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Towards Achieving a Reliable Leakage Detection and Localization Algorithm for Application in Water Piping Networks: An Overview

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ABSTRACT Leakage detection and localization in pipelines has become an important aspect of water management systems. Since monitoring leakage in large-scale water distribution networks (WDNs) is a challenging task, the need to develop a reliable and robust leak detection and localization technique is essential for loss reduction in potable WDNs. In this paper, some of the existing techniques for water leakage detection are discussed and open research areas and challenges are highlighted. It is concluded that despite the numerous research efforts and advancement in leakage detection technologies, a large scope is still open for further research in this domain. One such area is the effective detection of background type leakages that have not been covered fully in the literature. The utilization of wireless sensor networks for leakage detection purposes, its technical challenges as well as some future research areas are also presented. In a general remark, practical application of these techniques for large-scale water distribution networks is still a major concern. In this paper, an overview of this important problem is addressed.

INDEX TERMS Leakage detection, leakage localization, pipeline, water distribution network, wireless sensor network.

I. INTRODUCTION

Pipelines transporting fluid are part of a country's important assets, contributing to the nation's economy. These pipelines which are usually installed to serve cities across the country, experience failures along their length. The failure of pipelines is usually attributed to the aging infrastructure, severe environmental conditions and third party damage [1], [2]. As a result, a portion or parts of a pipeline wall is perforated over time, thus causing leakage. When this happens, a loss of fluid (for instance water) through leaks is observed. Water loss through leakages is recognized as a costly problem worldwide, due to the waste of precious natural resources, as well as from the economic point of view. Survey work conducted by Thornton *et al.* [3], revealed that almost 20% of the US water supply is lost through leaking pipes. In South Africa, a water-scarce country with limited water resources and steadily growing water demand, high water losses threaten its municipal water service with an estimated value of more than R7 billion annually [4]. Furthermore, the global demand for water is increasing due to improved standard of living, and resources are diminishing. In the last few years, this has rendered the pipeline leakage detection problem increasingly prominent [5]. Leakages through piping network can be classified as reported, unreported and background type leakages [6]. The former often surfaces on the ground and reported by the public or utility personnel. This type of leakage such as pipe burst is detectable by applying an appropriate leakage detection technique discussed in the next sections. The unreported leakage often does not surface on the ground but in a similar manner to the reported one, can be detected applying a suitable leakage detection method. When both type of leakage (reported and unreported) occur in piping networks, pressure reduction is usually noticed at the downstream of the pipes. The background type leakage (such as flow through creeping joints) is not characterized by pressure drop and are difficult to detect. These types of leakages are hidden and run continuously in distribution networks. Since they are difficult to detect and go unreported for a very long period of time, such kind of leakages posed the largest threat to water distribution networks [7]. Nonetheless, modelling a distribution piping network to analyze flows through the pipelines including background leakage flows should give a remarkable breakthrough in detecting such kind of leakages [8].

Numerous studies, reports and standards that deal with this problem have been published. Of particular interest are the various standards and regulations developed [9]–[12]. The API 1555 [9] and CFR Part195 [11] constitute an excellent introduction to the topic and are particularly useful for pipeline engineers and the water industry. In order to obtain a good leak detection system, API 1555 sets performance requirements that must be met [9]. These include sensitivity, accuracy, reliability and robustness. Further research efforts led to the classification of leakage detection systems based on their technical nature as internally-based and externally-based system [13], [14] as illustrated in Fig. 1, each having relative advantages and certain limitations.

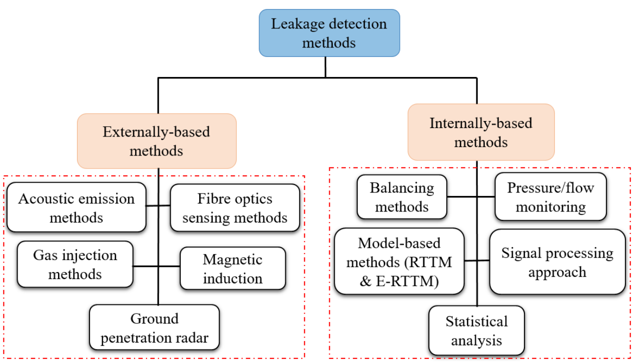

FIGURE 1. Classification of some leakage detection methods.

The traditional leakage detection technique requires huge human involvement due to visual inspection by personnel, and thereby, is time consuming, labor intensive, and has low reliability in detecting leaks. Moreover, externally-based methods use sensors installed outside the pipe to generate a leak alarm. System costs and complexity of installation are usually high for this type of leakage detection methods and therefore, their application is limited to high-risk areas [14]. Internally-based systems on the other hand, use field sensors to monitor internal pipeline parameters such as flow, pressure and fluid temperature. These field signals are used for inferring a leak [14].

Some review work is available in the literature that neither focuses on a particular issue of pipeline leakage nor gives an up to date research progress. For instance, in [15] and [16] factors contributing to pipe leakages and its control policies are reviewed. Liou *et al.* [17] present leak detection technologies for hazardous liquids. In some other research work [17], [18], the review of some leakage management involving pressure reduction methodologies as well as wireless sensor networks for water networks are presented. This paper aims to provide a comprehensive survey of the state-of-the-art development in leakage detection and localization methods. The paper also adds extensively to the existing surveys on leakage detection and leakage localization in piping networks. It is important to emphasize that the focus of this study is only on pressurized piping systems. Previous and recent research progress as well as some open research area are discussed. Technical research challenges and design specifications using WNS for leakage detection and localization in piping networks are also discussed. The rest of the paper is organized as follows. Section II elucidates some basic internally-based leakage detection systems as well as previous research efforts in this domain. In Section III, the externally-based classification is briefly discussed, also featuring some notable research efforts. Section IV presents some of the techniques for localizing leakage in pipelines. The use of wireless sensor networks (WSN) for leakage detection as well as its challenges are discussed in Section V while Section VI concludes the paper and presents some future work.

II. LEAKAGE DETECTION USING EXTERNALLY-BASED METHOD

In this section, some of the externally-based methods for leakage detection are discussed and their localization is outlined.

A. ACOUSTIC EMISSION METHODS

A leakage detection technique using acoustic emissions is based on the principle that escaping liquid creates an acoustic signal as it passes through a perforation in the pipe [20]. When a leak occurs, acoustic sensors installed outside the pipe, track and detect the acoustic emission (AE) signal as it propagates along the pipeline as illustrated in Fig. 2.

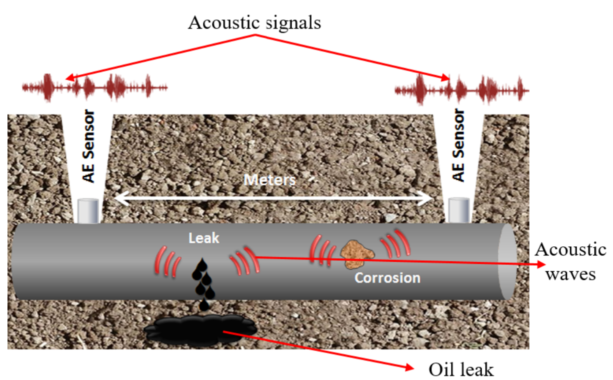

FIGURE 2. Acoustic emission method for pipe leakage detection [21].

The received signal is higher in magnitude near the leak point thereby giving an indication of the leak's location. The detected AE signal is analyzed by the system processor using signal processing techniques. However, signal characteristics as well as the variation in the environmental parameters surrounding the pipelines make it difficult to classify

AE signals [22]. Nevertheless, various signal analysis techniques have been applied to AE signals in order to obtain signal characteristics and locate leakage points, among which are correlation based techniques [23], as well as wavelet transforms [24]–[26]. The application of these techniques depends on the pipe material. The correlation based technique is effective in identifying leaks in metallic pipelines [27]. Muggleton and Brenna [27] investigate experimentally a low frequency acoustic propagation and attenuation in plastic water pipeline. Experimental results show that the leak signal is well attenuated in plastic pipelines, and as a result, cannot be easily detected by correlation based technique.

Acoustic emission based systems have been used in a wide variety of applications within piping systems. In [28], the feasibility of using this approach to provide early detection and corrosion of pipeline wall are investigated. Acoustic signals are greatly influenced by background noise from the environment as well as those produced by pipe burst. Nevertheless, Fang *et al*. [29] proposed the use of de-noising techniques employing band pass filtering methodology to eliminate the background noise from the leak signal. In some cases, a combination of acoustic and piezoelectric sensors has been used for leakage detection purposes [30]. This method has the advantages of high detection and localization accuracy when applied to short-range pipelines. However, for longer pipeline applications, the system requires a large number of sensors which increases the system cost.

B. FIBER OPTICS SENSING METHODS

The fiber optic sensing leakage detection method involves the installation of a fiber optic cable to measure the temperature over the entire pipeline length. Conventionally, leakage from pipelines introduce local temperature anomalies in the vicinity of the pipeline [31]. By scanning the entire length of the fiber in short intervals, the temperature profile along the fiber is obtained and the leakage point can be detected. This method provides accurate leakage detection and location [31]. However, the cost of implementing such a system is quite high, especially for a long-range pipeline. Further developments lead to the use of distributed fiber optic sensing technologies such as Raman distributed temperature sensor (RDTS), Brilloun optical time domain reflectometry (BOTDR) and Fiber Bragg Gratting (FBG) for pipeline health monitoring [32]. These technologies allow the measurement of the temperature/strain at many points along a single fiber and are commercially available. The detailed operating principle of these technologies may be found in [32]. Some of these technologies have been tested in the past for leakage detection and monitoring purposes. For instance, the research conducted by Khan *et al*. [33] has shown that distributed temperature sensing technologies can be used to monitor leakages in dams. A number of other field applications for pipeline health monitoring may be found in the literature [34], [35]. Despite success in various applications, distributed optical fiber sensing technologies can only be used for monitoring linear pipelines. Consequently, substantial research work is still required to improve these technologies for application in more complex piping networks.

C. GAS INJECTION METHODS

This technique makes use of a non-hazardous gaseous tracer to be guided into the pipeline. When a leak occurs in the pipeline, the tracer is seen as a volatile gas, which can be detected by an electronic nose at the exact location of the leak as it diffuses through the ground surface [36]. Low false alarm coupled with the ability to detect very small leaks are the major advantages of this method, and are increasingly being used for localizing leakage in non-metallic pipelines. However, for large low-pressure applications, the high volume of gas required rules out using this technique for leakage detection [36].

D. MAGNETIC INDUCTION METHODS

The magnetic induction (MI) method for pipeline leakage detection makes use of sensors installed inside and outside the pipelines to obtain information relating to pressure and flow monitoring. These sensors communicate with the help of a magnetic induction transceiver. The magnetic induction methods have been used for leakage detection and localization in harsh underground environments [31]. Their high implementation cost is a major limitation due to the number of sensors necessary to provide sufficient performance.

E. GROUND PENETRATION RADAR METHODS

The ground penetration radar (GPR) method for detecting leaks in pipelines is a reflection technique, which uses electromagnetic wave propagation and scattering to identify changes in the electrical and magnetic properties of the soil around the pipeline [36]. GPR method has the ability to detect the difference in the density and water content of soils around the pipeline and can be used to detect leakage from the mains [36]. With this method, it is possible to carry out cross-country pipeline inspection for leaks by mounting the GPR on a small aircraft. This however incurs a high cost. The major limitation of this technology is the complexity in the interpretation of GPR data. Furthermore, this method is greatly influenced by the type of soil in which the pipe is laid. For instance, in clay soils, corrosion products can hide cast iron pipes from the GPR signal. This is because corrosion products of iron pipes in the soil, increases the radio frequency signal attenuation and reduces reflection [37]. In the last few years, an ongoing project funded by the European Union aimed at developing an integrated system of ground penetration imaging radar (GPIR) for detecting leakages and damage to buried water pipes [38] has been investigated. The output of this project is expected to improve the reliability of leak detection techniques.

F. COMPARISON OF THE HARDWARE BASED METHODS

In this Section, the performance of some hardware based leakage detection techniques is compared using the metrics shown in Table 1. This shows the leak localization ability of

TABLE 1. Compared performance analysis of the externally-based method.

Leak detection methods	Performance metric							
	Operational cost	Leak localization	Leak size estimate	Usage	False alarm rate	Accuracy	Response time	Application
Acoustic systems	High	Yes	Yes	Easy	Low	High	Fast	Can be used on an existing and new pipeline.
Fibre optic sensing methods	High	Yes	No	Easy	Low	High	Fast	Can be used for monitoring linear pipeline configuration.
Gas injection	High	Yes	Yes	Easy	Low	Accuracy depends on the gaseous tracer used	Slow	Can only be used in an underground application for gas transporting pipeline.
Magnetic induction method	High	Yes	-	Easy	Low	High	Fast	Can be use in an underground and above ground application
Ground penetration radar	High	Yes	No	Easy	Low	Accuracy depends on soil type	Slow	Not suitable for long-range applications.

these hardware based leak detection techniques. In terms of estimating the leak size, fewer techniques such as the fiber optic sensing cable and the ground penetration radar have this capability. The installation cost of these techniques is another important feature among other performance metrics. Most of the hardware-based techniques have high installation cost and their implementation is limited to long-range pipeline applications. This is due to the large number of sensors needed to be mounted at strategic points along the length of the pipeline increasing the installation cost to a prohibitive level.

While these techniques generally perform better with regard to the usability and false alarm rate, the detection accuracy of some of these techniques depends on some other factors. For instance, the detection accuracy of the ground penetration radar method depends on the type of soil in which the pipeline is buried. If the pipeline is installed in clay soils, iron pipe corrosion products can hide cast iron pipes from the GPR, due to the presence of corrosion products in the soil, which increases the radio frequency signal attenuation and reduces the reflection [37].

III. LEAKAGE DETECTION USING INTERNALLY-BASED METHODS

In this section, some of the internally-based methods for leakage detection and localization are discussed.

A. BALANCING METHODS

The balancing methods (mass or volume balance) for leakage detection are based on the principle of mass conservation; a fluid entering a pipe section either remains or leaves the section. Under steady state condition and in the absence of leakage, the inflow and outflow of a pipe section must be balanced. In general, the difference in mass flow at the two ends of the pipe must be balanced against the change of mass inventory (mass imbalance) [14], [39]. In the absence of leak, leads to the equation

$$M_I - M_O = \Delta M_{pipe} \tag{1}$$

In (1), M_I and M_o represent the mass flow entering and leaving the pipe while ΔM_{pipe} is the mass imbalance between these two flow. A leak alarm is triggered once the mass flow difference exceeds some pre-defined threshold [39], [40].

Moreover, using a volume-balanced method for pipeline leakage detection, the following relationship [41] must be satisfied:

$$Q_l = Q_I - Q_o \geq dQ_m + \frac{dV_s}{\Delta t} \tag{2}$$

where, Q_l represent the leak flow rate, Q_I and Q_o are the measured inflow and outflow respectively, dQ_m represents the bound of uncertainty in flow measurement while dV_s is the bound of uncertainty in line pack changes over a time interval Δt. A wide variety of balancing systems such as LEAKTRACK [42] and MassPack^{TM} [43] have been commercialized and are available in the market. The balancing method is simple and good for steady state operation of the piping network. However, the method is prone to false alarms during transient operation of water distribution piping networks. Another significant disadvantage of this method is that of its sensitivity to arbitrary disturbances and the dynamics of the pipeline [20]. Likewise, this method cannot be used to determine the leak point unless a leak localization technique is associated.

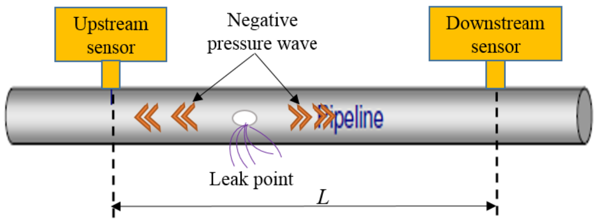

FIGURE 3. Illustration of the negative pressure wave method [16].

B. PRESSURE/FLOW MONITORING METHODS

The pressure/flow monitoring leakage detection method is based on the principle that a leak results in a sudden change of pressure and flow at the inlet and outlet of the pipeline. Conventionally, the pressure in a pipeline drops as a result of a leak. This leakage detection methods may be categorized into two, namely the wave alert or negative pressure wave (NPW) and the pressure point analysis (PPA). Considering the NPW method, when a leak occurs and the pressure of fluid in the pipe drops, a pressure wave signal (known as a negative pressure wave) propagates outwards from the leak point towards both sides of the leak point (upstream and downstream) as shown in Fig. 3. The pressure wave signals travelling towards the ends of the pipeline section as a result of a leak, can be detected by pressure transducers stationed at the terminal ends of the pipeline [44]. The position of the leakage point can be estimated by applying a cross-correlation method to the time difference at which both pressure sensors detect the negative wave signal. The negative pressure wave method is most useful in liquid pipelines, as pressure waves are quickly attenuated in gas pipelines [39]. In addition, some NPW techniques such as ATMOS Wave [45] are available in the market and can be used to estimate the leak size. However, practical application for long-range pipelines is a major challenge. Another notable limitation of its high rate of false alarm. During transient operation of pipelines such as opening and closing of valves, large pressure drop is usually observed. Therefore, a NPW method declares this as a leak event and a false alarm is given.

Further research efforts aimed at improving the NPW method were conducted by Tian *et al.* [46]. In this work, the authors identify three key areas to enhance the reliability and accuracy of this technique. These include data quality, adaptive thresholding and the false alarm reduction. Since NPW signals are masked by background noise signals, data quality may be improved by data processing and the application of appropriate filtering techniques [46]. Moreover, adaptive threshold can be used to detect anomalies in the slope curve of a pressure transducer, which varies as a function of work conditions [46]. Finally, in order to reduce the false alarm rate of this approach, three possible solutions have been proposed. Firstly, the negative pressure wave method may be combined with other leakage detection methods such as the magnetic induction method [47], and secondly, the use of a pattern-matching algorithm [46]. The pattern-matching algorithm can be used to distinguish between the pressure as a result of a leak and that caused by opening and closing of valves is proposed. Finally, multiple sensors may be paired on the pipe to reduce the false alarm rate [46]. In this, operation of each sensor is independent on the other, each giving its own leak results. The leak results of the sensor which differ from the combination of sets of other sensors is neglected. Consequently, the false alarm rate is reduced which, in turn, improves the reliability and accuracy of the system.

The pressure point analysis (PPA) method requires continuous measurements of pressure at several points along the length of the pipe. Thereafter, a statistical analysis is applied to these pressure measurements and consequently, a leak alarm is raised when the mean value of the pressure measurements obtained falls below a pre-defined threshold [39]. The PPA^{TM} technique developed by EFA Technologies Inc. [47] is available in the commercial market. Scott and Barrufet [13] investigate the effectiveness of this method. The results obtained show that the leakage detection method works well in underwater and cold environments. The cost effectiveness and the ease of use are the major advantages of using this method. A major limitation of using this method is its unreliability in detecting leakages during transient conditions of the piping distribution networks. Additionally, the method cannot be used to localize the leakage points.

C. TRANSIENT BASED METHODS

The transient based methods for leakage detection extract information about the presence of a leak from a measured/modeled transient pressure traces within a piping network. Several research studies based on the transient analysis of the pressure and flow within a piping network for leakage detection are described in the literature featuring the inverse transient analysis (ITA) [49]–[53], the leak reflection method [54], [55] and the transient damping method [56]. Several numerical, laboratory and field investigations have been conducted to validate the use of ITA methodology for detecting leakage in pipelines. The research efforts of Vítkovský *et al.* [50] and Tang *et al.* [53] are among the notable studies to report on laboratory test for validation of the ITA methodology. In [51], a performance assessment of the ITA methodology is conducted. Though laboratory results show that this methodology is able to locate leakages at several points in the tested piping network, several false leakages are reported.

Brunone [54] proposed a cost-effective leak reflection method for detecting leakages in pipelines. In this work, a series of experimental tests are performed to validate the proposed method. However, the method is largely influenced by the pressure signal alteration caused by leakages. Consequently, a high-level data analysis tool is required to identify and interpret these alterations. Even with its ability to detect leakage characterized by pressure drop such as that occurring due to pipe burst, its effectiveness in detecting background type leakages is a major challenge. Background type leakage is not characterized by a sudden pressure drop which is the basis for the operation of this method. Likewise, the practical application of this method in a large-scale water distribution systems is another notable limitation.

In a similar manner to the acoustic emission methods, several factors influence the effectiveness of the transient based techniques. These include pipeline and leakage characteristics, state of flow within the pipeline, the state of the surrounding soil as well as the operational data collected [57]. Nevertheless, several computational tools such as independent component analysis [58], support vector machines (SVM) [59], [60], artificial neural networks (ANN) [61], [62] and a combination of fuzzy-ANN [63], [64] have been proposed to handle and analyze the pressure wave transients. In [58], a method of enhanced independent component analysis and the support vector machine was proposed for examining pressure traces. The proposed system provides a better accuracy than the direct SVM method. Another notable research effort conducted by Hu *et al*. [65] for the analysis of transient pressure waves was based on the use of interactive self-organizing data analysis technique algorithm (ISODATA). Although this methodology has been tested on a single pipeline using a small laboratory test bed, they do not work well when applied to large piping networks under field conditions. Also, most of these techniques cannot be used for real-rime applications.

D. LEAKAGE PREDICTION MODELS BASED ON STATISTICAL METHODS

Traditionally, statistical methods are mostly used to predict pipe bursts in water piping networks. The method uses statistical approaches from the decision theory to analyze the pressure and flow measurements from historical data to detect a leak [14], [39]. Consequently, a leak alarm is raised if the system encounters some patterns from the statistical analysis that show significant changes in pressure and flow rates. The technique is simple as the development of a mathematical model is not required and can also be used to estimate the location of a leak in the pipeline [66]. In the past, a number of statistical models have been proposed in the literature for prediction of pipe bursts. These techniques range from the time linear regression models [67], time exponential models [68], generalized linear models (GLM) [69], to the Bayesian belief networks (BBN) for predicting pipe breaks in WDNs [70]. Most of these models have been compared by the authors in [71] and found that the GLM has superior performance above others. Further improvements proposed in the work of [69], lead to a logistic GLM proposed by Yamijala *et al*. [72]. In this work, the statistical method proposed shows a good estimate of pipe reliability and can be useful for water utilities in planning pipe inspection and maintenance. Buchberger and Nadimpalli [73], developed a new statistical method based on the sequential statistical analysis of continuous measurements taken at one location. This approach provides information on the leak magnitude in a pipeline section. However, the actual location of the leak cannot be determined. It also requires field investigation for validation. Conventionally, statistical techniques are developed to reduce the rate of false alarm and have been successfully tested in oil pipeline systems [74]. However, there is difficulty in estimating the leak volume and they are costly. Also, a leakage detection system based on statistical methods has poor sensitivity when the pipeline is operating under transient conditions. An approach using a real-time transient model [39] has been proposed to overcome this problem.

E. SIGNAL PROCESSING METHODS

Another method for leakage detection based on the measurement of flow and pressure is the use signal processing techniques. In this case, the response of the pipeline to a known input is measured over a period of time. This response is then compared with the later measurements and a signal processing technique such as frequency response or wavelet transform coefficients is applied. The detection is then based on comparison of their features extracted from the signals to detect changes in the system response. This technique was first proposed for pipelines transporting liquids [75]. Currently, solutions for pipelines transporting liquid and gas are available [76].

The techniques used in signal processing methodology for leakage detection involve the use of the frequency response method [77], [78], inverse resonant and peak sequencing [79], standing wave difference method [80], filter diagonalization method [81], impedance method [82], and wavelet transform analysis [83]. Most of these approaches have been tested in a small laboratory test beds involving simple pipeline arrangements. Mpesha *et al.* [77] report the success of the frequency response method in detecting leakages in a simple piping system. However, further investigation is required for its application in large-scale water distribution networks.

The research work of Lee *et al*. [79] attempts to improve on the research effort conducted by Mpesha *et al.* [77] by introducing the inverse resonant and the peak sequencing method. About a year later, an experimental investigation was performed by Lee *et al.* [84] to validate this technique. The overall results give vital information on the effect of leakages on the system frequency response.

Another notable research effort for leakage detection using the signal processing methodology leads to the use of the standing wave difference method (SWDM) proposed by Covas *et al*. [80]. Detailed analysis of the SWDM based on the technology used in electrical engineering to determine cable fault position can be found in [80]. Although the performance of this method when tested numerically on several pipeline configurations indicated that the SWDM would be a promising method for leakage detection in complex piping networks, practical (laboratory and field) verification is a major concern and further work is required before adopting this methodology in real WDNs. Other notable research efforts in this domain involve the use of cross-correlation analysis [85] and the wavelet transform analysis [83]. Detailed analysis of these techniques may be found in references [83], [85]. Most of these techniques require a huge set of real-time pipe network operational data and lead to high computational cost. In most cases, they are difficult to adopt for real life situations.

F. MODEL-BASED LEAKAGE DETECTION METHODS

In this method, mathematical formulations are derived to represent the operation of a piping network. Then a leak alarm is raised if the estimated flow rate (including leakage flow) exceeds a pre-defined threshold. In this method, the network leakage flow is usually modelled as a pressure dependent flows/demand simulated as emitter flow at selected nodes in the network. Previous research works [86]–[89] revealed that leakage flow is sensitive to pressure according to the relation shown in (3)

$$Q_{leaks} = \alpha h^{n} \tag{3}$$

where, Q_{leaks} represents the leakage flow rate, α is the leakage discharge coefficient which depends on the pipe material, leak opening as well as the soil structure, h is the pressure head and n is the pressure exponent. For detectable leaks and burst on metallic pipes, n is found to be 0.5 [86], [88].

From (3), it may be safely concluded that the leakage flow rate (both burst and background leakage) may be reduced by minimizing the network pressure without compromising the necessary pressure head required to satisfy demands at the network nodes.

The literature is enriched with numerous research works focusing on pressure control in piping networks [90]–[98]. Thus, pressure dependent leakage flow model should be a breakthrough in estimating the network background type leakage flows. To this end, Germanopoulus [99], Germanopoulus and Jowitt [100] expressed background leakage Q_{leak} as

$$Q_{leak} = \begin{cases} C_k L_k \left(P_k\right)^{n} & if\ P_k > 0 \\ 0 & if\ P_k > 0 \end{cases} \tag{4}$$

where, C_k denotes the leakage discharge coefficient, L_k the length of the kth pipe and P_k represents the average pressure at the end nodes of the k^{th} pipe.

This model is based on the assumption that leakage is uniformly distributed along the length of the k^{th} pipe. With this model integrated into the classic water distribution network hydraulic model as in [6] for estimating the network leakage flows, an appropriate leakage detection algorithm may be developed [6]. Wu *et al.* [101] developed a pressure dependent leakage detection model using a genetic optimization approach. The leakage model is formulated using emitter flows equation at selected model nodes and translated to an optimization problem solved by the use of genetic algorithm. The developed model is tested on district water system. It is quite obvious from the field observed pressure and flow measurements that the model only works well for burst type leakage flow in the system. It remains unclear if the developed model adapts well to background leakage flows.

A major uncertainty in developing the leakage model is the contribution of the interior of the pipe in the network. The available leakage detection models are based on the assumption that the pipe diameter remains constant over the entire service life of the pipe. In reality, with ageing of the pipes, the pipe roughness coefficient increases which results in corresponding decrease in the pipe diameter. Thus, any leakage detection model must take into account these very important parameter (pipe diameter and age) for a more realistic representation.

More so, some leakage detection models were developed for real-time operation and application in piping networks. These include real-time transient models (RTTM) and extended RTTM [102]. The real-time transient models for leakage detection use mathematical models of the flow within a pipeline based on the principles of mass conservation, momentum and conservation of energy. The RTTM methods may be seen as an enhancement of the balancing methods, as they use, in addition to the mass conservation principle, the conservation principle of momentum and energy. The Extended RTTM technique uses the combine concepts of RTTM technology and statistical methods for its operation. A detailed analysis of these techniques may be found in [14] and [39]. The RTTM and ERTTM based techniques can be used to detect leaks in pipelines during both steady state and transient conditions of the piping networks [31]. They may also be used to detect small leaks (less than 1 per cent of flow) [13] and a commercial system of these techniques (PipePatrol SMB and PipePatrol E-RTTM) has been developed and supplied by Krohne Oil & Gas Inc., Netherland [102]. However, a major limitation of using these techniques is the associated cost as they require extensive instrumentation for collecting the networks' operational data. Additionally, the techniques are not easy to use as the models employed are complex and can only be handled by an expert [13], [103].

G. COMPARISON OF THE INTERNALLY-BASED METHODS

In this Section, the compared performance for some of the internally-based leakage detection techniques, as illustrated in Table 2, are presented. The cost of implementing the balancing methods (mass/volume balance) as well as the pressure/flow monitoring methods (NPW and PPA) is quite low compared to the other techniques shown in Table 2. Moreover, the leak localization ability cannot be achieved with the use of either the mass/volume balance method or the pressure point analysis method, having better performance in terms of cost as discussed earlier. In terms of implementing these techniques, the balancing methods, pressure monitoring methods as well as the statistical methods are easier to use. The transient based methods such as the real-time transient model (RTTM) and its extended form (E-RTTM) are very complex since they involve complex mathematical models [39]. Consequently, they can only be handled by an expert or a trained user. Although these two techniques are complex and not easy to implement, their false alarm rate is relatively low compared to other software based technique except for the statistical methods that have similar performance. While these techniques, apart from the balancing methods, generally perform better in terms of detection speed, their detection accuracy depends on some other factors. The detection accuracy of the balancing methods, for

TABLE 2. Compared performance analysis of the internally-based method.

Leakage detection methods	Performance metric							
	Operational cost	Leak localization	Leak size estimate	Usage	False alarm rate	Accuracy	Response time	Application
Balancing methods	Low	No	Yes	Easy	High	Accuracy depend on leak size and the measuring instrument	Slow	Only applicable during steady state operation of pipelines
Negative pressure wave	Low	Yes	Yes	Easy	High	Accuracy depend on the position of sensors and leak size	Fast	Most suitable for liquid transporting pipelines. Un-practical for long-range application
Pressure point analysis	Low	No	No	Easy	High	Accuracy depend on pressure measurement	Fast	Not suitable in pipelines operating under transient conditions.
RTTM and ERTTM models	Very high	Yes	Yes	Complex; require trained personnel	Low	Accuracy depends on the mathematical model used	Fast	Applicable during both steady state and transient condition of pipelines.
Statistical methods	High	Yes	Yes	Easy	Low	Accuracy depends on leak size	Fast	Can be used for complex pipeline applications
Signal processing techniques	High	Yes	No	Not easy to implement	-	Medium; accuracy depends on leak size	Fast	Suitable for both liquid and gas transporting pipelines.

example, depends on the leak size and the measuring instrument used [66], [104]. Furthermore, the detection accuracy of the transient models depends on the mathematical model used. If there is a latency/computation error in the used model, the detection accuracy is affected. In estimating the leak size, all the software-based techniques can be used. However, the pressure point analysis and signal processing methods do not have this ability.

IV. LEAK LOCALIZATION

For effective leakage management and control of water loss, identifying the exact position of the leakage is vital to hasten pipeline leakage repairs and maintenance. Numerous leak localization techniques are available in the literature each with different accuracy and variability in their operating environments. Some leakage detection techniques can estimate the exact location of the leak themselves, while in some other techniques, a leak localization algorithm needs to be incorporated. In the past years, traditional methods for localizing leakage points involve the use of acoustic logger [105], and step testing [106]. Most of these technologies have slow response in the event of a leak and are generally labor intensive. Further research efforts involved the use of leak noise correlator [107], pig-mounted acoustic sensing [108], live camera inspection systems [109] and tethered acoustic systems [36] most of which have been deployed in district meter areas (DMAs) of water distribution networks and are available commercially. More recently, a leak localization algorithm that limits human involvement has been proposed and is generally classified as gradient intersection method (GIM) and the wave propagation method (WPM) [14], [39]. The former is based on the fact that leak occurrence changes the pressure gradient along the pipeline in a characteristic manner. Conventionally, the pressure drop in a leak free pipeline is usually linear. In the presence of a leak, the pressure profile develops a flaw at the leak point [39]. The leak location can be determined by estimating the intersection point of the pressure profiles upstream and downstream of the leak as shown in Fig. 4. The wave propagation method illustrated in Fig. 5, analyses the pressure waves that result from a leak and the leak position determined by comparing the arrival time of the pressure wave at the pipeline inlet and outlet pressure sensors. This leads to the traditional leak localization formula given as [14], [46]

$$x_{leak} = \frac{1}{2}\left(\left(x_{down} - x_{up}\right) + a.\left(t_{up} - t_{down}\right)\right) \tag{5}$$

where, x_{down} and x_{up} represent the location of the downstream and upstream pressure sensors from the leak point. a is the leak signal wave speed while t_{up} and t_{down} are the time it takes the pressure sensors to detect the wave signal.

In (5),

$$x_{down} - x_{up} = L \tag{6}$$

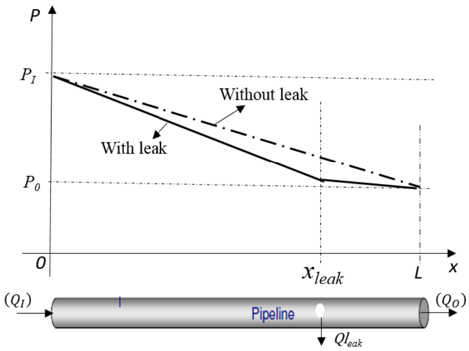

FIGURE 4. Illustration of the gradient intersection leak localization method [39].

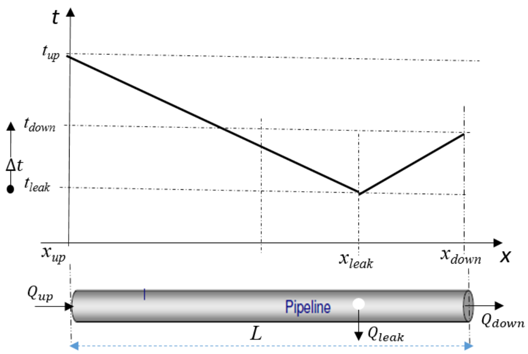

FIGURE 5. Illustration of the wave propagation leak localization method [39].

where, L is the length of the pipe in which the pressure sensors are located.

While the GIM has a good localization accuracy during stationary operation of the pipeline, it suffers from inaccuracies during transient conditions. The wave propagation method boasts good accuracy during both stationary and transient operations [39]. However, its localizing accuracy depends on the length of the pipeline as well as the leak size; creeping and spontaneous leaks that are not large enough cannot be detected. This is because a large leak produces a pressure wave of higher magnitude that travels faster to the upstream and downstream pressure sensor. Therefore, if the wave magnitude is not strong enough, it would have died down before reaching the pressure sensor at both ends of the leak site, and consequently the wave will not be detected. The conventional leak localization method (WPM) based on time delay estimation requires that the accurate length of pipeline between two detection points is known as shown in equation (5). Another method, which does not require the knowledge of the pipe length was proposed by Yang *et al.* [110]. The proposed method is based on blind system identification. However, practical application in large-scale WDNs is still a major limitation.

V. UTILIZATION OF WSN FOR LEAKAGE DETECTION

Leakage detection methods have been examined in the past and recent times by many scientific organizations and research institutes leading to numerous research reports, papers and Technical Standards. Nevertheless, the widespread deployment of wireless sensor networks (WSNs) for detecting leakages in real-time cannot be overlooked. Thanks to the proliferation in technology, especially in the area of micro-electro-mechanical systems (MEMS) which saw the development of inexpensive smart sensors with both wired and wireless communication technologies [111]–[116]. These technologies have been deployed in real-time for monitoring pipeline health through leakage detection [30], [117], [118]. As an example, in Fig. 6, a WSN architecture for application in pipeline leakage monitoring is illustrated. In this architecture, several pressure sensors arranged in sensor nodes are mounted on a pipe to measure pressure drop due to leakages. The pressure data collected/measured by these sensors can be transferred to a remote control center for processing. Mudumbe and Abu-Mahfouz [119] utilize WSN to remotely monitor the water flow. A sensor node called WaterGrid-Sense has been developed to provide a real-time monitoring and control platform for various WDN components such as water meter and pressure sensor. The collected data is used for various applications, such as leakage detection, hydraulic model and demand prediction to improve the efficiency of the WDN [120], [121].

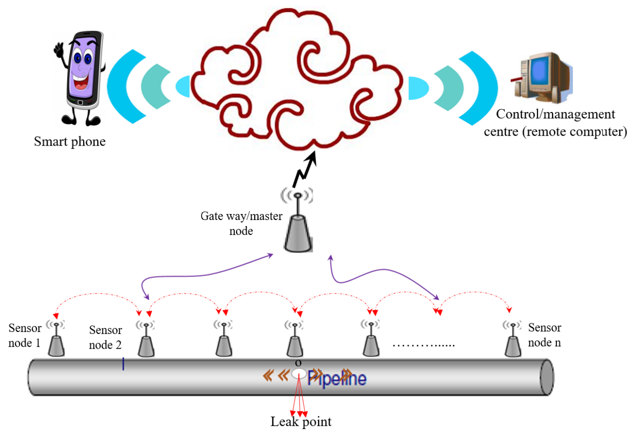

FIGURE 6. WSN architecture for pipeline health monitoring.

Likewise, a combination of several sensors such as vibration sensor, acoustic sensor, temperature monitoring sensors, can be mounted on pipelines, though at the expense of cost, for monitoring pipeline health as in Fig. 7. These sensors collect data related to the internal or external parameters of the pipeline, and send the data to a remote control system, where the information is processed. The processed data may be used for numerous purposes such as detecting leaks in the pipeline. While WSNs use radio communication technology to transmit the sensed signals, its design for pipeline leakage detection depends on the type of fluid transported by the pipeline as well as the environment within which the pipeline is installed [122]. These factors play a major role in the sensor type and its placement. Sensors can be placed in contact with the fluid inside the pipeline (known as invasive sensor) or placed without contact with the fluid (known as non-invasive

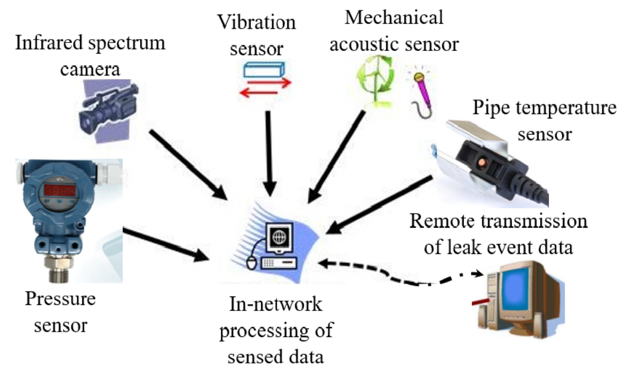

FIGURE 7. Sensor array for pipeline health monitoring.

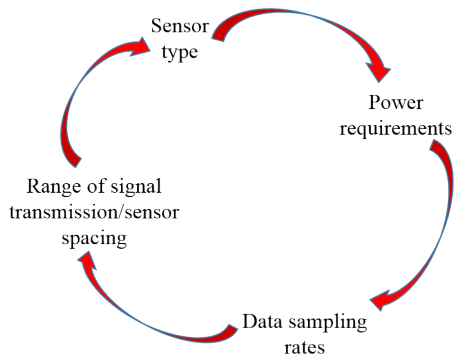

FIGURE 8. WSN specification for pipeline health monitoring.

sensor) [47], [123]. Since sensor nodes are battery powered, energy conservation and power efficiency, among others, are the major limitations of using this technology [124]–[127]. These pose a serious threat to the design and specification of WSN for the real-time application in pipelines health monitoring (see Fig. 8). In spite of this limitation, several research works have been conducted in the past on the energy management of wireless sensor nodes. These include energy harvesting strategies [128]–[130], energy conservation and routing protocol schemes [131], [132]. Several small-scale energy harvesting prototypes employing wind energy and the vibration energy caused by the movement of objects around the operating environment of the sensor nodes have been developed [128], [129]. The developed energy harvesting prototypes can be used to boost the energy efficiency of sensor nodes application in pipelines. Although, only intermittent energy can be provided by these prototypes, the power issue of sensor node is still an ongoing research area. A comprehensive review of these schemes may be found in [131]–[133].

Shinozuka *et al.* [118] present an intelligent WSN system for real-time non-destructive monitoring of water pipelines in an underground application. In this work, the authors use accelerometers to measure the vibration on a pipeline surface. Notable limitations of this research include power management of sensor nodes, effective bandwidth usage and precise time synchronization of data. Accurate time synchronization is very important since a small-time deviation of monitoring device can cause a large location error [46]. Further research efforts by Abu-Mahfouz and Hancke [124] focused on improving the power management issue in [118]. However, more research effort is still required to improve the overall system challenges.

Another notable research is that of Meribout [134], where a WSN-based infrastructure is developed for real-time and online pipeline inspection and leakage detection in multiphase fluid pipes. In this pioneer work, leakage detection is achieved using an air-ultrasonic sensor and a bidirectional microphone for continuous checking of the existence of eventual leaks and their location. Almazyad *et al.* [135] present a scalable design for leakage monitoring in a water pipeline systems using radio-frequency identification (RFID) and WSN technologies. While the energy conservation solution is achieved, the leak location point as well as the leak size estimate is not included in the design.

In the work of Sadeghioon *et al.* [117], several force resistive sensors (FRS) are deployed to measure pressure changes in plastic pipes. Both laboratory and field trials conducted on a small piping system revealed that leakage detection was achieved. Communication between sensor nodes is provided by the use of radio frequency (RF) signals. Practical verification for large scale piping networks is required. Furthermore, a poor communication signal strength is obtained while using RF signal for communications in underground environments. This is because the electromagnetic waves undergo high attenuation in underground applications [136], [137]. In [47], a magnetic induction based communication system is proposed to provide less attenuation for underground applications.

More recently, further research effort by Mysorewala *et al.* [138] proposes the use WSN-based approach for detecting leakages in a straight horizontal pipeline using four pressure sensors uniformly distributed to measure the pressure profile across the pipeline. This work shows a promising way for leakage detection in a straight horizontal pipeline. However, practical applications in a more complex pipeline configuration are still a major concern. Although, attractive reduction is relatively achieved in the energy consumption of the sensing, processing and communication tasks of the sensor node, the use of energy harvesting techniques proposed by the authors in [128]–[130] will further enhance the energy efficiency of the system.

Other research progress in the use of WSN based technology for monitoring pipeline health through leakage detection and localization may be found in the literature. In most of these research efforts, a reliable energy efficient WSN based leakage detection technique has not been fully achieved. Secure and reliable communication between sensor nodes is another notable research challenge [139]–[142].

VI. CONCLUSIONS AND FUTURE WORKS

An efficient leakage detection technique plays a vital role in loss reduction in any piping network. In this paper, the authors present a comprehensive survey of the existing leakage detection and localization methods as well as the research progress in this area. It is crystal clear from this survey that the current leakage detection methods have different accuracies, cost of deployment and applicable environments. Nevertheless, combining several leakage detection methods to form a hybrid system is a common practice and is recommended [143]. It is understood from the review presented that the existing methods are to some extent, able to detect burst type leakages. However, there is uncertainty in their application in detecting background type leakage. In a large-scale piping network, as in water distribution networks (WDN), background leakage is often hidden and difficult to detect compared to sudden pipe burst, which has been the focus of the numerous research works. As a result, the current leakage detection techniques applying signal processing/analysis to abrupt changes in pressure and flow within a pipeline for leakage detection are ineffective in detecting background leakage in a WDN, and do not meet the need for detecting leakages in large-scale water distribution networks. More research effort should be devoted to this type of leakage as a higher percentage of water loss is caused by this leakage [7].

A considerable amount of research is being conducted in the area of using wireless sensor networks for real-time leakage detection and localization in pipelines. However, the deployment strategies of these sensors in a wireless sensor nodes need to be considered. Energy management of sensor nodes, secure communication between sensor nodes in an underground application, among others, are some of the research challenges mentioned in this paper. Transmitting the reading of these sensors from an underground sensor node to a remote control/admin center in a reliable way is still an open research problem. There are numerous studies that highlight the importance of continuing research in pipeline leakage detection and diagnosis. Generally, the literature on leakage detection and diagnosis acknowledges high levels of uncertainties and a reliable leakage detection methodology has not been fully achieved.

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