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*Review Article*

# Pipeline Monitoring System: A Feasibility Study

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***Abstract** - Pipeline is a medium through which fluids can be transported from one location to another. It is basically used to efficiently transport liquid and gaseous commodities over long distances at a low cost. Water, regular gases, petroleum products, and liquid hydrocarbons are examples of transportable pipeline commodities. The need for an efficient and reliable pipeline system is increasing by the day as a result of the detrimental effect of unreliable ones on society. Failure can result in environmental pollution and explosions, which can destroy lives, properties, and the ecosystem; moreover, the cost of restoring the ecosystem to its origin or natural form may be very costly or nearly impossible. To this effect, there is a need for pipeline monitoring systems (PMS) that will manage the pipeline network against such detrimental effects. This paper review some of the existing PMS highlights their sensing techniques, merits, de-merits, and areas of possible applications either onshore (surface or underground pipelines) or offshore (underwater pipelines). It also highlighted key components of PMS and classified the existing PMS into direct and indirect sensing, based on the sensing medium employed in their various methodologies.*

***Keywords** - Infrared, offshore, onshore, Pipeline Network, Pipelines Monitoring Systems (PMS), Radio Frequency (RF), Sensor Clusters, Sensors Node, Wireless Sensor Networks (WSNs)*

## I. INTRODUCTION

Pipelines are basically used to efficiently transport liquid and gaseous commodities over long distances at low cost. Water, regular gases, petroleum products, and liquid hydrocarbons are examples of transportable pipeline commodities. Pipeline failure can be a result of erosion, wear, and tears in the pipeline wall, intentional and accidental vandalism, extreme environmental events such as earthquakes, erosions, and volcanic eruptions, among others. The cause of failure can be classified as natural and man-made. Oil and natural gas consumption are forecasted to increase in the next several decenniums [1]. This assertion makes pipeline safety, distribution, and usage critical.

Pipeline damage or failure can result in manifold consequences [2]. Pipes convey highly volatile and hazardous liquids and gases that pose a serious threat to human lives if there is unchecked spillage to the environment. Pipeline failure can result in financial losses from operation downtime, lost-product, clean-up cost (direct financial loss), and losses in the form of lawsuits and fines (Indirect financial loss). Pipeline failure can also result in environmental pollution and explosions, which can destroy lives, properties, and the ecosystem. The cost implications of pipeline failure can be extremely difficult to predict. The importance of pipeline monitoring cannot be over-emphasized; it will minimize losses due to failure and also save the environment from damages.

Pipelines are fabricated to resist rust, corrosion, and degradation. The manufacturing processes involve the use of quality materials that can stand the test of time and reduce the deterioration rate. Coating and Cathodic protection are used to reduce rates of corrosion and degradation in pipes [3]. However, pipelines are still subject to leakages, wear and tears due to various aforementioned reasons. Pipeline Monitoring System (PMS) is the network of hardware and software components involved in detecting possible leakage and vandalism before the occurrence, during, or early after occurrence before getting out of control. PMS can be on-line or periodical. On-line PMS are systems capable of detecting leakage or attacks on Pipeline in real-time, while periodic PMS are those that may detect leakage or attacks a bit later after the deed is done. Pipeline leakage has gained recognition as an international problem in that it causes serious fluid and gas shortages in virtually every country of the world.

This can result in revenue losses and also adversely affect national reserves. An example of such a case was the report that in Europe, at least 25% of water is being leaked in the pipeline network. In some developed countries, it was reported that water leakage in the pipeline is as high as 50% [4], [5], [6]. Several developed Countries experience serious water shortages yearly [4]. Hence, there is a need for an efficient and reliable pipeline system that limits these detrimental effects on society to the barest minimum. Also, in the production and distribution of Natural gas or oil, reliable and economical infrastructure is needed, and one important component in the infrastructure is the pipeline [7].

There is a significant increase in water, gas, and oil usage yearly, and this has led to serious research efforts to design PMS, which will minimize or eliminate leakages in pipelines. Such systems are known as Pipeline Leak Detection Systems (PLDS). Wireless Sensor Networks (WSNs) are reported by PMS researchers as one of the effective ways to detect leaks. There are several advances in WSNs that enable researchers to have easy, efficient, flexible, and practicable ways to design on-line monitoring models for pipelines [8]. WSNs basically employ a communication mechanism that uses General Packet Radio Service (GPRS), microwave, and radio modems. WSNs are comprised of sensor nodes that could be stationary or mobile. A node can consist of one or more sensors measuring different parameters of the content or the pipeline itself. The mode of deployment of the sensors can be external (on the surface of /around the pipeline) or internal (inside the pipeline). The mode of deployment depends on several factors like the type of pipeline and so on.

Nigeria is the eleventh biggest oil producer in the world and the biggest in Africa; the Petroleum sector is the backbone of Nigeria's economy; it contributes 25% of the Gross Domestic Products (GDP) and about 90% of the country's remote trade income. The nation relies heavily on pipelines for oil transportation to various parts [9]. Pipelines are dedicated to transporting delicate and valuable contents such as petroleum, chemicals, and common gas. The pipelines are damaged by hoodlums so as to get the contents inside. Hence, pipelines are prone to terrorism, vandalism, and unintentional damages through excavation. Pipeline leakages, if not tamed, can result in inconceivable calamities.

Pipeline systems can be installed onshore (above the ground or underground) or offshore (underwater). They can traverse thousands of kilometers, be channeled through severe and remote terrain, and be set-up in places that may be prone to natural threats such as avalanches or tremors [10]. The underground pipelines are one of the essential mediums through which a large amount of fluid (freshwater, sewage, fuels, crude oil, and natural gases) is transported, and this is as a result of their merits in terms of concealment and safety [11]. Although the underground pipeline system provides a safe way of transporting a large amount of fluid over a long distance, it is still faced with other challenges like extreme soil condition, corrosion, and malicious attacks by human activities (like vandalism, constructions, and digging) which may result to leakage or leakages in the system.

Pipeline systems may be used in transporting different contents at different times; such a system is known as a multiphase flow system. Multiphase flow pipelines cannot be accurately monitored using many of the techniques currently developed. Also, the position of the pipeline (off-shore, on-shore, underground) requires different detection/sensing techniques. These make it impossible to develop a single standard PMS that can be used for all piping systems. The main purpose of PMS is to detect, locate and classify threats before it causes leakage or initiates necessary action to forestall the aftermath of leakage(s) [12].

## II. CLASSIFICATION OF PIPELINE MONITORING SYSTEM (PMS)

Numerous sensor network frameworks have been designed and implemented, some to detect faults, others to detect, locate and report any irregularities in the system [13]. There are several classifications for PMS in kinds of literature; some categorized PMS as 'hardware' and 'software' based methods [14], [15], [16], [17]. Some authors classify PMS as earlier and added a third category, i.e., biological or non-technical method [18]. Other authors categorized PMS as optical and non-optical methods [19]. In recent times, PMS has been classified as automated, semi-automated, or manual detection methods in respect to the required level of intervention by humans for operation [20]. In this study, PMS is classified as shown in Fig 2.

## III. KEY COMPONENTS OF PIPELINE MONITORING MODELS

The key components of PMS are the power supply module, the sensors clusters, the communication module, the sensor node, the communication medium, and the base station, as shown in Fig 1. These are discussed in detail in the sections below.

### *A. Power supply module*

The power supply is critical for the hardware components of PMS, such as sensors, nodes, transceivers, processors, display units, and so on, both at the monitoring points and the base station(s). Since pipelines are designed and fabricated to last for several years, proper power management is needed. Therefore, the associated monitoring system should also last long, if possible, outlive the pipeline. Low power hardware components should be used to limit power usage by PMS, especially in the case of on-line PMS. For proper power management, diverse techniques were developed, such as solar cells, low power components, data filtration and aggregation, and routing protocols management [21].

A wireless sensor node is majorly used when it is nearly impossible to run mains to the sensor node. Moreover, changing of battery regularly in wireless sensor nodes in hard terrain might be inconvenient, costly, or nearly impossible. It is of paramount importance to ensure that adequate energy is available for all the components in a PMS. The sensor node requires power for sensing, data processing, and communication. Power is stored in batteries, which can be either rechargeable or non-rechargeable. Sensors are mostly powered by batteries which could be classified by the electrodes' electrochemical materials. They can be NiZn (nickel-zinc), NiCd (nickel-cadmium), and lithium-ion. Current technologies have made it possible to have a way of charging sensor node batteries using energy from solar sources, temperature differences, and other sources. Two power management schemes were discussed by [22], are Dynamic Voltage Scaling (DVS) and Dynamic Power Management (DPM).

### *B. Sensors Cluster*

Sensors are devices that detect changes in the physical properties of substances or its surrounding. They are designed to send information out to other electronic devices for further processing. Sensors can be digital or analog depending on the signal it produces. A system with more than one sensor is known as a multi-sensor system. Due to technological advancements, sensors now come as a microscopic devices as opposed to conventional macroscopic sensors. Hence, sensors can be classified as microscopic and macroscopic, depending on size. Microscopic sensors are faster, more efficient, and sensitive than macroscopic sensors [23], [24]. Sensors can be of wired and wireless type. Wireless sensors are cheap due to complementary metal-oxide semiconductors (CMOS) technology. A power source must be connected to a sensor before it can operate. Sensors are used in various applications such as smoke detector systems, intruder alarms, PMS, surveillance systems, and so on. Sensors can be used to capture data in its environment. A sensor is a hardware device that responds to changes in physical conditions like pressure, temperature. Sensors have characteristics such as sensitivity and accuracy. An analog sensor can be digitized by using an analog-to-digital converter (ADC). The digital output is then sent to a microcontroller for the required processing. Digital sensors possess in-built electronics that convert raw signals to digital readings, which can be transmitted via a digital link. Sensors are usually miniature, with low power consumption, and can be autonomous and adaptive. Sensors can be classified into four categories: omnidirectional, passive, narrow-beam, and active sensors. Passive sensors acquire data without the manipulation of the environment by actively probing it. Active sensors (radar sensors) probe the environment actively and require a constant energy supply from a power source. Narrow-beam sensors have defined measurement ranges and directions. Omnidirectional sensors have no direction of coverage - it has a 360-degree coverage. Each sensor has a coverage area in which it can accurately report its observed quantity.

### *C. Sensors Node / Processing Module*

A sensor node, otherwise known as a mote, is a point in the sensor network capable of performing some information gathering, processing, and communication to other nodes or directly to the base station in the network. The sensor node is made up of a microprocessor chip, transceiver, power source, external memory, and one or more sensors. The sensors node is the junction where two or more sensors interconnect. The function of the chip is to aggregate and process signals/measurements from the sensors and send them to a control/base station

#### *a) Microcontroller*

The microcontroller gathers sensor data, processes it, and controls how other components in the sensor node function. The choice of microcontroller in most embedded systems such as sensor node is due to its low cost, low power consumption, and ease of programming. A Digital Signal Processor may be used for broadband communication but is not always chosen for sensor nodes due to its higher cost and power consumption.

#### *b) Transceiver*

Sensor nodes often make use of the Industrial Scientific and Medical (ISM) band, which is globally available and provides free radio spectrum allocation. A transceiver is a device with the functionality of a transmitter and a receiver that uses an ISM band for operation. The state of operation of a transceiver can be sleep, idle, transmit and receive. A transceiver connected to a microcontroller can perform some operations automatically due to how the microcontroller is programmed. If a transceiver is in idle mode, its power consumption is close to that of when it is in receive mode. When switching from sleep to transmit mode to transmit a packet, a significant amount of power is consumed. Hence, there is a need for proper power management, especially for PMS, to ensure that its operational [25].

#### *c) External memory*

Microcontrollers always have on-chip memory or RAM, but flash memory or off-chip RAM might be needed if the application demands it. There are two categories of storage, and the first is program memory used for device programming and identification data storage. The second is user memory used for storing application data.

### *D. Communication Module*

This can be on the transmitting end (mote) or receiving end (base station), having a transmitter and receiver module. The communication module can have wireless or wired capabilities. The transmitters are responsible for sending out data, while receivers are used as receptors of data/signals.

### *E. Communication Medium*

This is the path through which data (signal) is propagated. This largely depends on the communication module to be used. The transmission path can be an optical fiber, through the wire and by electromagnetic means. Hence, the communication interconnectivity can be either wired or wireless. Wireless Sensor Network (WSN) is widely used in PMS because of low cost, compatibility with other methods, suitability for use under adverse conditions, and reliability. Its challenges are power sustainability and multimedia transmission requirement. The possible choices of wireless transmission media are radio frequency (RF), optical communication (laser), and infrared. Lasers require line-of-sight for communication, less energy, and sensitivity to the atmosphere. Infrared needs no antenna but has a limited broadcasting range. Radio frequency-based communication is the most widely used for WSN applications. WSNs make use of license-free ISM frequencies: 173, 433, 868, and 915 MHz; and 2.4 GHz. [22].

### *F. Base Station*

In a PMS, the base station is where the data from various nodes are received, analyzed, classified as a possible leak; the point of action location is stored to be retrieved for future use. The base station can be fixed or mobile and usually has a receiver/transceiver, computer, or mobile system with possible software to process the data to detect, classify and locate leaks in the pipeline.

## IV. MONITORING TECHNIQUES FOR PIPELINE

The aim of PMS leak detection is to detect, locate and estimate the size of pipeline leaks in real-time. Several pieces of research have been carried out to achieve this aim, one

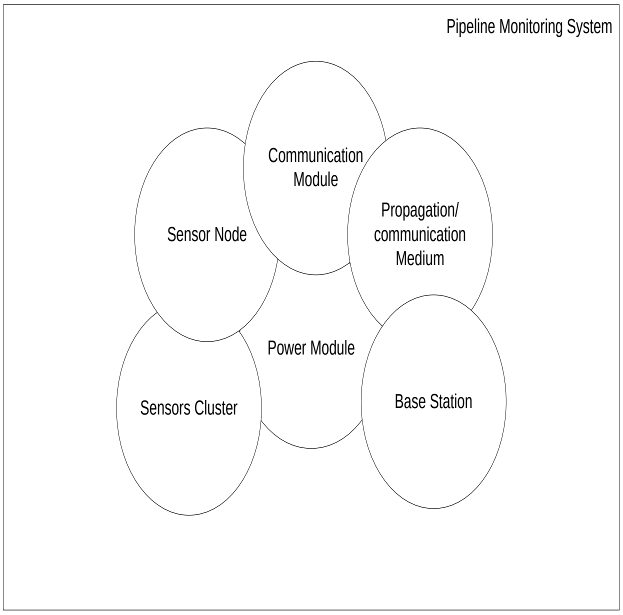


**Fig. 1 Interconnectivity of Key Components of Pipeline Monitoring Systems**

of the early papers in pipeline leak detection is a review a paper published in 1967 by Morris. He investigated water pipeline damages in terms of modeling and management [26]. Morris highlighted key factors to predicting water pipe damages. [27] and [28] gave a comparison of PLDS models available for PMS. Many researchers have used monitoring frameworks that are externally placed sensor nodes from the pipelines. Sensors are used in taking physical properties such as pressure, temperature, soil properties along and pipeline route others. For underground pipelines, sensors are installed along the pipelines at intervals and buried with the pipeline. Such detection modalities can result in accurate leakage detection and localization.

### *A. Direct Methods*

These methods are further subdivided into visual and biological methods, as shown in Fig 2. That is either the use of autonomous events capturing or the use of living animals or trained specialist (skilled human beings) to capture events around the pipeline network.

#### *a) Visual Methods*

This method involves the use of helicopters, Unnamed Aerial Vehicles (UAVs), Remotely Operated Vehicles (ROVs), and satellites to capture real-time multispectral images of pipeline routes which can be analyzed by certified personnel to detect the leak and its location. UAVs can monitor pipeline surroundings for leakage or threats of damage, can also detect bursts and cracks along pipelines [29]. The development of various ROVs has made an inspection and monitoring pipelines in hazardous, inaccessible, and remote environments possible [30]. The drawbacks of this method are the high cost of ROVs and performance restrictions due to Chicago agents such as clouds and winds.

#### *b) Biological Methods*

This is the traditional method of leak detection. It involves walking along a pipeline to search for a moist spot that is a resultant of leaks [15]. It involves the use of experienced personnel and trained animals like dogs to monitor pipeline surroundings for leakage or threats of damage. In some cases, a trained dog is more sensitive to gas odors than pigging and humans [31], [32].

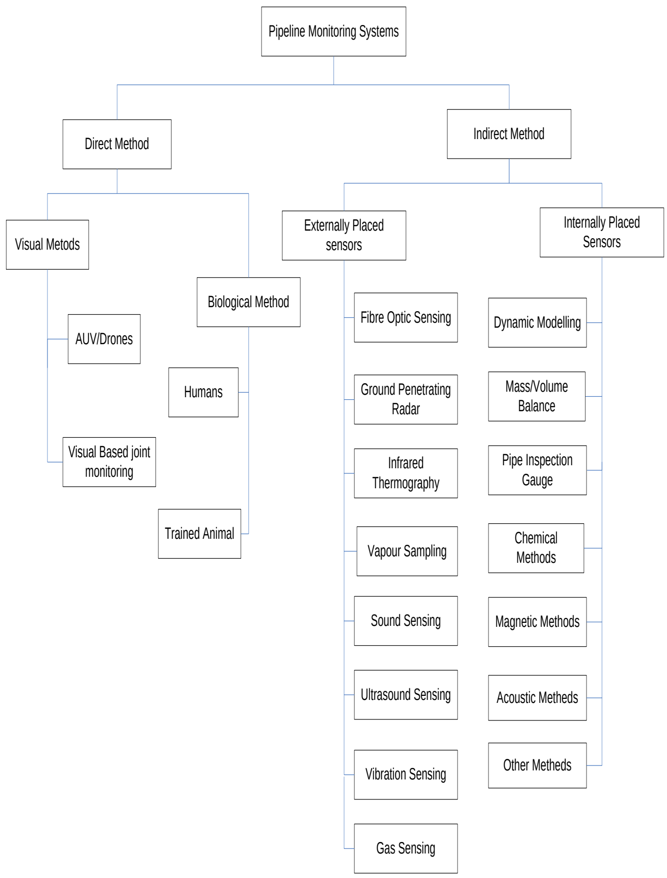


**Fig. 2 Classification of Pipeline Monitoring System**

Limitations: Humans and dogs cannot effectively monitor pipelines for more than 120minutes continuously due to fatigue [33]. The high cost of implementation due to the frequency of inspection in order to be effective requires a high level of human involvement. It is also inadequate for off-shore and underground pipeline monitoring.

### *B. Indirect Methods*

These techniques use special measuring devices; these devices have been proven to be efficient in the detection and localization of leaks in pipelines. They can be sub-classified based on the nature of the detection device.

#### *a) Exterior Based Methods*

Exterior methods are techniques that employ specific sensing devices to monitor pipelines exterior. These methods can detect leakage occurrence and pipeline surrounding abnormalities. The sensing under these methods typically requires contact with the pipeline surface. This section discusses the strengths, limitations, and operational principles of these methods.

#### *1) Acoustic Emission Sensors*

Acoustic emission utilizes the vibration or noise generated due to sudden drop or rise in fluid pressure to determine if there is leakage or risk of leakage due to too much pressure. Pipeline leakage can generate elastic waves of up to 1MHz [34] as a result of pressurized contents escaping through a small opening which makes leakage detection possible [35] . Two acoustic sensors are used in detecting the leakage point by measuring the time lag between the signals of the two sensors [36]. Acoustic methods can be either passive or active [37]. Active acoustic methods use pipeline wall reflected echoes that originate from the leakage sound pulses emission. The passive method simply utilizes changes in pressure wave sounds to detect leakages.

Acoustic sensors can be of three categories: Geophone, aquaponic, and acoustic correlation techniques. Geophones and aquaponics can locate and detect leakages, but both techniques are slow in operation. Acoustic correlation, which gives better performance, proves to be a more complex technique [38], [39]. Several literatures report acoustic emission usage in pipeline leak detection [40], [41], [42].

Hidden Markov Model (HMM) and Linear Prediction Cepstrum Coefficient (LPCC) were used to analyze damaged acoustic signals in [43]. [44] placed acoustic sensors at different points on a 3.13km gas pipeline to detect leakage. The conclusion was that low-frequency signals could be used to detect leaks successfully. Acoustic emission techniques can result in early leak detection, leak size estimation, and leak localization [45] . Despite the listed advantages of these techniques, the limitation is that background noise can cloak leak sound, which could result in false leak signals. Several signal analytics were proposed in kinds of literature to overcome this limitation, like interrogation methods, Waverley transforms, and use of other sensor types with acoustic sensors [46], [47], [42], [48].

The cross-correlation method was used to detect multiple leakages in underground pipes by [49]. The technique proved that two detectors positioned at either side of the pipe could be used to efficiently measure acoustic emission signals. [50] proposed feature extraction and noise elimination on weak leak signatures using wavelet entropy. Generally, acoustic emission techniques for PMS are easy to install

#### *2) Accelerometers*

Most accelerometer operates on the principle of piezoelectric effect which is the conversion of accelerator forces to electrical signals. The electrical signals are then processed to determine the voltage and orientation of the disturbance. Piezoelectric accelerometers perform this task by using microscopic crystals. It is similar in operation to acoustic sensors in that they are both vibroacoustic devices.

The accelerometer can also be used in pipe-shell low-frequency vibration detection [51]. Accelerometer-based leak detection and localization techniques were proposed in the literature [52], [53] . In [52] wireless accelerometer was placed on the exterior of the pipeline to detect leakage. [53] proposed the use of the accelerometer to analyze cross-spectral density vibration at crucial points (bends and joints) of the pipeline. [54], [55] used hydrophones in conjunction with accelerometers for PMS. Researchers that employed the use of accelerometers for PMS reported that it gives satisfactory performance and can be used with other sensors for more robustness.

#### *3) Fiber Optic Sensing (FOS)*

This method involves running fiber optic cable in close proximity to the pipeline and must extend through the whole pipeline length. When there is a leak, the cable will sense a temperature change at the leakage point [56]. One of the main advantages of FOS is that it is resistant to electromagnetic interference; hence it can accurately measure a very small change. In this method, fiber optic sensors are placed on the pipe surface at different points. FOS can be installed as the point or distributed sensors. The fiber optic method of leak detection operates on the principle that when pipe contents leak and come in contact with the cable coating, the temperature of the cable will change. The temperature variations in the fiber optic cable indicate anomalies in the pipeline [35]. Distributed Optical Fibre sensor (DOFS) uses Raman, Rayleigh, and Brillouin scattering to measure environmental parameters [57]. Brillouin scattering is highly sensitive to strain but can also measure stress and temperature. Raman scattering is sensitive to the only temperature, and it can measure as low as 0.01 ◦C [57]. It gives backscattered fluctuations of light intensities, which are a result of temperature changes. It employs a frequency shift mechanism that has two components: stoke and anti-stoke, which constitute the backscattered light [58] . Several examples of fibre optics-based PMS are found in literature [59], [60], [61] [62]. The main advantage of fiber optics-based PMS is the ability to detect minute leaks [63]. It can also be used in subsea and surface pipelines and can monitor long pipelines.

Limitations: Unsuitable for the underground pipeline; costly in terms of implementation and maintenance, short lifespan, challenging installation because of the cables fragile nature and inability to estimate leakage rate. It cannot be used in conjunction with other methods.

#### *4) Ground Penetrating Radar (GPR)*

Ground Penetration Radar (GPR) is an environmental tool that has proved to be effective in the identification of underground pipelines, landfill debris, and other buried materials [64]. Hence, GPR is an underground monitoring tool. It is useful in mine detection and dates back to the 1990s [64]. GPR utilizes scattering and electromagnetic wave propagation techniques to find abnormalities in the electrical and magnetic properties of the soil around the pipeline. It produces high-resolution images in a non-intrusive manner [65]. [66] proved that GPR is an effective tool in the detection and monitoring of buried objects. The radar generates and propagates electromagnetic waves to the ground, and the wave is reflected back to the surface on encountering dielectric properties of a pipe. This method can be deployed on a large scale for PMS [23].

Limitations: Unsuitable for offshore, and underwater pipelines, it is costly in terms of implementation and may not be suitable for real-time monitoring. GPR can be corrupted by noise such as background or surrounding noise. To overcome this shortcoming, signal processing approaches were employed to eliminate the noise from the GPR signals [67] [68]. Kalman filter was employed in [69] to filter impulse GPR signals to detect landmines. A particle filter was used as an improvement on [69] by [70].

#### *5) Vapor Sampling Method*

This method is basically used to detect if there is a degree of hydrocarbon vapor in the pipeline neighborhood. [71] reported that oil leaks can be detected by measuring the concentration of gas captured by a sampling tube as a function of the pumping time. The sampling tube is filled with atmospheric pressured air, which is pressure-dependent. If there is leakage, vapor diffuses to fill the tube, and this will in-time create an amassed signal, suggesting hydrocarbon presence in the surrounding tube [16]. [20], [72] and [73] are some of the vapor sampling-based PMS available in the literature. [73] proposed hydrocarbon permeable cylinder-based sniffer tubes to detect oil spillage from pipeline. [7] reported that a sensor hose must be installed under the pipeline to accurately detect gas diffusion due to leakage.

Merits of vapor sampling PMS are: the ability to detect small leaks, ability to detect leaks in multiphase flow pipeline systems and, independence to pressure and flow balance [45]

Limitation: Vapor sampling-based PMS has a slow response time, i.e., it detects leaks probably several hours or days after leak occurrence [72]. This suggests that vapor sensors should be used in conjunction with other sensors to give a better response time.

#### *6) Infrared Thermography (IRT)*

Some PMS are infrared thermography (IRT) based, in that they utilize infrared imaging technology, the use of infrared cameras of 900 - 1400nm range to detect temperature changes in the pipeline surrounding [74]. IRT use in pipeline monitoring has been widely accepted owing to its ability to detect changes in temperature in real-time and in a contactless manner [75], [76]. IRT camera performs some basic functions such as scanning, condensing, detection, amplification, display, and synchronization [74]. [77] presented details and theories of IRT. IRT based pipeline monitoring were presented in [78], [79], [80], [61]. [80] presented a gas leak detection using thermal imaging. An infrared camera was used for pipeline surrounding inspection, and the captured image was filtered, followed by a region of interest enhancement and segmentation.

The segmented image is passed through feature extraction to extract features suitable for pipeline leakage identification. The resultant PMS was shown to have the ability to classify the images as normal and abnormal gas pipeline conditions. The benefits of IRT PMS are fast detection, suitability for various pipelines, and easy installation.

Limitations: High cost of the high-resolution camera, inability to detect the leak, inability to detect leak size of less than 1mm. To overcome the shortcoming of the inability to detect small leaks, [81] proposed a combination of ultrasound and IRT. [82] combined IRT with platinum resistance detector to achieve precise spot temperature measurement.

### *B. Interior Based Methods*

These methods make use of internal gas or fluid measuring devices to monitor fluid flow parameters in pipelines. These devices can be used to measure parameters such as pressure, flow rate, temperature, volume, and density. The fusion of information derived from the measured parameters is then used to determine if there is a discrepancy between different pipeline sections. The discrepancy is then used to determine if there is leakage in the pipeline or not. Examples of computational methods are mass-volume balance, pressure point analysis, negative pressure waves, digital signal processing, dynamic modeling, among others.

***a) Mass-volume Balance***

Mass-volume balance-based PMS is straightforward, it operates on mass conservation principle [83], [84]. The mass conservation principle postulates that gas or fluid that flows into a pipeline section remains in the pipe until it flows out of the pipe section [85]. The inflow can be metered as well as the outflow, and these flows must be balanced. Any discrepancy within the measurements indicates the presence of leakage(s). This method is widely used in the commercial oil and gas industry. Examples of available flow meters are positive displacement, turbine and mass flow devices, and orifice plate. Scientific articles of PMS based on mass-volume balance method are freely available [86], [87], [88].

Limitations: Drawbacks of mass-volume-based PMS are: sensitivity to pipeline dynamics and random disturbance [89], and inability to locate leakage points. To overcome these limitations, the mass balance method can be used in conjunction with other methods.

***b) Dynamic Modelling***

This approach uses physics principles to mathematically model pipeline operation. Leak detection using this method can be either statistical or transient. Statistical-based dynamic modeling assumes that fluid parameters inside the pipeline remain constant unless there is the use of decision theory principles [90]. Transient-based dynamic modeling is adjudged the most complex and sensitive leak detection method by the Alaska Department of Environmental Conservation [91]. It utilizes the equation of conservation of momentum, states of pipeline content, conservation of mass. The transient events are monitored and compared with simulated values to detect leakage. Various transient based PMS were proposed in the research arena, such studies are presented in [92], [93], [94], [95], and [96]. An equation of state of fluid-based hydraulic transient modeling was proposed by [93]. The dynamics of fluid flow in the pipeline were modeled using partial differential equations.

Limitation: It is a very complex technique that involves advanced mathematical understanding and practical training to operate.

## V. PIPELINE MONITORING MODES

PMS systems can operate in different modes, which can be on-line/real-time or off-line/periodic. The system of choice depends on the available resource and environment of the application. On-line PMS is more efficient; however, the power demand can be enormous.

### *A. On-line Monitoring techniques*

The online monitoring method refers to PMS that can remotely monitor pipelines continuously and give real-time data without interfering with the pipeline operation. These methods require a cluster of sensors, data aggregation equipment, and data analysis devices to process data and decide if there is a threat to PMS integrity or leakage occurrence as it happens. Sensors' sensitivity and calibration, equipment integrity, and accuracy of devices involved in the system directly affect the reliability of the system. Overview of current on-line PMS is hereby presented. The techniques are pressure change, line flow balance, and real-time transient monitoring. These methods rely on sensors (pressure, temperature, flow rate) for flow variable monitoring.

### *B. Off-line Monitoring techniques*

Despite the advancement of on-line monitoring methods, they cannot detect leaks and their locations in real-time with complete accuracy. They are also power demanding, costly, and detects fault after it has occurred. To have a sustainable monitoring system, another method can be used to supplement on-line systems. These methods are known as off-line methods; they take readings and send them to the base station at intervals. These are referred to as periodic inspection and monitoring methods. It comprises methods for leak detection and localization and non-destructive testing techniques, such as inline inspection. Inline Inspection of the pipeline can be used to accurately detect and locate defects before pipeline failure occurs. Some of these methods can only be used periodically because they interfere with pipeline operations; some are too laborious to be constantly applied, while others are dependent upon environmental factors and therefore are not constantly available.

## VI. PIPELINE FAILURES AND COST MANAGEMENT

This section discusses the causes, effects, and cost of management of pipeline failures.

### *A. Causes and effects of pipelines failures*

Pipeline failures are leakages, rupturing, and the explosion of the pipeline, which can be caused by corrosion of the pipe wall, abnormal pressure surge, poor quality of fittings and workmanship, soil movement, traffic loading, and aging of the pipeline [97], [98]. The primary causes of pipeline failure are numerous, and it can be erosion, wear, and tears in the pipeline wall, intentional and accidental vandalism, extreme environmental events, such as earthquakes, among others. The causes of failure can be classified as natural and man-made [10].

Pipes convey highly volatile and hazardous liquids and gases that pose a serious threat to human lives if there is unchecked spillage to the environment. Pipeline failure can result in direct financial loss from operation downtime, lost product cost, and cost of clean-up. Indirect financial loss can result from pipeline failure in the form of lawsuits and fines. Pipeline failure can also result in environmental pollution and explosions, which can destroy lives, properties, and the ecosystem. The cost implications of pipeline failure can be extremely difficult to predict.

### *C. Cost of Pipelines Failure Management*

Revenue loss due to oil spillage, vandalism, pipeline bursting, and damage can amount to millions of dollars annually; recent studies between 2001 to 2010 stated that Nigeria as a country losses 7 billion US dollars to crude theft (USD), and about 2,500 people had lost their lives as a result of fire explosion during oil bunkering. Approximately 35,000 barrels of crude oil were spilled or wasted during the period. This is also responsible for environmental hazards or degradation [13]. Another study showed that about 12 billion dollars are lost yearly in Nigeria as a result of petroleum pipeline vandalism, and over 130 million barrels of crude oil has been reported stolen since the Niger delta insurgence of militancy [99], [100], [101]

## VII. REVIEW OF PIPELINE MONITORING TECHNIQUES

Recent advances in the pipeline monitoring techniques have contributed immensely to the improved performance of the pipeline monitoring techniques and also gave both academic and industrial researchers an edge to develop a better easy, efficient, and inexpensive deployable approach for real-time monitoring systems. [102] designed a leak detection system using google earth which gives a leak alarm when an abnormality occurred during the normal operation of the pipeline system. [5] Based its work on using Operational Modal Analysis (OMA) application for condition monitoring of operating pipelines, with key attention on the topicality of OMA for defining the dynamic features of the pipeline frequencies and mode shape in operation. [4] Performed a study of existing wired and wireless monitoring techniques, and it was obvious that the wireless sensors network is variable and the best for the pipeline monitoring system.

Acoustic correlation is one of the popular technologies used for leak detection and localization in pipelines. Many PMS researches based on acoustic technologies are documented in literatures, examples of such are [103], [104], [105], [106], [107], and [108]. The principle these methods use is that leaks emit some acoustic wave which magnitude and frequencies depend on the diameter of the leak, fluid type, and pressure [103]. The cross-correlation method is thereby applied to the signals to detect leaks and locations [105].

The time of wave travel to each sensor from the point of leak is different, and this principle is used to detect the leak and its location. Sensitivities of sensors are used to determine the performance of such acoustic-based PMS. [104] stated that acoustic sensors with low noise floor and higher sensitivity could detect weak acoustic signals it can detect small leaks. Despite having all these attributes, the detriment of acoustic PMS is that it isn't suitable for buried pipelines using the WSN technique. Also, the system requires high power for operation. Acoustic PMS are not suitable for deployment with plastic pipelines because of the high attenuation of acoustic waves in such pipes [108]. [109], [110], [111], and [112] stated that Ground Penetrating Radar (GPR) is widely used for leak detection and localization in buried pipelines. In GPR PMS, antennas placed on the surface transmit radio frequency signals into the ground. The differences in the electromagnetic properties of soil layers and other objects will make the signals undergo reflection and refraction. These phenomena are received by a receptor and analyzed by a GPR unit, usually above the ground. Pipe leaks are detected via leaking fluid created voids in the ground by GPR. It can also be detected through measured pipe depth abnormalities owing to local fluid content change caused by changes in soil attenuation [113]. Despite successful usage of GPR for pipe leak detection and location, it's not suitable in high attenuative soils like saturated clay or at deep depths. Difficulty in GPR measurement interpretation is another limitation of GPR; a skilled operator is required for this task and to accurately differentiate between objects similar to the fluids as a result of similar GPR signatures [114]. Fiber optic technology is identified as a potentially viable technique for large-scale monitoring of infrastructures by [115]. Numerous technical reports on fiber optic usage for pipeline and other infrastructure monitoring exist in kinds of literature [116], [117], and [113]. Fiber optic has a high level of performance, and this makes it a method of choice for many researchers in the PMS field. Fiber optic-based monitoring does not require a local power supply, has high monitoring coverage, immune to outside interference, and has a multi-sensing capacity, as other techniques. Superior performance characteristics of fiber optic monitoring have made fiber optics amongst the most suitable techniques for permanent monitoring of pipelines. The limitations of this method are that optic fiber is fragile, and any cut or point of discontinuity in the fiber will result in total system failure, and it is costly and labor-intensive, and also must be wired throughout the whole length of the pipeline [118]

## VIII. OPEN ISSUES

The performance of PMS depends on the type of pipeline, conditions of operation, sensitivity, adaptability, reliability, and accuracy, among others. From the reviewed works, it can be deduced that each technique has its own shortcoming(s). Hence, to achieve the goal of a practical PMS that has acceptable performance, different types of sensors should be deployed.

WSN for PMS has the advantages of fast response, low cost, compatibility with other methods, scalability, and reliability, among others. Despite these desirable attributes, WSN driven PMS are still faced with some design issues that call for researches. These issues are sensing coverage, sensing modalities, leak localization, energy management, fault tolerance, optimal sensor nodes placement, etc. Sensors are basically deployed for steady-state condition monitoring, with pipeline context remaining steady during operation time. Hence, physical parameter variations recorded by the sensors will indicate the incidence of anomalies. If leaks are out of the coverage range of the sensors, the leaks won't be detected. This implies that several sensors are needed to cover a large distance pipeline.

It is expected that some sensor nodes can fail during the life span of a WSN based PMS; such failure may lead to network failure or limit the efficiency of such a network. Hence, communication mechanisms and modalities between sensor nodes can be researched to effectively cover failed nodes within the network. Energy consumption is as important as placement in WSNs [119]. It determines how long the network will last [120]. Sensor coverage issues were addressed in literature [121], [122], and [123]. How to achieve higher sensor coverage was proposed by [124], [125], and [126].

## IX. CONCLUSION

This paper gives a summarized guideline in choosing a suitable PMS for pipeline management either in offshore (surface and underground) or onshore (underwater or subsea) pipeline networks. It has provided a comprehensive study of the classification of PMS; it also highlights the structures of some PMS systems as used in different settings, either onshore or offshore, with their advantages and disadvantages. It discusses the power supply module, sensors/sensors clusters, sensor node, communication module, communication medium, and based station as key components of PMS with power management as the core. Most PMS is designed to tackle the problem of leakage, detection, and location of leakage immediately after the occurrence. Some have achieved this aim but mostly are not sustainable over time. Other PMS is designed to tackle the problem of man-made threats (vandalism, excavation, and un-authorized access, among others). Future PMS research should try to tackle both leakages and man-made threats in real-time using state-of-the-art technology.

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## COMPETING INTEREST

The above-mentioned authors have declared that there is no competing interest in this research.

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