Achilike and MacDonald, "Securing Nigeria's crude oil and gas pipelines - change in current approach & focus on the future". ISSN 2201-2796, Harlow: Prentice Hall, 2017.

[9] M.A. Aibinu, J.A. Ojo, J.A. Oke, I.D. Solomon, P.O. Idowu, "Pipeline Monitoring System: A feasibility study", International Journal of Computer Trends and Technology ISSN:2231 – 2803, 2021

[10] Premium Times News (2019). *Nigeria loses $1.35 billion to oil theft in six months* [Online]. Available: URL https://www.premiumtimesng.com/news/headlines/353301-nigeria-loses-1-35-billion-to-oil-theft-in-six-months.html

[11] J. Sun, Z. Zhong, X. Sun. "The intelligent crude oil anti-theft system based on ICT under different scenarios," in Conf. Knowledge-Based and Intelligent Information and Engineering Systems, York, United Kingdom, pp. 1581-1588, 2016

[12] Vanguard News (2019). *Breaking: Many feared killed as pipeline explodes in Ijegun-Ikotun, Lagos* [Online]. Available: URL vanguardngr.com/2019/07/breaking-oil-pipeline-explodes-in-ijegun-ikotun-Lagos/.

[13] J.Tejedor, J. Macias-Guarasa, H.F. Martins, D. Piote, J.Pastor-Graells, S. Martin-Lopez, M. Gonzalez-Herraez, "A novel fiber optic based surveillance system for prevention of pipeline integrity threats" Sensors, vol. 17(2), 355, 2017

[14] P. Stajanca, S. Chruscicki, T. Homann, S. Seifert, D. Schmidt, A. Habib, "Detection of Leak-Induced Pipeline Vibrations Using Fiber—Optic Distributed Acoustic Sensing" Sensors, vol. 18(9), pp. 2841-2853, 2018

[15] L. Ren, T. Jiang, Z. Jia, D. Li, C. Yuan, H. Li, "Pipeline corrosion and leakage monitoring based on the distributed optical fiber sensing technology" Measurement, vol. 122, pp. 57-65, 2018.

[16] Z. Jia, L. Ren, H. Li, W. Sun, "Pipeline Leak Localization Based on FBG Hoop Strain Sensors Combined with BP Neural Network", Applied Sciences, vol. 8, no. 2, pp. 146-158, 2018.

[17] M. Niklès, F. Briffod, R. Burke, G. Lyons. "Greatly extended distance pipeline monitoring using fibre optics," in Conf. Offshore Mechanics and Arctic Engineering ,Vol. 41979, pp. 539-546, 2005

[18] J. Tejedor, H. Macias-Guarasa, J. Martins, P. Pastor-Graells, P. Corredera, S. Martin-Lopez, "Machine Learning Methods for Pipeline Surveillance Systems Based on Distributed Acoustic Sensing: A Review", Applied Sciences, vol. 7, no. 8, pp. 841-852, 2017.

[19] F. Karray, A. Garcia-Ortiz, M.W. Jmal, A. M Obeid, M. Abid. "Earnpipe: A testbed for smart water pipeline monitoring using wireless sensor network," Procedia Computer Science, vol. 96, pp. 285-294, 2016.

[20] G. He, Y. Li, Y. Huang, L. Sun, K. Liao, "A framework of smart pipeline system and its application on multiproduct pipeline leakage handling" Energy, vol. 188, pp. 11603-11611, 2019.

[21] M. Abdelhafidh, M. Fourati, L.C. Fourati, A.B Mnaouer ,Z. Mokhtar. "Cognitive internet of things for smart water pipeline monitoring system," In Conf. IEEE/ACM Symposium on Distributed Simulation and Real-Time Applications, pp. 1-8, 2018

[22] K. R. Anupama, N. Kamdar, S. K. Kamalampet, D. Vyas, S. Sahu, S. Shah. "A wireless sensor network based pipeline monitoring system," In Conf. on Signal Processing and Integrated Networks pp. 412-419, 2014

[23] M. Abdelhafidh, M. Fourati, L. Fourati, A. Abidi. "Remote Water Pipeline Monitoring System IoT-Based Architecture for New Industrial Era 4.0," in Conf. on IEEE/ACS Computer Systems and Applications. 2017

[24] S. Ahmed, F. Le Mouël, N. Stouls. "Resilient IoT-based monitoring system for crude oil pipelines" In Conf. IEEE on Internet of Things: Systems, Management and Security, pp. 1-7, 2020

[25] T. Ayeni, B. Ayogu, "Intelligent Pipeline Monitoring System Based on Internet of Things," Scientific Research Journal, vol. 8(8), pp.44-49, 2020.

[26] W. E. Roper, S. Dutta. Oil spill and pipeline condition assessment using remote sensing and data visualization management systems. In Freshwater Spills Symposium, Natural Disasters, Human Error, and Equipment Failure-Causes for Major Inland Oil Spills and the Resulting Multifaceted Response, 2006.

[27] G. He, Y. Li, Y. Huang, L. Sun, K. Liao, "A framework of smart pipeline system and its application on multiproduct pipeline leakage handling," Energy, vol. 188, 2019.

[28] M. Abdelhafidh, M. Fourati, L. ChaariFourati, "A genetic algorithm-based intelligent solution for water pipeline monitoring system in a transient state" Concurrency and Computation: Practice and Experience, vol. *34*(7), 2022.

[29] Z. Shi, M. Wang, H. Lin, H. Lin, Z. Gao, L. Huang. "NB-IOT pipeline water leakage automatic monitoring system based on cloud platform" in Conf. on Anti-counterfeiting, Security, and Identification, pp. 272-276, 2019.

[30] E.N. Aba, O.A. Olugboji, A. Nasir, M.A. Olutoye, O. Adedipe, "Petroleum pipeline monitoring using an internet of things (IoT) platform" SN Applied Sciences, vol. 3(2), pp. 1-12, 2021

[31] M.A. Adegboye, W.K. Fung, A. Karnik, "Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches" Sensors, vol. 19(11), 2019.

[32] R. Singh, M. Baz, C.L. Narayana, M. Rashid, A. Gehlot, S.V. Akram, A. S. AlGhamdi, "Zigbee and long-range architecture based monitoring system for oil pipeline monitoring with the internet of things". Sustainability, vol. 13(18), 2021.

[33] G. Giunta, K.L. Nielsen, G. Bernasconi, L. Bondi, B. Korubo. Data driven smart monitoring for pipeline integrity assessment. in Conf. OnePetro Petroleum Exhibition & Conference. Abu Dhabi. UAE, 2019

[34] W. Khan, M. Aalsalem, M. Khan, M. Hossain, M. Atiquzzaman. "A reliable Internet of Things based architecture for oil and gas industry" in Conf. on Advanced Communication Technology, 2017.

[35] W. Ji, M. Chen, J. Davies, Z. Xu, B. Wang, K. Sun. "The Development of a RFID-based Smart Pipeline Tracking and Information Management System" in Conf. on Automation and Computing, 2018.

[36] F. Nasheed I. Mossa1, F. Waleed F. Shareef Faez F. Shareef, "Design of Oil Pipeline Monitoring System based on Wireless Sensor Network" Iraqi Journal of Computer, Communication, Control and System Engineering, pp.53-62 2018

[37] W.E. Roper, S. Dutta, S. Oil spill and pipeline condition assessment using remote sensing and data visualization management systems. In Freshwater Spills Symposium, Natural Disasters, Human Error, and Equipment Failure-Causes for Major Inland Oil Spills and the Resulting Multifaceted Response, 2006

[38] C. Gómez, D.R. Green, "Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping" Arabian Journal of Geosciences, vol. 10(9), pp. 1-17, 2017.

[39] R. Sujatha, P. ParixitHariprasad, "Robot based Smart Water Pipeline Monitoring System. IOP Conference Series: Materials Science and Engineering" vol. 906(1), 2020.

[40] Kim, Jong-Hoon, "Sensor-based autonomous pipeline monitoring robotic system" Sensors, vol. 3, 2011.