PAPER 9

# A review of acoustic pipeline monitoring systems used to detect bursts and blockages

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## ABSTRACT

Pipeline leakages, bursts, and blockages are issues that are experienced by many urban communities globally and locally. These issues emerge from numerous variables such as pipe deterioration and human-instigated assembly faults. Leakages and bursts of the pipelines are some of the major causes of the increased scarcity of drinking water. These pipeline issues do not only affect the society but also apply pressure to the economy and the environment. As such, these issues need an undivided attention to prevent them from escalating. This study proposes a system design of an acoustic monitoring system for pipeline leakages, bursts, and blockages. To achieve this, a review of the existing methods and models for pipeline monitoring was conducted. Comparison of existing methods was based on system characteristics, i.e., operation efficiency, maintenance efficiency, ease of installation, cost efficiency, energy efficiency, and overall reliability. These characteristics form part of the most vital characteristics of a system concerning its reliability. To better propose the best solution, the social, environmental, and economic influences of the above-mentioned pipeline issues are just as important to consider.

A comparative analysis on the performance of the existing models and systems was performed to provide the best guide in determining the best model in pipeline monitoring for leakages, bursts, and blockages. These systems include a) Conventional and Visual Method, b) Wireless Sensor Network Systems, c) Acoustic Monitoring Systems Based on WSNs, d) Sound Variation Vibration Sensor Systems, e) SmartPipe Based on WSNs Approach, f) ADIGE Method, g) SPAMMS System, h). EARNPIPE Systems, and i) Magnetic Induction Based WSNs (MISE-PIPE). Comparisons made were based on other works by different authors, no empirical measurements were taken. A framework was then proposed and executed to examine the best design for monitoring pipelines. Based on available methods and models, the model proposed in this paper is a hybrid model which combines the best of what the existing models can offer to monitor a pipeline under and above ground. Many existing models can only manage to perform task exceptionally but with a lot of drawbacks on other features such as burst detection. The combination of the most efficient models to a single model comes with a lot of benefits and less drawbacks. As with any system in existence, a maintenance plan is needed and was discussed to ensure the best operation of the system.

## INTRODUCTION

Many developing nations lack detection strategies for pipelines which increase the shortage of drinkable clean water. This also make it difficult to transport fuel and other commodities. There is a great need for new methods of monitoring pipelines as about R1 billion worth of water goes to waste every year in Johannesburg alone through unnoticed leakages and pipeline bursts (Molatlhwa & Smillie, 2015). The biggest cause to leaks, blockages and bursts is the deteriorated pipeline systems. If detection systems were detected earlier, such problems would be avoided through pipeline maintenance. Over R100 billion was allocated to fix household plumbing issues, replacement of pipelines, and to compensate for the ever-growing water demand every year by 2.4% on average (Molatlhwa & Smillie, 2015). The sum of money allocated for fixing the pipeline systems issue and the money lost in leakages, bursts and blockages is extremely large for the economy of a developing country.

Pipeline monitoring systems are important in reducing abovementioned problems. There are many different monitoring systems available in the market. They operate differently and provide different outputs. Research has shown that detection systems have proved to be the best and most useful strategy for many pipes in a wide range of these systems (Datta & Sarkar, 2016). One good reason behind this claim is because of the ability of some of these monitoring systems to detect leakages, blockages, and bursts promptly in a pipe as significantly little as 1% of its diameter (Datta & Sarkar, 2016). Most of these systems have also been found to be very economical as well as being able to operate in pipes of different shapes, pipe sizes, pipe lengths as well as for various densities (Datta & Sarkar, 2016). South Africa is faced with both water and energy crisis. This research paper will propose a system that prevents water losses while being energy efficient.

## PIPELINE MONITORING SYSTEMS

When pipelines are properly maintained, they last for a considerable time without leaks or bursts (Boaz, et al., 2014). To achieve this, a leak detection system should be adopted. The primary function of a leak detection system is to aid those in charge of controlling and monitoring the pipeline distribution networks (Boaz, et al., 2014). The systems detect and localise leaks in the pipeline hence they guarantee optimal functioning as well as maintenance of pipeline distribution networks (Boaz, et al., 2014). Pipeline leakage often leads to the actual burst of the pipeline. This is due to the pipeline not being able to withstand the high pressure it is subject to. As a result of identifying and dealing with pipeline leaks at an early stage accordingly, the bursting of the pipeline is prevented.

There are two types of monitoring systems namely internal system and external system. Internal systems are referred to as computational pipeline monitoring systems (Boaz, et al., 2014). These systems use internal instruments inside the pipeline that is being monitored. These instruments are field instrumentation or handheld devices that are used to measure parameters of the liquid being transported inside the pipe such as the pressure, temperature, and flow of the fluid (Boaz, et al., 2014). External systems on the other hand as the name suggests, are operated external to the pipe. Such example is optic fibre cables which are used to detect changes in temperature due to leaks which is dependent on the type of fluid that is transported (Stajanca, et al., 2018). Acoustic systems are also a good example of external monitoring systems. Acoustic detection system work on the basis of a signal or sound created due to a moving fluid in the pipeline (Boaz, et al., 2014). When the liquid passes through an opening in the pipe, it is detected, and a frequency signal is sent to the processors which then analyses the signal (Boaz, et al., 2014). In this paper, we will look into the different monitoring systems as well as their differences, similarities, strengths, and weaknesses. A lot of monitoring systems have been by far proposed and adopted although some of these systems are still undergoing research.

### Conventional and Visual Method

These are methods that require the use of observation by a personnel through the use of video capturing device and helicopter to scout for any suspicions on the ground of any leaks. Such systems are very time consuming, inefficient and ineffective. This is because underground pipeline leaks or bursts as well as blockages may take a considerable amount of time before the ground reflects the problem on the surface. At the time the problem shows, an inevitable as well as an extensive amount of damage such as sinkholes would have already occurred.

### Wireless Sensor Network Systems

These are monitoring systems that do not require the physical contact between the components and the operator but rather make use of the sensing technology to make a judgement on an existing pipeline (Akyildiz, et al., 2002). These systems are called wireless sensor networking systems (WSNs) due to the non-requirement for physical connections. The wireless sensor network system is the system upon which many pipeline detection systems are based. The wireless connection reduces the possibility of damage to the connecting medium and prevents the disturbance to the operation of the system. The basic set-up of a wireless sensor network comprises of sensor nodes, master nodes, and of course the operator. The sensors detect any action in the medium under investigation and send information to the nodes and the nodes then ultimately transmit the data to an end user for analysis (Haibat & Jae-ho, 2019).

### Acoustic Monitoring Systems Based on Wireless Sensor Networks

Acoustic monitoring system is a leak detection system that makes use of the hydrophone sensors to detect any unusual activity on the pipeline (Bernasconi, et al., 2012). These hydrophone sensors are placed at separate and distinct locations along the pipeline. Most acoustic monitoring systems are dependent on the emission of sound measured due to water escaping from a pipe through a leak (Khulief, et al., 2012). Acoustic detection systems basically listen to the activity of a pipeline for any unusual sounds whereby sensors work together to assess and locate leaks that may often go undetected. This system is comprised of sensors responsible for monitoring the pipeline for any variation from the normal sound on the pipeline. These sensors, should there be any changes to the sound on the pipeline, trigger other sensors to begin recording the acoustic data (Ismail & Yie, 2012). The triggered sensors only begin recording data when the sound emanating from the pipeline is higher than the ambient sound which in this case is taken as the normal sound in and around the pipeline (Ismail & Yie, 2012). This prevents false alarms or triggers as it was in the past where these systems could not differentiate between leak sounds and sounds on the ground surface (Yang, et al., 2008). The data, after being turned from signals into a digital form, can now be sent for analysis. General procedure for detecting leaks using an acoustic emission (AE) based technique is shown in Figure 1 where transformed AE signals are used to train the classifier instead of direct AE signals which improves the accuracy of the system. With the trained classifier, accurate classification of data into the presence of suspicious activity is guaranteed. As these systems are becoming more advanced, the operator is able to act on the leak as soon as possible before it turns into a secondary damage.

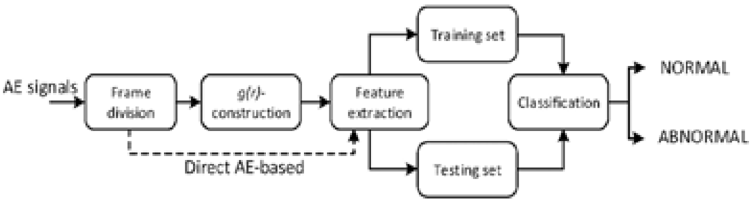

**FIGURE 1:** Procedure for leak detection based on acoustic emissions technique

### Sound Variation Vibration Sensor Systems

These systems use sensors which detect sound variations in the pipeline. The system detect any suspicious sound made by leaking water and compare it to the normal sound of the of the pipeline (Ng, et al., 2017). This is how water leaks, and their symptoms are identified before exacerbating the already deteriorating pipeline (Haibat & Jae-ho, 2019). This system has only been used on polyvinyl chloride (PVC) and metal pipes. It is not best suited for concrete pipes. As with many pipeline monitoring systems abovementioned, the sound variation system also has a constraint to it. This system work in its optimum state when it is near the position of the leak on the pipeline (Haibat & Jae-ho, 2019). For a detection system to be a good, it is imperative that it be able to work or survey a considerable length of a pipeline.

### SmartPipe Based on WSNs Approach

The SmartPipe system is a multimodal monitoring system based on WSNs. This approach is a non-invasive approach that monitors a pipeline for any variation in the pressure of the pipeline. The development of this system was on the basis of a force sensitive resistor whose resistance varies in accordance with the pressure it is subject to (Sadeghioon, et al., 2014). This system provides pipeline monitoring at low power consumption, reducing its overall cost of operation. This is achieved through a single measurement of the pressure after every 6 hours to increase the lifetime of the network (Sadeghioon, et al., 2014). The long intervals of measurements allow for the sensor node to cope and be compatible with the levels of power available through production and provision. The draw back about this approach is that it was only used on plastic pipelines. It is not known as to how it would react when used on different types of pipe materials. This approach needs to be tested on other types of pipe material.

### Adige Smart Water Network

This system is founded on a long-range wireless technology (LoRa) that helps improve its capacity of area under investigation. The LoRa allows for fewer uploading gateways to upload information found by the sensors (Haibat & Jae-ho, 2019). This has a significant influence on the batteries of the system as the LoRa technology allows for a considerable reduction in the consumption of energy from the batteries (Cattani, et al., 2017).

The LoRa technology was designed and developed to achieve the following goals (Haibat & Jae-ho, 2019):

- Increase the reliability of the system.
- Cover a relatively large area.

- Increase the energy efficiency of the system and lower the cost of the system.

Although the LoRa technology promises to be very reliable or rather checks virtually all the boxes, is also has harbours constraints of its own. To accurately locate the position of a leak is the main constraint for this system. High accuracy is still a work in progress which is still undergoing a lot of research as this technology is not quite there yet. According to Cattani, et al. (2017) the system increases the condition of good health of the existing pipeline distribution networks.

### Sensor-Based Pipeline Autonomous Monitoring and Maintenance System

The Sensor-Based Pipeline Autonomous Monitoring and Maintenance System (SPAMMS) is a self-controlled water pipeline monitoring system that uses a robotic technology and a variety of sensors to monitor and locate leaks (Kim, et al., 2010). This system detects and locate leaks through a coordination of dynamic and static sensors which are sonar, pressure, charge-coupled device, and chemical sensors. Although this system is in its preliminary version, it promises to reduce the need for human intervention by a significant margin hence a robot is rather used for maintenance (Karray, et al., 2016). As the robot moves in the pipeline, it distinguishes any suspicious activity. Having the robotic agent makes localisation of suspicious activities much easier as it can get as close as possible to the pipeline activity. The reduction of the need for human beings will allow for a great deal of the reduction of errors that might have been as a result of human intervention. However, this system has a lot of mobile parts which makes it very likely that an error could occur during installation. Installation may also require too many instruments thus, increasing operational and maintenance costs of the system (Karray, et al., 2016).

### The Energy-Aware Reconfigurable Sensor Node for Water Pipeline Monitoring System

The energy-aware reconfigurable sensor node for water pipeline monitoring system (EARNPIPE) is a detection system proposed by Karray et al. This is a software dependant system that makes use of leak detection algorithms, localization algorithms as well as a system on cheap architecture with a wireless sensor node (Karray, et al., 2016). This system was founded on two methods namely, a leak detection predictive Kalman filter (LPKF) as well as a modified time difference of arrival (TDOA). The LPKF is a set of mathematical equations which are algorithms that make more accurate variable that are not known. The accuracy of this algorithm is dependent on the measurements of different accuracies such as noise previously measured as statistics. The newest measurements are contrasted against the already measured ones to produce variables with high accuracy (Welch & Bishop, 1997). When the sensors get information about the state of the pipeline, the information is taken to be filtered and undergoes analysis by the Kalman filter as a single algorithm (Karray, et al., 2016). One Kalman filter algorithm increases energy efficiency as compared to different algorithms working at once (Karray, et al., 2016). The system is developed for long distance pipelines. However, it only works on exposed pipelines and above ground (Haibat & Jae-ho, 2019).

### The Magnetic Induction-based Wireless Sensor Network for Underground Pipeline Monitoring

Unlike the EARNPIPE system, the magnetic induction-based wireless sensor network for underground pipeline monitoring (MISE-PIPE) proposed by Sun, et al. (2011) is designed to work underground. However, although this wireless sensor network works underground, it uses various sensors to locate a leak on a pipeline in a similar manner to the EARNPIPE systems (Sun, et al., 2011). The WSNs make use of a magnetic induction as a result of a changing external magnetic field made possible by pressure sensors, acoustic sensors which are based on sound detection, as well as the soil properties sensors (Karray, et al., 2016). The sensory data is transmitted to the processing hubs which are above the ground. This system is comprised of hubs that are made of devices that connect the sensors from underneath the surface of the ground. The pressure and acoustics sensors are placed in the hubs in known or verified locations from inside the pipelines (Haibat & Jae-ho, 2019). The soil property sensors are placed in the soil along the pipeline to measure different soil parameters such as soil temperature, soil humidity to name a few (Haibat & Jae-ho, 2019). The sensors in the hubs will measure the variation in vibration and in pressure as a result of pipeline leakage which will be sent for analysis using the magnetic induction technique (Sun, et al., 2011). However, due to the frequent communication between the nodes and base stations, the battery lives are affected hence this system may not be energy efficient as a result of high energy consumption (Karray, et al., 2016).

### Overview of the Different Pipeline Monitoring Systems

Pipeline monitoring systems are advancing in technology to better detect and localize leaks which habitually may turn in to a burst. Not only does this reduce the negative economic pressure but it also will prevent the loss of drinking water and environmental damage such as sinkholes for a few thus, thus preventing social pressures. However, pipeline monitoring systems still have to undergo more research as many of the systems make compromises somewhere in order to perform perfectly at a particular function. This results in a lot of pipeline monitoring systems having great strengths on one aspect and weaknesses on the other. Most monitoring systems are limited to short distances as they cannot work in very long stretches of pipeline distances. In addition, accuracy of the sensor nodes in locating the leak still need to be worked on. Some systems tend to not be cost efficient due to having a lot of parts which may be mobile. This adds to the cost of making and assembling the system. As a result, the reliability of the system is generally decreased.

A good, reliable, and efficient monitoring system possesses the following traits (Karray, et al., 2016):

- It must be able to provide active monitoring where it detects defects in damaged pipeline.
- It must be able to provide recovery action through the analysis of data and reaction provision.
- It must be relatively cheap or cost effective operationally as well as in maintenance.
- It must be scalable. This is so that the system is able to work on any length of the distribution network, that is it must adapt to different settings.
- It should be customisable and easily so.
- It should be dynamic where it is capable of allowing for a dynamic pipeline inspection. This can be from the inside of the pipeline or from outside of the pipe.
- It must possess efficient localisation techniques where a leak is located with minimal errors and a good accuracy.

Acoustic monitoring systems have been found to have been very efficient in their work and widely applied in the water and sewer industry (Yang, et al., 2008). Since 2000, pipeline monitoring systems have been advancing in technology. For example, the Enhanced Constant Fault Alarm Rate (ECFAR) is an acoustic monitoring system that makes use of fault alarm to detect any issues on the pipeline as discussed previously (Duong, et al., 2020). Comparison of different leakage detecting systems is shown in Table 1. From the table, "YES" means that the specific method is good in that criterion and "NO" means that it does not meet the criteria. System attributes rated with

**TABLE 1:** Key features of leak monitoring systems (Zhang, 1997)

| Method | Leakage sensitivity | Location estimation | Operational change | Availability | False alarm | Maintenance requirement | Cost |
|---|---|---|---|---|---|---|---|
| Biological | Yes | Yes | Yes | No | Low | Medium | High |
| Visual | Yes | Yes | Yes | No | Medium | Medium | High |
| Acoustic | Yes | Yes | No | Yes | High | Medium | Medium |
| Sampling | Yes | Yes | Yes | No | Low | Medium | High |
| Negative pressure | Yes | Yes | No | Yes | High | Medium | Medium |
| Flow change | No | No | No | Yes | High | Low | Low |
| Mass balance | No | No | No | Yes | High | Low | Low |
| Dynamic model | Yes | Yes | Yes | Yes | High | High | High |
| PPA | Yes | No | No | Yes | High | Medium | Medium |

a "HIGH" resembles a bad performance of the system and "LOW" resembles a good performance by the systems at the identified feature. It can be observed that the acoustic method of pipeline monitoring is excellent at sensitivity to leakage. However, this system has a very high false alarm rate. In the modern acoustic systems, filters are used as sieves to filter out any unwanted data from the pipeline.

## FINDINGS

This section discusses the proposed methodology and the method execution with reference to a monitoring system based on wireless sensor networks to counteract leakages, bursts, and blockages of buried and exposed pipes. The main criteria to be used in selecting the relevant works by other authors and criterial for an effective pipeline monitoring system is discussed. A comparative analysis procedure was performed between systems from literature and the proposed systems. A framework of the method will show a step-by-step procedure in selecting all the relevant sources of data from the internet which narrowed down on the type of pipeline detection system is best for monitoring.

### Data Sampling Criteria

The publications that were selected for data gathering were conference proceedings and journal articles. Different research databases such as Google Scholar, Science Direct, MDPI, IEEE Xplore, and Research Gate were used to find the relevant literature and base for this methodology. This allowed for the acquisition of quantitative data and qualitative data. In order to search for the relevant papers on the databases, keywords were used to bring out results that were required. The keywords that were used are acoustic monitoring system, pipeline detection system, pipeline monitoring system model, pipeline acoustic-emission, pipeline burst detection system, pipeline leakage detection system, and pipeline blockage detection system.

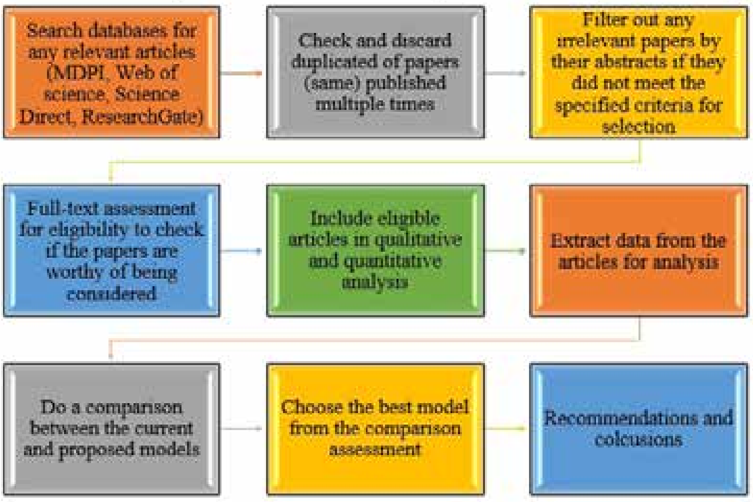

**FIGURE 2:** Framework of the data sampling criteria and analysis of results

### Framework and Data Analysis

Many papers proposing different pipeline detection systems have been published concerning the monitoring of pipeline network systems. As this is still a developing topic, there have been many suggestions by various authors to reach a common goal which is to prevent the occurrence of pipeline leakages, bursts and blockages through the use of systems that combine sensory hardware, transmission hardware as well as computer models and analysers to prevent such unwanted events. In order to select the right types of information sources, a framework has been proposed in Figure 2. The framework is a summary that shows the method or procedure used in this project to select the best models for the hybrid model. It shows the procedure that led to the acquisition of the right and relevant papers to recommend the models chosen to be used in this project.

Data was first obtained from the literature review from the journal articles and conference papers published on various databases. The selection of the relevant papers is in accordance with the process depicted in the framework of method section. A comparison between the current and proposed systems was done where the best system was chosen from the rest. The selection of the best system is influenced by the following characteristics of monitoring systems: a) Operation efficiency, b) Maintenance efficiency, c) Ease of installation and cost efficiency, d) Energy efficiency, and e) Overall reliability.

## RESULTS AND DISCUSSIONS

In total, 35 papers were used to extract information used in this study. These sources included journal articles and conference proceedings. Of the 35 papers, 4 were duplicate papers. All the irrelevant data sources were also filtered out by their abstracts where the abstracts were checked to find if they had the relevant data that was required. Eight papers were found to be irrelevant. Data was then extracted from the relevant sources to create this paper and a comparative analysis done on 9 papers that had proposed pipeline monitoring systems. In order to find all these papers, keywords were used to search these papers. Figure 3 shows the results of the data sampling criteria in a procedural manner in terms of the number of papers found on the databases.

There are various methods and systems proposed to monitor pipelines networks by many researchers and practitioners. Energy efficiency, cost efficiency, operation and maintenance efficiency, installation and placement of sensor nodes, and reliability of a proposed system are the components that influence how good a monitoring system is (Haibat & Jae-ho, 2019). As such, the accompanying Table 2 is a comparative analysis of the various proposed systems in terms of their efficiency in power, operation,

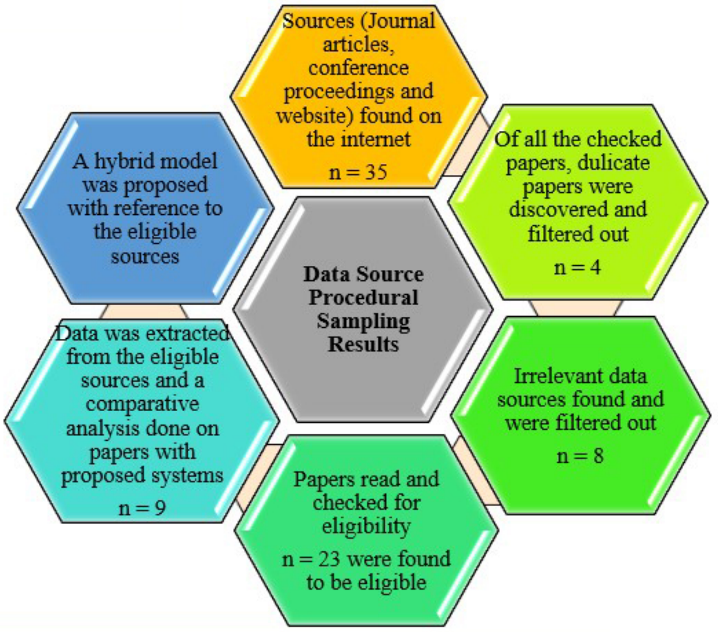

**FIGURE 3:** Results for data sampling criteria

maintenance, installation, and cost efficiency as well as their overall efficiency. This analysis shows that various systems are focused on different ideas of efficiencies in order to bring about the best reliability of the system. However, shifting the focus of the monitoring system to a single characteristic proved to show weaknesses in other components of the system proposed.

The model for monitoring proposed in this study is a hybrid model comprised of two models, the k-nearest neighbour (KNN) model and the Enhanced Constant Fault Alarm Rate (ECFAR). This model is able to detect a pipe burst as well as a pipe leak. According to the ECFAR monitoring model (Duong, et al., 2020) acoustic emission events happen as transients in a nonstop signal where the transient peaks overlap each other and are comprised of different lengths. To identify a burst of a pipeline, a threshold is chosen as a standard for setting off the alert. As such it is important that a correct standard is picked as this can influence the performance of the model. A low threshold will bring about a ton of alerts set off as a high number of the signals will be over the edge. A high threshold will result in not many signals identified. In that capacity, the model proposed for this method calculates a versatile (adaptive) threshold to permit the model to adjust to various noise powers or levels. The model distinguishes an impulse when the noise power surpasses the calculated threshold. The threshold for impulse detection and other parameter is determined using equations in Table

**TABLE 2:** Comparative analysis of various pipeline monitoring systems

| Monitoring systems | Power efficiency | Operation and maintenance efficiency | Installation and cost efficiency | Overall reliability |
|---|---|---|---|---|
| Conventional and Visual Method | – | Exhausting as it needs a lot of human physical intervention. | May be very expensive depending on the number of personnel that is on duty. | Not very reliable as it may have errors made by the personnel and it is time consuming. |
| Acoustic-Emission system | The usage of power has been reduced by using components with low energy usage. | Most of the work is done by the system and associated model which makes it easy to operate. | May be expensive to maintain due to the relatively complex system. | Very reliable in monitoring and detecting any suspicious pipe activities. |
| Sound Variation Vibration Sensor Systems | This system uses sensors that use relatively low energy which makes the energy efficient. | This system is also easy to operate as most of the work is done by the system with less human intervention. | The low energy consumption of the components used by this system reduces the cost of operation. | Has only been used on PVC and metal pipes, performance on concrete pipes is unknown |
| SmartPipe Based on WSNs Approach | Very energy efficient. It uses energy harvesting approach to save more energy. | Easy to operate and maintain as many of the functions are done by the system. | With energy usage so low, it makes it to be cost efficient in that department. | Guaranteed by its simple components as they don't have complex parts. |
| Adige Method | Uses the long-range technology allows for fewer uploading gateways to upload data from the sensors. this allows it to save more energy. | As most of the work is done by the system, operation is relatively simple. | Reduced costs. Installation of this system is rated as good as the long-range system needs less components. | The long-range method has a constraint of accuracy. Accurately locating a leak is still a problem. |
| SPAMMS System | Requires a relatively high amount of energy to operate in its dynamic mode. | The need for human intervention is eliminated by the use of mobile components. Maintenance is relatively high due to many moving parts. | Less required components may reduce the cost of the system. However, high maintenance costs due to installation errors. | Less human intervention means less errors. The system also easily locates any activity as it is mobile. |
| EARNPIPE Systems | This system uses the Kalman filter which is very energy efficient. | Software dependant system where errors are reduced. Easy to operate. | This system is easy to install as it is designed for exposed pipeline networks. | Less accurate. The system only works on exposed pipelines and not underground pipes. |
| Magnetic Induction Based WSNs (MISE-PIPE) | High energy consumption due to frequent communication between the nodes and base stations. | Operation of this system is relatively easy as the sensors do most of the work with very minimal human intervention. | Energy costs are high as a result of frequent communications between the sensor nodes and base stations. Installation is relatively okay. | This system may not be energy efficient due to frequent communication. However, it is able to work on underground pipelines. |

**TABLE 3:** The equations for the threshold for impulse detection

| Measurement | Equation | Remarks |
|---|---|---|
| The threshold for impulse detection | 1. $T = \alpha P_n$ | • where $P_n$ is the estimated noise power and $\alpha$ is the threshold factor (scaling constant)<br>• The threshold adjusts to any changes in the data because of the threshold factor. The signal is spilt into a progression of continuous windows |
| The estimated power | 2. $P_n = \frac{1}{N}\sum_{m=1}^{N} x_m^2$ | • where $N$ is the size of the window and $x$ is the cells (sample in window)<br>• The peak of the signal is placed on various cells on the windows<br>• The reference window is placed further away from the test cells where the cells next to the test cells are referred to as the neighbour cells |
| The threshold factor | 3. $\alpha = N(P_{fa}^{-1/N} - 1)$ | • where $P_{fa}$ is the required false alarm rate<br>• Should it happen that the signal value in the test cell exceeds the threshold value,T, an impulse will be declared to be present in the test cell |
| $P_{fa}$ is selected to meet the Neyman-Pearson theorem requirements for detection which are in accordance to | 4. $P_{fa} = \int_{\{x:\lambda(x)>\gamma\}} f(x\|H_o)dx$ | • where $\lambda(x) = likelihood\ ratio = \lambda(z) = \frac{f(x\|H_1)}{f(x\|H_0)}$<br>• where $H_0$ and $H_1$ represent the absence and presence of an impulse. |

3. In order to increase the accuracy of the model, modified acoustic-emission signal data is used to train the classifier rather than the direct acoustic-emission signal data as depicted in Figure 1. By using the direct AE-based signals, a step "g(r) construction" that allows for the modification of direct AE-based signals is skipped.

For leak monitoring, $n_i$ with $i$ = 1 and 2 (the two sensors that identify a release signal), are acoustic signals recognized by two sensors (1 and 2) in the typical (state in which no leak is available on the pipeline). The two acoustic signs are comprised of a mean and variance of $0$ and $N1 = N2 = N > 0$. At the point when a smal leak happens in the pipeline, it will bring about a little disturbance which will influence the flow in the pipeline around the leak location (turbulence). This causes a new and unknown signal be distinguished by the sensors. The first $n1$ signal is now viewed as a background noise and not related to the source of the disturbance.

### Maintenance Plan and Repairs

The hybrid model proposed is with a maintenance plan that should ensure the perfect operation of the model. The maintenance plan will also ensure that operators get accustomed with the system and thus be operated at its best condition. The maintenance plan of the model to the pipelines includes the following: a) Leak, burst and blockage surveys, b) Repairs, and c) Annual review of the maintenance plan. The maintenance plan for the system includes a) Regular checks of the sensor nodes, b) Regular checks of the base stations, c) Annual review of the maintenance plan, d) Leak surveys. The sensors placed along the pipeline system are required to take readings of the measurements done on the pipeline in intervals. The sensors listen for any form of sound that is above the threshold or the ambient sound level, that comes from the pipeline. Sensing should be done in intervals of 5 hours to ensure that the systems save power. In this way, leaks and bursts will be detected while still saving energy. As the system knows the different sound that different types of liquids make as they flow through the pipe, a blockage should be detectable should it happen. If a set of sensors reads the sound of a fluid passing and the next sensor does not, the system will automatically alert the operators for a check in the identified location by the system.

Should a pipeline show any indication of leakage or burst, the system automatically alerts the operators of a possible leak on the pipe and recommend a repair of the leak or burst. By identifying the event location, the operators should easily be able to make the right calls. For future purposes, the operators of the system are required to keep the records of every event that occurs. These records are of all the leaks and bursts that occurred on the pipelines. The records must show the following: a) Cause of the damage, b) The location of the damage, c) Date of the damage, d) Method of repair, e) Materials used in repairs, f) Responsible party for the repair, and g) Annual Review of The System Model Maintenance Plan. The maintenance plan of the model system has to be checked at intervals of a calendar year. The following are the things to check for when reviewing the maintenance plan: a) Any changes or updates to the system model, b) Any changes to the operators, c) Any repairs done, d) Any replacement of pipes, and e) Sensors and Base Stations.

Sensors are required to be checked as to whether they still operate to the best of their abilities in order to ensure the best operation of the entire system as everything starts with the sensors detection. Regular operation runs or tests need to be conducted on the sensors to ensure good operation. This will allow the operators to check as to whether or not there is a sensor node that needs attention. The data acquisition cards that are found in the sensors need to be checked for space for data storing. As these cards have a limit to how much data they can acquire, they need to be checked for data space as to whether or not more space is needed, or useless data needs to be erased. Data from sensors is sent to the base stations that stores the data in cloud where the end user can get access to the data for analysis and decision making. A perfect transmission of data from the base station to the cloud is required. For this to happen, regular checks on the base station are required. A check for good transmission speed is one of the checks required. The base stations, also known as master nodes, will also sample the data from the sensors along the pipeline. The sampling frequency for perfect operation is 8 Hz which needs to also be checked for good operation (Ismail & Yie, 2012). The maintenance plan of the actual system must be reviewed in intervals of a single calendar year. The review should check for: a) Any changes to the system, and b) Repairs to the system.

## CONCLUSIONS

From the comparative analysis, it was found that many systems focus on certain characteristic of the monitoring system such as energy efficiency, localisation ability and cost efficiency. This tactic makes the systems reliable to a degree as they are capable of doing a particular job exceptionally well. But it was also found that placing the focus of the entire system on a single characteristic has its drawbacks. This is very evident in the SPAMMS where many faults may occur during the installation of the system due to many mobile parts that need to be installed. However, the system has a good localisation of any pipeline suspicious activity as it is able to get as close as possible to the site of the event. With all the comparative analysis done, two best models namely the KNN model and ECFAR system were then selected from all the systems that were contrasted against each other. These are widely used reliable models in the detection of leaks and bursts in pipelines and are also used in other different studies. Research by Datta and Sarkar (2016) has revealed that acoustic monitoring systems detect leakages, blockages and bursts as quickly as possible in a pipe as significantly little as 1% of its diameter. From these two chosen models, a hybrid model which is a combination of both models is proposed to monitor pipeline networks systems for bursts and leaks. This model makes use of transformed acoustic-emission signals to train the classifier which makes the model more reliable and decreases its susceptibility to normal noises.

## RECOMMENDATIONS

Many available systems are focus on one characteristic which makes the systems prone to vulnerabilities in other characteristics of the system. Improvement needs to be done on the different components of the monitoring systems so that the system can work efficiently in all the areas of the system such as power consumption which will ultimately decrease the costs as far as the monitoring system is concerned. The future research may also look at obtaining empirical results for the system that was proposed in this paper.

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