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Review

Recent Advances in Pipelines Monitoring and Oil Leakage Detection Technologies: Principles and Approaches

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Abstract: Pipelines are widely used for transportation of hydrocarbon fluids over millions of miles over the world. The structures of the pipelines are designed to withstand several environmental loading conditions to ensure safe and reliable distribution from point of production to the shore or distributions deport. However, leaks in pipeline networks are one of the major causes of innumerable losses in pipeline operators and nature. Incidents of pipeline failure can result in serious ecological disasters, human casualties and financial loss. In order to avoid such menace and maintain safe and reliable pipeline infrastructure, substantial research efforts have been devoted to implementing pipeline leak detection and localisation using different approaches. This paper discusses on pipelines leakage detection technologies and summarises the state-of-the-art achievements. Different leakage detection and localisation in pipeline systems are reviewed and their strengths and weaknesses are highlighted. Comparative performance analysis is performed to provide a guide in determining which leak detection method is appropriate for particular operating settings. In addition, research gaps and open issues for development of reliable pipeline leakage detection systems are discussed.

Keywords: Leakage; Leak detection; Leak Characterisation; Leak localization; Pipelines; Wireless Sensor Networks

1. Introduction

The use of pipeline is considered as a major means of conveying petroleum products such as fossil fuels, gasses, chemicals and other essential hydrocarbon fluids that serve as assets to the economy of the nation [1]. It has been shown that oil and gas pipeline networks are the most economical and safest mean of transporting crude oils and has fulfilled a high demand for efficiency and reliability [2,3]. For example, the estimated deaths due to accidents per ton-mile of shipped petroleum products are 87%, 4% and 2.7% higher using trucks, ships and rails respectively compared to using pipelines [4]. However, as transporting hazardous substances using miles long pipelines has become popular across the globe in decades, the chance of the critical accidents due to pipeline failures increases [5]. The causes of the failures are either intentional (like vandalism) or unintentional (like device/material failure and corrosion) damages [6,7], leading to pipelines failure and thus result in irreversible damages which include financial losses and extreme environmental pollution, particularly when the leakage is not detected timely [8,9].

The average economic loss due to incidents of pipeline leakages is enormous [10]. To size the cost, in single incident of pipeline leakage at Sam Bruno community, USA on September 6, 2010. More than 840,000 gallons of crude oil spilled into Kalamazzo River with estimated cost of $800 million

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[11]. The cause of the pipeline damages varies. Figure 1 shows a pie chart that illustrates statistics of the major causes of pipelines failure which include pipeline corrosion, human negligence, defects befalls during the process of installation and erection work, and flaws occurs during the process of manufacturing and external factors [12].

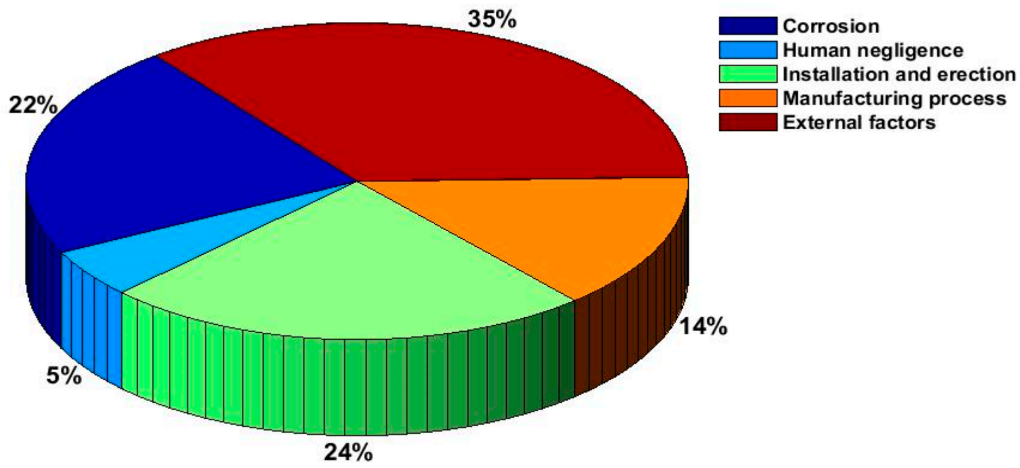

Figure 1. A pie chart for the statistics of the sources of pipeline failure. Data is obtained in [12].

Based on this statistics, incidents of pipeline leakage are hard to entirely avoid as the sources of failures are diverse. However, in order to reduce the impacts of oil spillage to the society it is very important to monitor pipelines for timely detection of leakage or even leak prediction as early detection of leak will aid quick response to stop oil discharge and proper pipeline maintenance. Hence, it is possible to abolish the loss rate, injuries and other serious societal and environmental consequences due to the pipeline failures.

Several pipeline leak detection methods have been proposed during the last decades using different working principles and approaches. Existing leakage detection methods are: acoustic emission [13-15], Fibre optic sensor [16-18], Ground penetration radar [19,20], Negative pressure wave [21-23], Pressure point analysis [24-26], Dynamic modelling [27,28] , Vapour sampling, Infrared thermography, Digital signal processing and Mass-volume balance [29-33]. These methods have been classified using various frameworks. Some authors have classified them into two categories: hardware and software-based methods [34,35]. In an attempt to group these methods based on technical nature further research efforts have been made [36-42] which led to the classification of available leakage detection systems into three major groups namely internal, non-technical or non-continuous and external methods [2, 4]. In this study, we will classify different methods to the following categories as exterior, visual or biological, and interior or computational methods. A detailed classification of these methods is shown in Figure 2. The exterior approach utilises various man-made sensing systems to achieve the detection task outside pipelines. Moreover, the biological approach utilises visual, auditory and/or olfactory senses of trained dogs or experienced personnel to detect leakage. In addition, the interior approach consists of software based methods that make use of smart computational algorithms with the help of sensors monitoring the internal pipeline environment for detection task. Remote monitoring can be achieved by carrying camera or sensing systems to designated locations by smart pigging, helicopter or AUVs/drones or sensor networks [2].

This paper aims to examine the state-of-the-art achievements in pipelines leakage detection technologies and to discuss research gaps and open issues that required attention in the field of pipelines leakage detection technology. The rest of the paper is organised as follows: Section 2 presents the exterior based leak detection methods and compares their strengths and weaknesses; Section 3 presents the visual/biological based leak detection methods; Section 4 presents the interior based leak detection methods and features their strengths and weaknesses. The comparative performance analysis of the reviewed methods is given in Section 5. Section 6 gives the guideline for

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selecting leak detection method under various operating environments. The research gaps and open issues on pipeline leakage detection and characterisation are discussed in Section 7. Finally, a summary of this paper, and possible future directions are presented in Section 8.

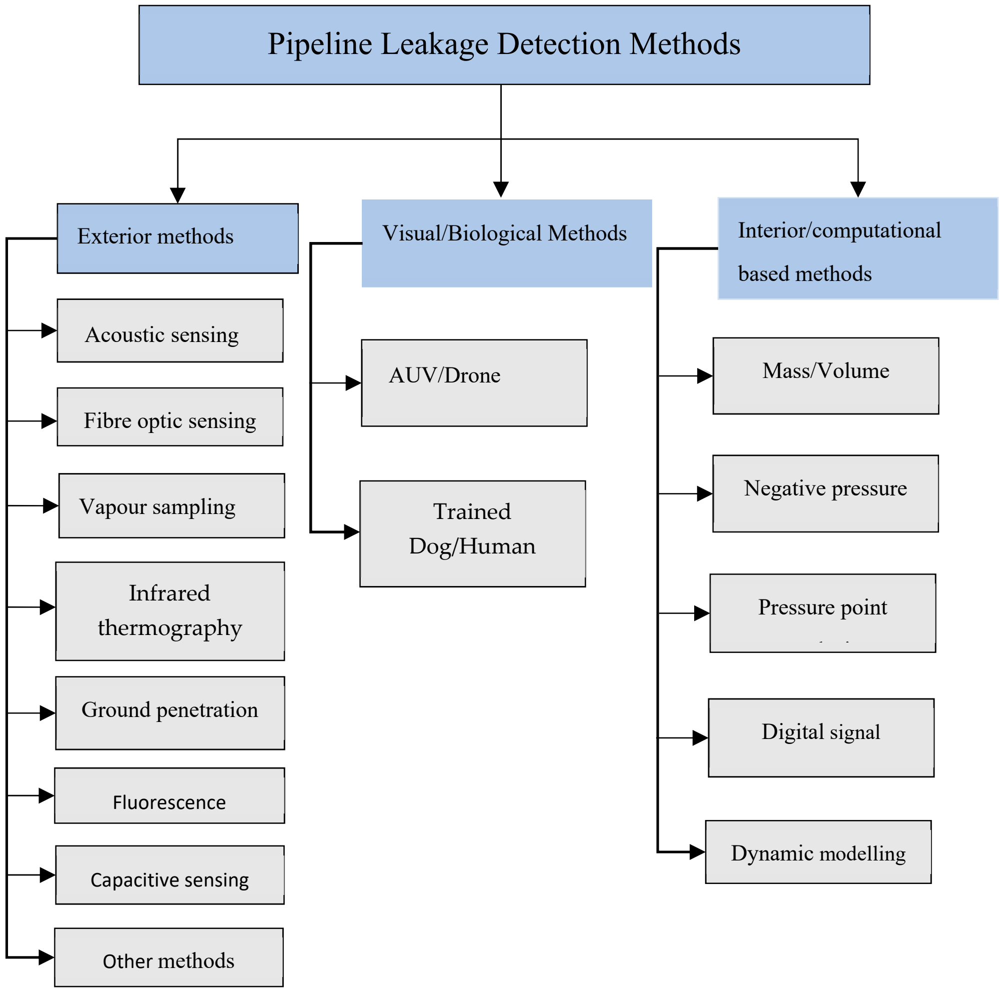

Figure 2. Flow chart of different pipeline leakage detection approaches

2. Exterior Based Leak Detection Methods

Exterior methods mainly involve the use of specific sensing devices to monitor the external part of the pipelines. These methods can be used to determine abnormalities in the pipeline surrounding and also detect the occurrence of leakages. Irrespective of the working principles these sensing methods based on, they require physical contact between the sensor probes and the infrastructure under monitoring. Examples of these devices include acoustic sensing, fibre optic sensing, vapour sampling, infrared thermography and ground penetration radar. The operational principle, strengths and weaknesses of these methods are discussed in subsequent sections.

2.1 Acoustic emission sensors

Acoustic emission employs noise or vibration generated as a result of a sudden drop in pressure to detect the occurrence of pipeline leakage. When a pipeline leak occurs, it generates acoustic emission (intrinsic leak signal) through high-pressure fluid escaping from the perforated point that can be sensed to determine the incidence of the leakage using information contained in elastic wave signal from the leak sources [4]. The time lag between the acoustic signals sensed by the two sensors is employed to identify the leakage position [43]. Acoustic method for leak detection can be divided into two classes [44]: active and passive. Active methods detect pipeline defect by listening reflected

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echoes of emitted sound pulses due to leakage. On the contrary, passive methods detect defects by listening to changes in sound generated by pressure waves in the pipelines. There are three major categories of acoustic sensors namely aquaphones, geophone and acoustic correlation techniques. Aquaphones require direct contact with hydrants and/or valves, while geophones listen to leaks on the surface above the ground directly. At the same time, steel rods can also be inserted into the buried pipe to transmit signal to mounted sensors on the rods. The amplitude of the measured pressure signal is measured as Sound Pressure Level (SPL) [2]:

$$SPL = 20\log_{10}\left(\frac{P}{P_0}\right) \tag{1}$$

where P_0 represents a reference sound pressure amplitude which is generally taken as 20 μPa [45]. As SPL is directly proportional to the gas generated power due to expansion it can also be expressed as:

$$SPL \propto \log_{10}\left(\frac{RT}{M}\dot{m}\right) \tag{2}$$

where R is the gas constant, T is the gas temperature at the orifice, M is the molecular weight and $\dot{m}$ represent jetting gas mass flow rate. Both aquaphones and geophones can be used to detect and locate leakage. However, these approaches are not effective due to its slow operating procedures [46]. Acoustic correlation method is more sophisticated than the above-mentioned methods. In this approaches, two sensors are required to position on either side of the pipe to detect leakage. The time lag between the acoustic signals when the sensors sensed the leak is used to detect and identify the point of leakage [43,47]. The uses of acoustic emission methods for pipeline leaks detection have been reported in several studies [48-50]. A reference standard for setting up and evaluating acoustic emission sensors deploy for detection of pipeline leakages proposed by [51]. The authors' aims at developing a reference standard for acoustic signal in order to provide a valuable threshold for checking out monitoring infrastructure and characterising source mechanisms to quantify leakages based on acoustic emission technology. By introducing several kind of controlled leakages, the effect of pressure and air injection were determined for the thread leak on the order of $0.1\ galhr^{-1}$. In [52], a combination of Linear Prediction Cepstrum Coefficient (LPCC) and Hidden Markov Model (HMM) was devised to examine the damaged acoustic signals. The HMM was used to identify corrupted signals while LPCC which represnts short-time acoustic signal was adopted as the signal characteristic parameters. The obtained results revealed that the acoustic signal recognition rate was improved up to 97%.

Jia *et al.* conducted a gas leakage detection experiment on a gas pipeline length of 3.13 km using measured acoustic wave with the sensors positioned at different locations along the gas pipeline [17]. During the experiment, it was observed that acoustic wave generated due to the leakage transmitted from rupture point to all sides of the pipeline at the rate of gas velocity, but the high frequency components of the acoustic decayed much faster than its low-frequency counterparts did. Therefore, they concluded that it is sufficient to detect leakage in gas pipelines using low-frequency signals. Applying acoustic emission for detecting leakage on pipeline networks can achieve early leaks detection, estimation of leak sizes and leak point localisation [39]. However, the effect of background noise can easily mask the actual sound of a leak. In order to overcome this challenge, several signal analysis techniques have been proposed in literature such as interrogation methods [13], wavelet transform methods as well as the combination of acoustic sensors with other types of sensors such as magnetic flux leakage [14, 50, 53].

The use of cross-correlation method for detecting multiple leaks points in buried pipelines was investigated in [54]. The study revealed that measuring acoustic emission signal using two detectors positioned at both side of the pipe is efficient. Noise elimination and feature extraction on weak leak signatures using wavelet entropy was proposed in [55]. The weak signal was revealed using nonlinear adaptive filtering in accordance with the different characteristics between the actual signal and noise. Chen et al. demonstrated that small pipe leaks signal can be efficiently differentiated from the noise and effectively localised. Oh et al. [49] has proposed an acoustic data condensation approach to determine and condense the distinguishable feature from the acoustic signals data so that high-

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pressure steam leakage can be diagnosed effectively. The obtained results showed that the proposed method successfully enable reduced sets of data to characterise the acoustic signature. Generally, the benefit of using acoustic emission for monitoring of pipeline network are easy utilisation of interrogation as well as the convenience of installation as it does not require system shutdown for installation or calibration. However, background noise can easily mask the sound of leakage at a high flow rate so that critical leakage may not be detected reliably.

2.2. Fibre optic method

This method involves installation of fibre optic sensors along the exterior of the pipeline. The sensors can be installed as a distributed or point sensor to extensively detect the variety of physical and chemical properties of hydrocarbon spillage along the pipelines. The operation principle of this method is that cable temperature will alter when pipeline leakage occurs and hydrocarbon fluid engross into the coating cable. By measuring the temperature variations in fibre optic cable anomalies along the pipeline can be detected [4]. Distributed Optical Fibre Sensor (DOFS) provides environmental measurement based on three scattering classes namely Raman, Rayleigh and Brillouin scattering [56]. These classifications are based on the frequency of the optical signals as illustrated in Figure 3. Brillouin scattering can measure both strain and temperature but is very sensitive to strain, while Raman scattering is only sensitive to temperature with greater ability to accurately measure temperature greater or equivalent to 0.01^0C resolution [57].

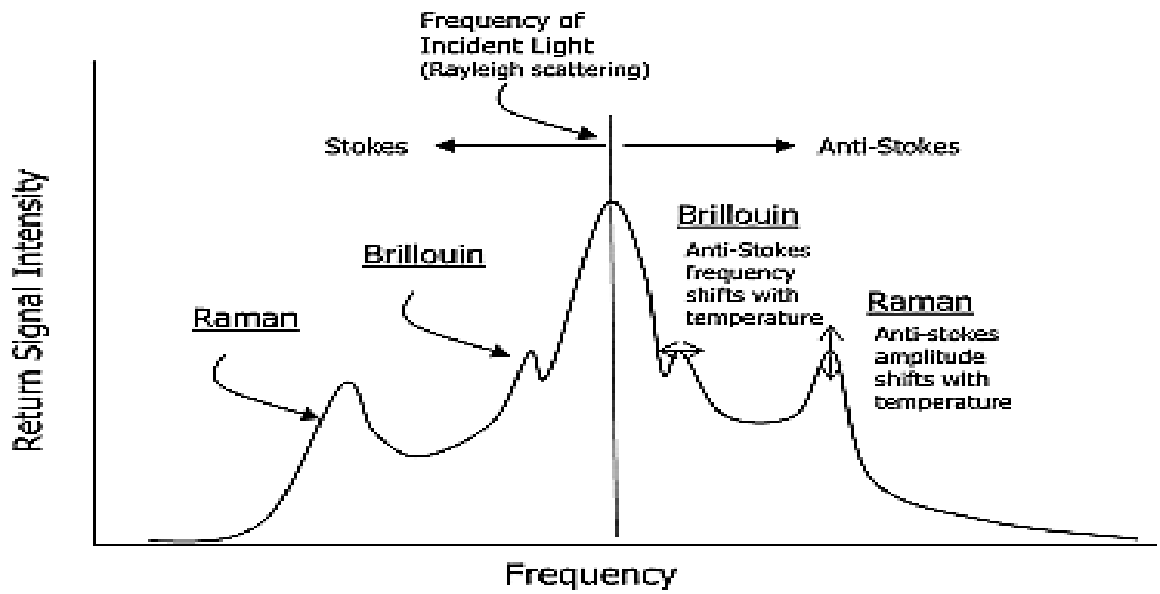

Figure 3. Schematic representation of the electromagnetic spectrum illustrating Rayleigh, Brillouin and Rayleigh [58]

The manifestation of Brillouin scattering takes place as a result of interaction between acoustic wave and propagated optical signal. This leads to shift in frequency components in received light, but in the case of Raman scattering approach changes in temperature only results in backscatter light intensity fluctuations. The frequency shift mechanisms in Raman backscattered light consists of two components namely, Stoke and Anti-stoke components [58]. The variation in temperature does not affect the amplitude of the stoke components, while the amplitudes of Anti-stoke components vary dynamically in accordance with temperature changes. The operation method of Rayleigh is based on elastic scattering (i.e. scattering without frequency variations) and the scattered power is directly proportional to the incident power which makes it attributed to non-propagation density fluctuations [59]. Brillouin scattering can be measured based on spontaneous or simulated ways; however, identification of the wavelength shift of the scattered light acts as a key means of measuring Brillouin scattering [58]. One of the benefits of pipeline leakage detection using fibre optic is its ability to detect

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small leaks [56]. Moreover, the potential of monitoring long pipelines and capability to accurately functioning in both subsea and surface pipeline networks can also be considered as another benefit of fibre optic based system [4]. However, its shortcomings include short lifespan and the inability to estimate the rate of leakages. Besides, the installation of fibre optics system over a large and complex pipeline network is challenging as optical fibres are fragile.

Several pipeline leakage detection systems based on fibre optic approach have been proposed in literature [5, 60-62]. The effectiveness of using distributed optical fibre for pipeline leak detection has been reported in [63]. In general, optical fibre is used for dual functions: signal transmission and sensing. The leak position is determined using the time order of the anti-stoke light received at the measuring station. A similar study based on macro bend coasted fibre optic proposed by [64]. In this study, bending structure and macro-bending loss was utilised as a sensing mechanism for leaks detection. The incident of leaks was determined through comparison of the power loss at a different bending radius, and wrapping turns number. The obtained result revealed that the proposed system was able to detect leakage at the frequency range of 20 Hz to 2500 Hz. In [17] the authors have implemented the loop integrated Mach-Zehnder interferometer for optical fibre based vibrational sensor in pipeline monitoring and leakage localisation. The implemented system was tested with a 40 m steel field pipeline and the obtained results shows good performance with an average percentage error of 0.4% and 2.64% at 2 bar and 3 bar of pressure respectively [18].

Water ingress is a major challenge in subsea pipelines system which commonly occurs in a low-pressure gas pipeline distribution network [65]. This occurs whenever groundwater enters the pipeline through a crack point and block the flow channel. In an effort to detect and determine the location of water ingression, distribution temperature sensing mechanisms based on fibre optics was experimentally studied in [57]. The observed alterations in temperature from the distributed sensors were utilised for detecting the presence of water ingress. Subsequently, the variations in cable temperature was employed to determine the window of interest which indicate the location of leakage. The outcome of this study indicates that distributed optical fibre sensors are capable of detecting water ingress accurately even if the water ingression position is dynamically changing. A recent study reported a design of a distributed Fibre Bragg Grating (FBG) hoop strain measurements in combination with support vector machine for continuous gas pipeline monitoring as well as leakage localisation [66]. In this study, various kernel function parameters are optimised through five-fold cross-validation to acquire the highest leak localisation accuracy.

2.3 Vapour sampling method

The vapour sampling is generally used to determine the degree of hydrocarbon vapour in the pipeline environment. Though, it is applicable in the gas storage tank system, it is also suitable to determine gas discharge in the pipeline surrounding environments. The tube is pressure dependent and filled with air at atmospheric pressure. Oil spillage can be determined by measuring the recorded gas concentration as a function of the pumping time for thus the degree of absorption [38]. In the events of pipelines leakages, vapour or gas diffuses into the tube as a result of concentration gradient which, after a certain period, will generate accumulated signal indicating hydrocarbon flit in the tube environment [37]. As the gas concentration increases the leak peak also increases. The higher the gas concentration in the tube surrounding, the more the leak peak increases.

Different types of vapour sampling based pipeline leaks monitoring systems have been proposed in literature [35, 67]. The use of Sniffer tube based on hydrocarbon permeable cylinder for detecting spillage around the pipeline environment was reported in [68]. According to the study in [2], sensor hose is required to be positioned underneath pipeline to detect gas diffused out of pipes due to leakage. Figure 4 illustrates sensor hose positioning in the pipeline for the maximisation of the system effectiveness.

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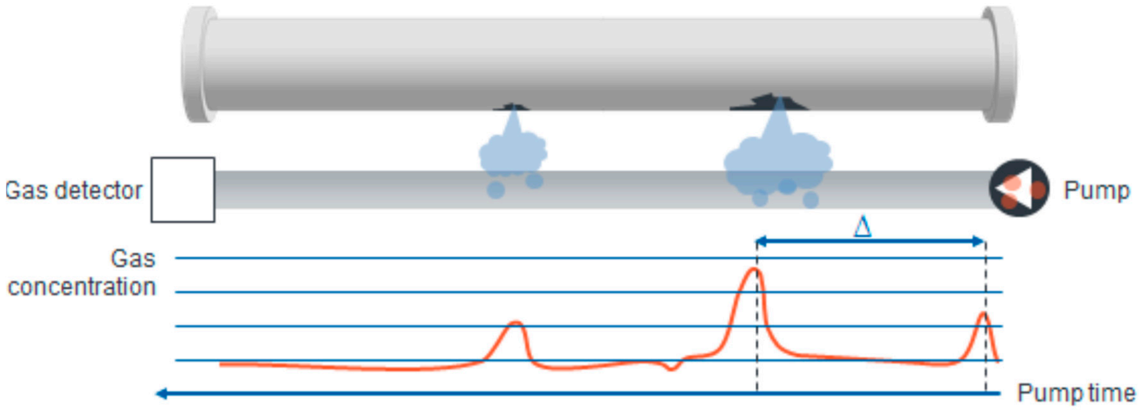

Figure 4. Sensor hose system for pipeline leakage detection [2]

The advantages of vapour sampling systems include the capability of detecting small leaks, independent of the pressure or flow balance and superlatively performance for detecting leaks in multiphase flow application [39]. Besides, the sensor can withstand significant hydrostatic pressure. However, one of the major deficiencies of this technique is the response time. Usually, it takes several hours to days to respond to leaks [67]. Therefore, coupling vapour sensor with another leaks detection method will provide better response time.

2.4 Infrared Thermography

Pipeline leakage detection system based on Infrared Thermography (IRT) mechanism is also applicable for the detection of pipelines leakages. IRT is an infrared image-based technique that can detect temperature changes in the pipeline environment using infrared cameras which shows the infrared range of 900-1400 nanometer [30]. The captured image using IR thermography camera is referred to as a thermogram. The basic function of thermography camera is illustrated in Figure 5. Since changes in temperature measurements are one of the common indications of gas discharge in the pipelines surrounding as gas leaks usually cause abnormal temperature distribution. Therefore, using IRT for pipeline monitoring become widely accepted due to its capability to measure temperature changes in real-time and in a non-contact manner [69,70]. IRT as a contactless and non-invasive condition monitoring tool is also applicable for various condition monitoring applications such as heat transfer [71], tensile failure [72], concrete and masonry bridges [73].

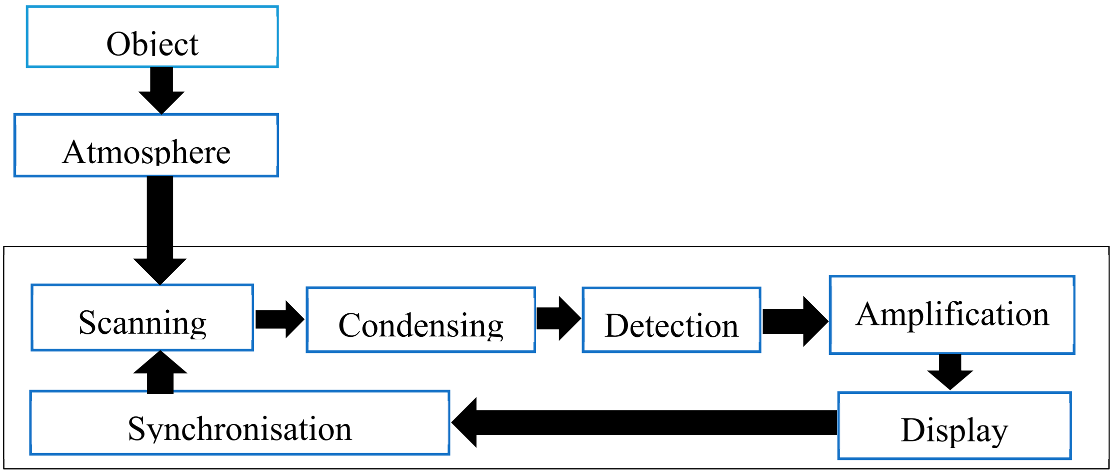

Figure 5. Basic functions of IR thermography camera [30]

Thermal camera is an effective device for sensing objects of various shapes at any perspective with different material properties. The object acquired using thermal camera can be processed to

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recognise anomalies in the pipeline environment through the warm and cooler area displaying in the thermal image with a different colour of that particular environment. Figure 6 illustrates the experimental setup of a typical IRT based system for anomalies detection in a pipeline environment. Thermography can be divided into two categories [30]: active and passive thermography. Active thermography features the area of interest with the background thermal contrast, while the area of interest focused on temperature variation and background in passive thermography. Unlike other temperature measurement mechanisms such as resistance temperature detectors (RTDs), and thermocouples, IRT provides contactless, non-invasive, real-time and distributed measurement of temperature across a continuous region. IRT can remotely measure the temperature distribution of an object and provide a visual image that indicates the degree of the measured data with different colours in that region.

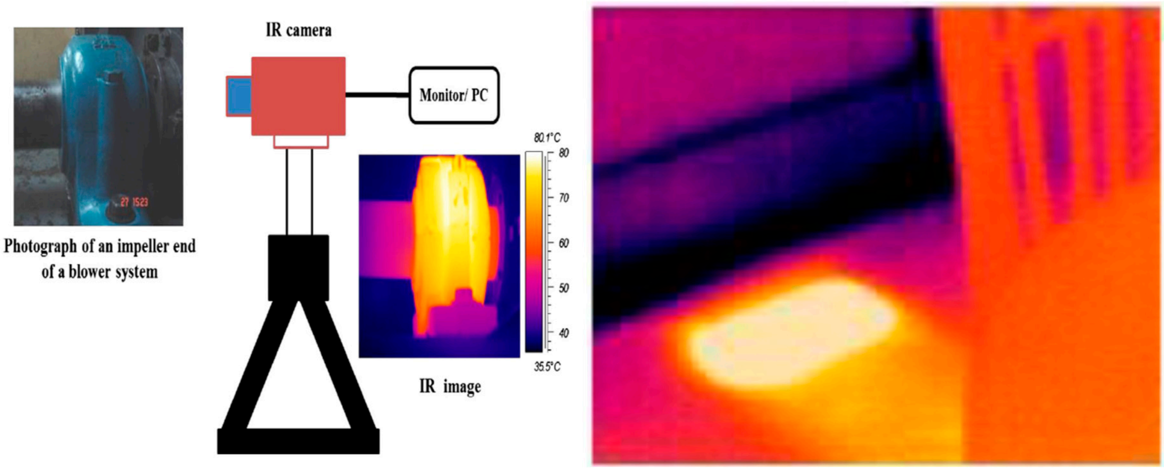

Figure 6. Experimental setup of IRT based system for anomalies monitoring [30, 69]

The improvements of IRT has been witnessed for several decades. Details of IRT origin and theory has been presented in [74]. IRT has been widely used in pipeline monitoring [75-77]. An innovative method of detecting pressure air and gas leakages using passive IR thermography was reported in [61]. A similar work reported in [30] proposed pipelines leaks detection system using IR thermography technique. In their approach, the fundamental principle of IRT was used to differentiate various kinds of anomalies from thermal images using basic image segmentation algorithms to distinguish the defect area in the images. This work concluded that cavitation erosion, clogging piping and steel tank can be inspected using an infrared camera. In the study of [77], a method for gas leak detection based on thermal imaging approach was proposed. Pipeline surrounding was inspected using infrared camera followed by filtering processing where the targeted region of interest was enhanced and segmented to extract features suitable for identification of rupture area in the pipelines. The designed system demonstrated the ability to distinguish between normal and abnormal gas pipeline condition.

The use of IRT system for pipeline condition monitoring enables timely detection of anomalies in the pipelines network thereby, reduce loss associated with gas wastage. Besides, the complexity of IRT system integration is not high. The major components to set up the system are camera stand, infrared camera and the display unit for visualisation of the acquired infrared thermal images. Moreover, the benefit of the IRT system includes efficient transmitting of scan object into a visualisation form [78], fast response time, and easy to use [79]. The operation of such system is so straightforward that no specially trained or experienced personnel is required for the monitoring task. IRT based system is suitable for any kind of pipelines size as well as various hydrocarbon fluid flowing through the pipelines [80]. However, the cost of an infrared camera with high resolution is very expensive. Moreover, quantifying a leak orifice lesser than 1.0 mm using IRT based system is challenging.

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In an attempt to address this shortcomings, leakage quantification mechanism using a combination of infrared thermography and ultrasound methods was proposed [80]. The reported results indicate that thermography is appropriate to quantify the pipeline orifices higher than 1.0 mm, while ultrasound was proved to be usable for all the orifices dimensions. A similar study reported in [81] combined thermal images (thermograms) and Platinum resistance temperature detector (RTD) method to achieve accurate spot temperature measurements. The study employed an experimental flow rig with an internal diameter of 50 mm and the volumetric rate of the leakage was determined using numerical computation. The leak flow through the crack in mass was quantified using equation given as follows [81]:

$$Q = \alpha A \varphi_{max} \sqrt{2P\rho} \tag{3}$$

where A is the cross-sectional area of the crack in m^2, α represents area correction factor, ρ represents gas density function in kg/m^3, P is the absolute pressure in Pa and φ_{max} is the maximum leak rate and is computed to be 0.4692. The flow dispersion function φ_{max} for CO_2 gas from the pressurised enclosure was computed as:

$$\varphi_{max} = \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)} \sqrt{\frac{\gamma}{\gamma+1}} \tag{4}$$

where γ represents the specific heat ratio of CO_2. The CO_2 gas density is adopted from the ideal gas law and is presented as:

$$\rho = \frac{P}{R_{co_2} T} \tag{5}$$

where R_{CO_2} represent specific gas constant of $CO_2\,(= 188.9\,J/kgK)$ and T represents flow temperature in degree Kelvin.

2.5 Ground penetration radar

The emergence of Ground Penetration Radar (GPR) is considered as an environmental tool which is valuable to detect and identify physical structures such as buried pipelines, water concentrations and landfill debris on the ground [82]. The use of GPR technology for underground monitoring is particularly to aid effort of mine detection which can be traced back to 1960 [83]. GPR is a non-invasive high resolution instrument which utilises electromagnetic wave propagation and scattering technique to detect alteration in the magnetic and electrical properties of soil in the pipeline surrounding [84]. Detection of subsurface object using radar approach was first proposed by Cook in 1960 [85]. Readers are referred to [86] for the basic working principle of GPR. In order to detect subsurface object reflections level, Moffatt and Puskar [87] reported an improved radar-based object detection mechanism for the investigation of man-made objects. An electromagnetic wave speed in any medium is dependent upon the speed of light (c) in free space (c = 0.3 m/ns). The speed of electromagnetic wave (V_m) in a given material can be determined as follow [89]:

$$V_m = \frac{c}{\sqrt{(\varepsilon_r\, \mu_r/2)((1+P^2)+1)}} \tag{6}$$

where ε_r is the relative dielectric constant of the material, μ_r is the relative magnetic permeability of the material (μ_r = 1 for non-magnetic material. P is the loss factor, such that $P = \frac{\sigma}{\omega\varepsilon}$, σ is the conductivity, $\omega = 2\pi f$ (where f is the frequency in Hz) and $\varepsilon = \varepsilon_r \varepsilon_o$ (where ε_o is the free space permittivity (8.85×10^{-12} F/m). In low-loss materials, loss factor $P \approx 0$, and speed of electromagnetic wave is given as:

$$V_m = \frac{c}{\sqrt{\varepsilon_r}} = \frac{0.3}{\sqrt{\varepsilon_r}} \quad (m/ns) \tag{7}$$

By first determining the medium velocity (V_m) using equation (6) and (7). The penetration depth (D) of electromagnetic wave can be computed [88] as follows:

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$$D = \frac{\sqrt{(T.V_m)^2 - S^2}}{2} \tag{8}$$

where S represents the fixed distance between the transmitting and receiving antennas of the GPR system, and T is the travelling time history of the GPR signal. The contrast in the relative dielectric constant between adjacent layers is a function of electromagnetic radiation. The proportion of the reflected energy given as reflection coefficient (R) and determine as:

$$R = \frac{V_1 - V_2}{V_1 + V_2} \tag{9}$$

where V_1 and V_2 represents velocities in layer 1 and layer 2 respectively of the medium, and V_1 is smaller than V_2. Additionally, the reflection coefficient can also be determined as:

$$R = \frac{\sqrt{\varepsilon_{r2}} - \sqrt{\varepsilon_{r1}}}{\sqrt{\varepsilon_{r2}} + \sqrt{\varepsilon_{r1}}} \tag{10}$$

where ε_{r1} and ε_{r2} represent relative dielectric constants of layer 1 and layer 2 respectively.

The GPR has proved impressive potential as an effective non-destructive tool for detecting underground objects [89]. However, GPR signals can be easily corrupted by environmental noise [90]. In order to overcome this shortcoming and enhance GPR profile features, several signal processing approaches have been reported in [91, 92]. Zoubir et al. [93] proposed a Kalman filter for detection of landmine using impulse ground penetration radar. An improvement of this study using particle filter was proposed in [94]. In order to remove false alarm in GPR system, a novel cluster suppression landmine detection algorithm based on a correlation method was reported in [95].

Bradford et al. implemented oil spill detection in and under snow assessment using airborne GPR technique [96]. In this study the authors observed that oil located underneath of snow tend to reduce the impedance contrast with core ice and result in anomalous low amplitude radar reflection. The outcome of this research revealed that, using 1 GHz GPR system, a 2 cm dense oil film trapped between sea ice and snow can be detected with a 51% reduction in reflection forte. The authors reported that this approach shows better performance even though in the presence of weak Signal to Noise Ratio (SNR). Besides, GPR based pipeline leak detection system is highly suitable for underground pipelines, reliable and provide detailed information of subsurface objects. However, it is not applicable for long pipeline networks. Similarly, the operation is limited in a clay soil environment as iron pipe corrosion materials can hide cast iron pipelines from the GPR. Hence, for the GPR to be effectively operated an adequate bandwidth is required for the detected signal at the desired resolution and noise levels. Effective coupling of electromagnetic radiation in the ground, and sufficient penetration of the radiation through the ground regardless of targeted depth is paramount essential.

2.6 Fluorescence method

Fluorescence method for hydrocarbons spill detection employed light sources of a specific wavelength for molecule excitation in the targeted substance to a higher energy level [44]. The detection of the spill is based upon the proportionality between amount of hydrocarbon fluid discharged and rate of light emitted at a different wavelength which can then be picked up for detection of occurrence of the hydrocarbons spillage. Detection of the leakages have been successfully implemented using fluorescent dyes (unfiltered ultra-violent) light [97]. Since the fluorescence detectors have high capability of spatial coverage, quick and easy scanning can be performed by mounting the sensors on the ROV manipulator and detection of the leakage can be easily achieved regardless of tidal flow direction. However, the concentration of the fluorescent dyes is very high, the visibility of the monitoring environment must be high to achieve optimal system performance. Another shortcoming of the fluorescent dye most especially in underwater environment is the effects of un-tuned black light that can easily mislead observer from tracking the leak location [98]. Although, this issue has been partially solved by developed submersible (tuned) fluorimeters that

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can transmit data up to attendant vessel to provide a real time display, this challenge still remains as an issue in turbid water.

2.7 Capacitive sensing

The change in the dielectric constant of the medium surrounding the sensor is measured to identify existence of hydrocarbon spillage [44]. The capacitive sensor is a local coverage point sensor which is generally employed in subsea pipeline. The sensors use variation in dielectric constants between seawater and hydrocarbons to detect existence of hydrocarbons which cause an imbalance in measured capacitance once it gets in contact with the sensor. Sensor sensitivity with respect to the leak size is dependent of distance between the leak position and drift of the leaking medium [99]. Capacitive sensor has been introduced to the market for environmental monitoring [100]. However, a numbers of false alarms have been reported from the operator [99]. The causes of these errors may largely due to the sensor that requires direct contact with the leaking medium. Besides, buoyancy effect may carry the leaking medium away from the sensor vicinity which can be overcome by installing a collector for hydrocarbons spill over the monitoring structure.

2.8 Other methods

This section briefly presents less popular methods for pipeline leaks detection techniques based on information provided by Joint Industry Project (JIP) offshore leak detection [44], equipment suppliers [101], industry using some of these technology and some of the available literature [102]. Techniques covered include spectral scanners, Lidar systems and electromagnetic reflection. Spectral scanner is a passive sensor that analyses reflected solar light for a material. It detects pipeline leakage by comparing spectral signature against normal background. Lidar system uses pulsed laser as the illumination source to determine the presence of methane. The absorption of the energy by the laser along the pipeline length is determined using a pulsed laser detector. The emitted energy at different wavelengths is measured through electromagnetic reflection. Electromagnetic reflection and other leak detection mechanisms such as ultraviolet scanner, microwave radiometer and visual surveillance cameras are regarded as passive monitoring devices through detecting either the radiation emitted by leaked natural gas or the background radiation. This makes passive based system less expensive in general.

Table 1 provides a summary, strengths and weaknesses of the exterior leak detection techniques.

Table 1. Summary of exterior pipeline leak detection methods

Methods	Principle of operation	Strengths	Weaknesses
Acoustic Emission	Detect leaks by pickup intrinsic signal escaping from a perforated pipeline.	Easy to install and suitable for early detection, portable and cost-effective.	Sensitive to random and environmental noise, prone to false alarms and not suitable for small leaks.
Fibre Optics Sensing	Detect leaks through the identification of temperature changes in the optical property of the cable induced by the presence of leakage.	Insensitive to electromagnetic noise and the optical fibre can act both as sensor and data transmission medium.	The cost of implementation is high, not durable and not applicable for the pipelines protected by cathodic protection system.
Vapour Sampling	Utilise hydrocarbon vapour diffused into the sensor tube to detect trace	Suitable for detecting small concentration of diffused gas.	Time taken to detect a leak is long, not really effective for subsea pipeline.

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	concentrations of specific hydrocarbon compounds.		
Infrared Thermography	Detect leaks using infrared image techniques for detecting temperature variations in the pipeline environment.	Highly efficient power for transmitting detected object into visual images, easy to use and fast response time.	Quantifying the leaks orifice lesser than 1.0 mm using IRT based system is difficult.
Ground Penetration Radar	Utilise electromagnetic waves transmitted into the monitoring object by means of moving an antenna along a surface.	Timely detection of Leakage for underground pipelines, reliable and leak information is comprehensive.	GPR signals can easily be distorted in a clay soil environment, costly and require highly skilled operator.
Fluorescence	Proportionality between amount of fluid discharged and rate of light emitted at a different wavelength.	High spatial coverage, quick and easy scanning for leak.	Medium to be detected must be naturally fluorescent.
Capacitive Sensing	Measuring changes in the dielectric constant of the medium surrounding the sensor.	It can be employed for detection in non-metallic target.	Require direct contact with the leaking medium.
Spectral Scanners	Comparing spectral signature against normal background.	Capable to give identification of oil type (light/crude) and thickness of the oil stick.	The amount of data generated by a spectral scanner is large which limited its ability to operate in nearly real-time.
Lidar Systems	Employed pulsed laser as the illumination source for methane detection.	Able to detect leaks in the absence of temperature variation between the gas and the surrounding.	High cost of execution and false alarm rate.
Electromagnetic Reflection	Measure emitted energy at different wavelengths.	It can indicate leak location	It can be affected by severe weather.

3. Visual/ Biological Leak Detection Methods

Visual/biological method of detecting leakages is referred to the traditional process of detecting oil spillage in the pipelines surrounding using trained dogs, experienced personnel, smart pigging or helicopters/drones [2]. This method usually utilises trained personnel who walk along the pipelines and search for anomalies condition in the pipelines environment. Trained observers can recognise the leaks through visual observation or smelling the odour coming out from cracking point. Similarly, the noise or vibrations generated as oil escaping from rupture point also applicable in this method to detect and locate pipelines failures. Both dog and smart pigging functioning in a similar way to the experienced personnel. The pig is sometimes equipped with sensors and data recording devices such as fluorescent, optical camera or video sensors with great sensing range if the visibility level is high. A trained dog is more sensitive to the odour of certain gases than human being or pigging in some cases [103, 104]. Conversely, the dog cannot be effective for prolonged operation for more than 30-120 minutes of continuous searching due to fatigue [105]. These on-site inspection methods can only be applied to onshore or shallow offshore pipeline networks. Besides, the detection time is also based on the frequency of inspections which normally takes place in some countries such as the USA for at least once in every three weeks [35]. The recent development of Remotely Operated Vehicles (ROVs) has transformed the operation style of offshore oil transportation operators. It has been shown that ROV is durable for performing subsea pipeline inspection task and functioning in deepwater that cannot be accessible by dog, pigging or human divers [106]. The operation principle of ROV is based on teleoperation that involves a master-slave system. The slave is a ROV which is designed to interact

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with extremely hazardous subsea environment while the master human operator is located in a safe place to remotely control slave robot motions using input devices, like joysticks or haptic devices [107]. All robot commands, sensory feedback and power are sent through an umbilical cable connecting the ROV and the deployment vessel.

The emergence of Autonomous Underwater Vehicles (AUVs) in subsea pipeline inspection and monitoring has reduced the extent of human operator involvement in unmanned vehicles through the implementation of intelligent control machinery and thus drastically lower the chance of human causality. Though, the operation principle of AUV is similar to teleoperation in ROV, only limited skilled operator is required in supervisory control of AUVs [108]. There are numerous types of AUVs and ROVs available for oil and gas infrastructural monitoring. Examples of commercially available ROVs and AUVs primarily deployed in the oil and gas industry are shown in Figure 7. The use of unmanned vehicles for pipelines inspection has the advantage of being a remote operating system; it is suitable for inspection in a remote and hazardous environments. Lower cost of maintenance and higher operation safety are also part of the advantages of unmanned vehicles. Unfortunately, these systems have drawbacks. For example, the cost of purchase or hiring AUV/ROV is extremely high. Additionally, bad weather condition such as cloud, wind or other climatological agents can restrict the performance of these vehicles. There are also legal constraints for the use of the unmanned system in some certain areas due to safety concern because unmanned vehicles are usually lack of onboard capacity to sense and avoid other AUV in advance [109]. However, great effort has been spent on underwater robot sensing and navigation research to realise fully autonomous AUVs for pipeline inspection and monitoring tasks with minimal human intervention. [110,111].

Figure 7. Different kinds of AUVs and ROVs [106].

4. Interior/Computational Methods

Interior or computational methods utilises internal fluid measurement instruments to monitor parameters associated with fluid flow in the pipelines. These systems are used to continuously monitor the status of petroleum products inside the pipeline such as pressure, flow rate, temperature, density, volume and other parameters which quantitatively characterise the released products. By fusing the information conveyed from internal pipeline states, the discrepancy at two different sections of the pipeline can be used to determine the occurrence of leakage based on various methods namely: mass-volume balance, negative pressure wave, pressure point analysis, digital signal processing and dynamic modelling. Details of each of these techniques are discussed in the subsequence sections.

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4.1 Mass-Volume balance

The mass-volume balance approach for leak detection is straightforward [112]. Its operation is based on the principle of mass conservation [113]. The principle states that a fluid that enters the pipe section remains inside the pipe except it exits from the pipeline section [114]. In a normal cylindrical pipeline network, the inflow and outflow fluid can be metered. While in the absence of leakage, the assumption is that the inflow and outflow measured at the two ends of the pipeline section must be balanced. However, the discrepancy between the measured mass-volume flows at the two ends of the pipeline indicate the presence of leakage. The inconsistency of the values in measurement can be determined using the principle of mass conservation given as follows [115]:

$$\dot{M}_\iota(t) - \dot{M}_o(t) = \frac{dM_L}{dt} \tag{11}$$

where $\dot{M}_\iota(t)$ and $\dot{M}_o(t)$ represent mass flow rate at the inlet (i) and outlet (o) respectively. The mass stored across the pipeline length is denoted by M_L, while L represent the length of the pipeline section. In a cylindrical pipeline system, the mass stored M_L for a pipeline of length L changes over time as a result of changes in fluid density (ρ) and cross-sectional area (A) satisfies equation (12).

$$\frac{dM_L}{dt} = \frac{d}{dt}\int_0^L \rho(x)A(x)dx = \int_0^L \frac{d}{dt}\langle\rho(x)A(x)\rangle dx \tag{12}$$

where $\rho(x)A(x)dx$ represent the differential mass stored across the length of the pipeline (M_L) and ρ changes in accordance to the relation; $\rho(x)A(x)dx$ is measured with coordinate position x, $0 \leq x \leq L$. If ρ and A is assumed to be constant, $\frac{dM_L}{dt} = 0$. Then equation (12) becomes:

$$\dot{M}_\iota(t) - \dot{M}_o(t) = 0 \tag{13}$$

Similarly, according to [108], assuming $\rho_i(t) = \rho_i = \rho_l$ and $\rho_o(t) = \rho_o = \rho_l$ are equal and constant for inlet and outlet mass flow, by introducing volume flow $\dot{V}$ with $\dot{M} = \rho\dot{V}$ then

$$\dot{V}_\iota(t) - \dot{V}_o(t) = 0 \tag{14}$$

The imbalance (R) between inlet and outlet volume can be estimated and compared as given in (15) and (16) respectively:

$$\dot{R}(t) \doteq \dot{V}_\iota(t) - \dot{V}_o(t) \tag{15}$$

$$R = \begin{cases} < R_{th} & in\ absence\ of\ leak \\ \geq R_{th} & if\ there\ is\ a\ leak \end{cases} \tag{16}$$

where R_{th} is a threshold to evaluate the imbalance of the volume between inlet and outlet volume.

This method has been commercialised and widely adopted in the oil and gas industry [38]. Some of the existing flow meters in the industry include orifice plate, positive displacement, turbine and mass flow. Some scientific papers based on this method have been reported in literature [116,117]. A robust mean of detecting leakage in the pipeline networks using mass imbalance technique was proposed in [118]. In this study, the activities of calibration and prediction were unified to infer the presence and characterisation of leakages. A similar study [117] reports a mass balance compensation method for oil pipeline leak detection system. The difference in mass at the two ends against mass balance experiments. The obtained result showed that the proposed system can function in various pipelines networks under different operating conditions. The occurrence of leakage with a low rate of changes in pressure or flow rate can be detected using this method. However, one of the biggest limitations of this method is the uncertainty inherited in the instrument. It is sensitive to random disturbances and dynamics of the pipelines [29]. Besides, the inability to locate the position of leakage is another disadvantage of this method. Nevertheless, a hybrid of mass balance and other leaks detection techniques will enhance the effectiveness of the system. In addition, by increasing the number of measuring devices along the pipeline, localisation of points of leakage will be achieved.

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4.2 Negative pressure wave

Leak detection technique using negative pressure wave (NPW) is based on the principle that when leakage occurs, it causes pressure alteration as well as decrease in flow speed which results in instantaneous pressure drop and speed variation along the pipeline. As instantaneous pressure drop occurs, it generates a negative pressure wave at the leak position and propagates the wave with a certain speed towards upstream and downstream ends of the pipe. The wave containing leakage information which can be estimated through visual inspection and signal analysis to determine leakage location by virtue of the time difference that the waves reach the pipeline ends [119]. A NPW based leakage detection technique is cost-effective as it only requires few hardware in the whole pipeline network to detect and locate leaks.

This method has been widely employed in pipeline monitoring due to its fast response time and leak localisation ability [120]. However, it is only effective in massive instantaneous leaks and easily leads to false alarms due to the difficulty in differentiating between normal pressure wave and leakage. Similarly, precise determination of the leak location using time difference in pressure wave detection at the two ends of pipeline is another critical challenge of this method. In order to alleviate this shortcoming, several efforts have been devoted to improving leaks detection and localisation mechanisms using NPW [23,121,122]. Identification of the signal that indicates a leak and normal pipeline operation using structure pattern recognition was proposed by [123]. The use of adaptive filter and Kalman filter for extraction of pressure wave inflexion information was proposed in [124] and [125]. In the study of [126], a negative pressure wave signal analysis system based on Haar wavelet transformation was proposed. The authors demonstrated an effective way of detecting signal variations in the pressure wave signal and established a systematic way of using wavelet de-noising schemes to overcome the noise attenuation destructive problem.

The pressure wave signal created by small leakage can be easily mixed with noise and background interference. This makes accurate signal detection and thus the oil spillage detection process challenging. An effective method of identifying small leakage signal using improved harmonic wavelet was proposed in [127]. The proposed scheme was used to extract the pressure wave signal from the background noise, but the shortcoming of this approach is the decay rate of pressure wave signal in time domain. In order to address this issue, the authors adopted a window function to smooth harmonic wavelet. Different methods of addressing the effect of background interference from leakages signal have been proposed in the literature. An independent component analysis (ICA) technique for separation of characteristic signature of the pressure wave signal mixed with the background noise was reported in [128]. A similar study proposed an improved robust independent component analysis method for effectively separating mixed oil pipeline leak signals [129]. The proposed method was based on statistics estimation and iterative estimation technique using information theory.

An alternative method of detecting small leakage using a specially designed morphological filter has been presented in [21]. The morphological filter was employed to filter background noise and retain the basic geometry features of the pressure signals. A time reversal pipeline leakage localisation approach using adjustable resolution mechanisms was proposed in [130]. The proposed scheme formulated a method of fine-tuning leak localisation resolution in the interval of time. Experimental study on leakage localisation based on dynamic pressure wave was proposed in [131]. In that study, an improved wavelet transform approach was developed, and the theoretical propagation model of dynamic pressure wave was established. Similarly, Li et al. proposed to detect negative pressure wave with intelligent machine learning technique using moving windows least square support vector machine [132]. As the interested parameter in the study centred on wave arrival time from leak point to the end sides of the pipeline (i.e. $t_1(s)$ and $t_2(s)$) using negative pressure wave signal and sensors positioning principles as shown in Figure 8.

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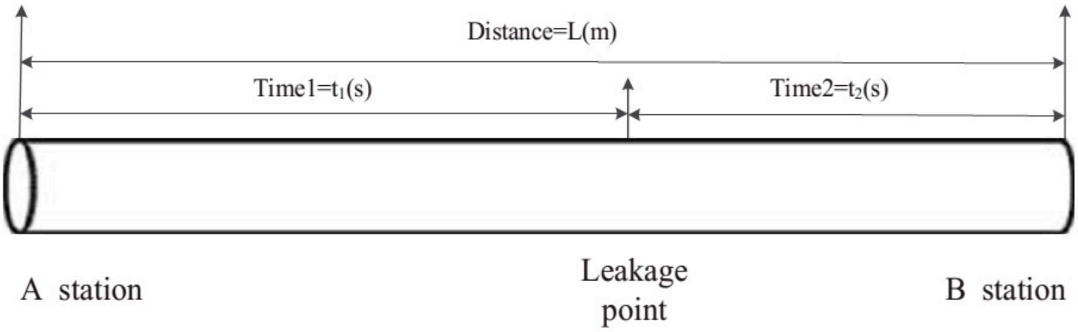

Figure 8. Negative pressure wave monitoring system [132]

The location of a unknown leakage along the pipeline between stations (sensors) A and B shown in Figure 8 is determined using mathematical models (17) and (18) [132]:

$$t_1 - t_0 = \int_0^X \frac{1}{a_X - V} dX \quad (17)$$

$$t_2 - t_0 = \int_X^L \frac{1}{a_X + V} dX \quad (18)$$

where $X(m)$ is the distance from leak position to the sensor A, $L(m)$ represents the distance from sensor A to B, $a_X\ (m/s)$ represent the propagation velocity of the negative pressure wave in the pipeline, t_0 is the time leak occur and $V\ (m/s)$ is the liquid velocity. Assume that the time difference in which the wave travelled from the first station to the end of the sensor is represented as $\Delta t = t_1 - t_2$, the above equations were reformulated and given as:

$$\Delta t = \frac{X}{a - V} - \frac{L - X}{a + V} \quad (19)$$

where a is the velocity of negative pressure wave and X is the distance from leak point to the pressure sensor A. When the fluid temperature, density and elasticity of the negative pressure wave propagation change, the fluid velocity will also change accordingly, owing to this, the negative pressure wave velocity was formulated and given as:

$$a = \sqrt{\frac{k/\rho}{1 + (k/E)(D/e)C}} \quad (20)$$

where $\rho\ (kg/m^3)$ is the liquid density, $k\ (Pa)$ is the liquid bulk modulus of elasticity, $E\ (Pa)$ is the modulus of elasticity, C is the correction factor related to the pipeline constraints, and $e\ (m)$ is the pipeline thickness.

4.3 Pressure point analysis

Pressure point analysis (PPA) method is a leak detection technique based upon the statistical properties of measured pressure at different points along the pipeline. The leakage is determined through the comparison of the measured value against the running statistical trend of the previous measurements [133]. If the statistical pressure of the new incoming data is considerably smaller than the previous value or smaller than a predefined threshold, it indicates a leakage event. This method is considered as one of the fastest ways of detecting the presence of leakage in a pipeline based on the fact that existence of leak always results in immediate pressure drop at the leakage point [8, 35].

The PPA has been successfully applied in underwater environments, cold climate and sufficiently functioning under diverse flow conditions. Small leakage which cannot be easily detected by other methods can be detected using PPA. However, it is difficult to determine leak location using

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this method [134]. The ease of usages and low cost of implementation are the major advantages of this method, but in a batch process where valves are opened and closed simultaneously, transient state may arise and create a period which may easily lead to a false alarm. In order to overcome this drawback, the operation changes must be defined so that detection of leakage can be restrained pending the steady state operation returns to the pipeline. Similarly, integrating this method with other techniques such as mass-volume balance improve its effectiveness.

4.4 Digital signal processing

In digital signal processing approach, the extracted information such as amplitudes, wavelet transform coefficients and others frequency response is employed to determine events of leakages. Generally, pipeline leak detection using digital signal processing involves five steps as illustrated in Figure 9. The steps are as follows: (1) initially internal sensors measure in-pipe pressure or flow; (2) After data acquisition, the acquired data is pre-processed to filter background noise for efficient feature extraction; (3) In the feature extraction step, various statistical, spectral and signal transform techniques are employed to extract relevant features to monitor the state of hydrocarbon fluid transport in the pipeline; (4) The pattern of the extracted feature is compared with the known pre-set signal or previous features for decision making; (5) Leakage detection is achieved through the comparison of the pattern with the threshold.

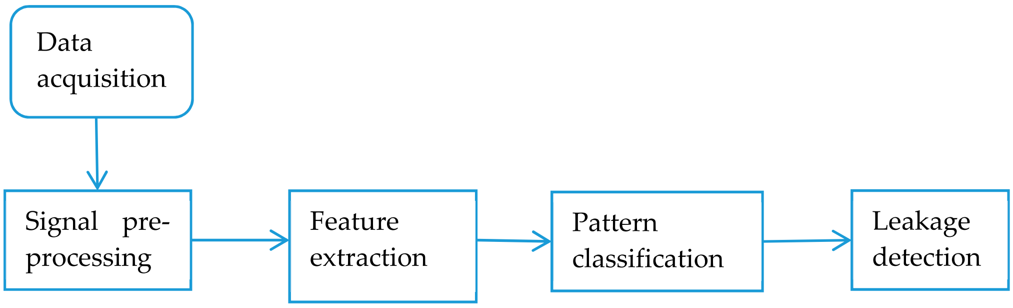

Figure 9. The architecture of pipeline leaks detection based on digital signal processing

Different signal processing techniques have been employed in this research domain. Some of the existing method includes wavelet transform [135,136], Impedance method [137], Cross-correlation [32] and Haar wavelet transform [126]. Shibata *et al.* devised a leakage detection system using Fast Fourier transform (FFT) [138]. The proposed method detects pipe crash position through analysis of the data obtained at a certain distance from the leakage point. The classification and discrimination of the orifice signals are carried out based on the obtained signal patterns. Lay-Ekuakille *et al.* proposed a spectral analysis of the leak detection system in a zig-zag pipeline using the filter diagonalisation method (FDM) [139]. That study aimed to utilise the FDM as an improved way to the Fast Fourier transform (FFT) to minimise the FFT recovery error in a narrow pipeline network. Santos-Ruiz *et al.* proposed an online pipeline leakage diagnosis system based on extended Kalman filter (EKF) and steady state mixed approach [140]. The efficiency of the method was evaluated using online detection, localisation and quantification of non-concurrent pipelines leakages at different positions. The obtained results indicated average error estimate of less than 1% of the flow rate and 3% of the leak localisation.

The authors of [141] proposed a small leak feature extraction and recognition scheme on natural gas pipeline using local mean decomposition envelope spectrum entropy to decompose the leak signal into product function components. Based on the obtained kurtosis features, the principal product function components with higher leaks information was chosen for further processing. Sun *et al.* proposed a hybrid ensemble local mean decomposition (ELMD) and sparse representation for recognition of leakage orifice in a natural gas pipeline [31]. In that study, an ELMD scheme was employed to perform adaptive decomposition of the leak signatures and acquisition of information

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feature of the leak signal based on different orifice scenarios. An application of phased antenna arrays for improving resolution in detecting leakage was proposed in [12]. Xiao et al. [3] proposed a hybridisation of cross-time-frequency spectrum and variational decomposition analysis for natural gas pipeline leakage localisation. The variational mode decomposition was used to decompose leakage signal into mode components, while the adaptive selection model based on mutual information was utilised to process the mode components to obtain feature closely related to the leak signatures. The proposed system was experimentally validated and the results obtained revealed that average relative localisation errors can be reduced dramatically.

A recent study by Liu et al. proposed a new method of leak localisation for the gas pipeline using acoustic signals [142]. Two methods based on the amplitude attenuation model using a combination of wavelet transform and blind source separation was proposed to address the challenges of leak localisation. The authors observed that when the decomposition level of the signal increases, the contribution to localisation error by leak time deviation and amplitude decreases. It also revealed that the combined methods are effective in solving the signal attenuation problems for pipeline leakages. The advantage of digital signal processing techniques is their simplicity in implementation as pipeline leakage is detected through sophisticated algorithms for leakage data signature (in time, frequency, or both domains) extraction running on common embedded computing hardware or digital signal processors (DSPs). However, the challenge associated with this approach is the detection accuracy as the acquired data is usually attenuated and contaminated by noise. Besides, in order to effectively detect leakage, a large sensor network to cover the whole pipeline network is required.

4.5 Dynamic modelling

The dynamic modelling based pipeline leak systems are gaining considerable attention as it appears to be a promising technique for the detection of anomalies in both surface and subsea pipeline networks. In this approach, mathematical models are formulated to represent the operation of a pipeline system based on principles in physics. The detection of leakage using method is performed in two different points of views: (1) statistical point of view and (2) transient point of view. From the statistical point of view, the system utilises decision theory based on the assumption that parameters associated with fluid flowing remain constant except in the presence of anomalies along the pipeline [143]. Hypothesis testing involved for detecting leakage is based on the uncompensated mass balance through the utilisation of either single or multiple measurements carried out at different time instants.

According to the technical report of the Alaska Department of Environmental Conservation [144], the most sensitive, but also complex pipeline leak detection technique in use is the transient leakage detection technique. Detection of leakage in pipelines mainly requires the formulation of the mathematical model using fluid flow equations. The equations of state for modelling fluid flow includes the equations of conservation of mass, conservation of momentum, conservations of energy and states of the fluid. This method requires measurements of flow, temperature, pressure and other parameters associated with fluid transport at the inlet and outlet of the pipeline or at several points along the pipeline. The transient event or noise levels are continuously being monitored using discrepancy between the measured values and simulated values to detect the occurrence of leakages. Transient based leak detection approach has been proposed in various studies by the research community [26, 27,145-147].

Yang et al. proposed a characterisation of hydraulic transient modelling using the equation of states of the fluid [27]. Partial differential equations that modelled the dynamics of fluid flow in the pipeline are simplified into ordinary differential equations using a fixed grid to represent the numerical solution at some discrete points. A similar method of detecting pipeline leakage using flow model analysis was proposed in [148]. In that study, a mathematical model was formulated to predict the flow distribution of soil gas through porous probes at various positions on the horizontal sampling line. A computational fluid dynamics (CFD) based method was proposed to describe the underwater gas release and dispersion from subsea gas pipelines leakage [149]. The simulation was

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based on Eulerian-Lagrangian modelling concept to predict the released gas plume by considering bubble as discrete particles. The simulation result was validated against experimental data, and the obtained results revealed that CFD model could provide valuable output in subsea pipeline leakage such as gas release rate, horizontal dispersion distance and gas rise time. However, it can only be applicable in Shallow Ocean as the sea wave can easily alter the gas dispersion movements. Besides, in the event of large leakages, the gas release rate and dispersion pattern vary. Therefore, the deviation of parameters associated with gas product transport in subsea pipelines appears to provide useful information that can reveal the state of hydrocarbon fluid in subsea gas pipeline networks. Similarly, according to the report of Pipelines and Installations-RU-NO Barents Project [150], a suitable subsea pipeline leak detection system should be able to provide information about the internal flow condition without being affected by subsurface ice situation as well as ocean activity such as sea wave, ocean current and so on.

Table 2 provides a summary, strengths and weaknesses of the interior leak detection approaches.

Table 2. Summary of the interior pipeline leak detection methods

Methods	Principle of operation	Strength	Weakness
Mass-volume Balance	Utilises discrepancy between upstream and downstream fluid mass-volume for determining the leakage.	Low cost, portable, straightforward and insensitive to noise interference.	Leak size dependent, not applicable for leak localisation.
Negative Pressure Wave	Utilises negative pressure wave propagated due to pressure drops as a result of leakage.	Fast response time and suitable for leak localisation.	Only effective for large instantaneous leaks.
Pressure Point Analysis	Monitor pressure variation at different point within the pipeline system.	Appropriate for underwater environments, cold climate and adequately functioning under diverse flow conditions.	Leak detection is challenging in batch processes where valves are opened and closed simultaneously.
Digital Signal Processing	Utilises extracted signal features such as amplitude, frequency wavelet transform coefficients etc. from acquired data.	Good performance, suitable to detect and to locate leak position.	Easily prone to false alarms, and be masked by noise.
Dynamic Modelling	Detects leaks using the discrepancy between measured data and simulated values based on conservation equations and the equation of state for the fluid.	Applicable for leak detection and localisation, fast and large amount of data can be handled.	Highl computational complexity, expensive and labour intensive.

5. Performance Comparison of Leaks Detection Technologies

This section presents qualitative performance analysis of various pipeline leaks detestation approaches based on literature taken above and American Petroleum Institute (API) performance requirements guides [4,84]. Various performance criterion are considered for comparison such as system operational cost, sensitivity, accuracy, leak localisation, system mode of operation, ease of usage, leak size estimation, ease of retrofitting and false alarm rate. The analysis is performed using two and three-level performance comparison. In the three-level analysis comparison, the operational cost, sensitivity and false alarm rate are compared in the range of low, medium and high. Figure 10 shows the bar chart representing the three-level analysis of the reviewed methods based on unique strengths and weaknesses. As shown in Figure 10, most of the techniques require high operational cost except NPW and Vapour Sampling. However, the high rate of false alarms and slow leakage

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detection rate are the major weaknesses of these two methods. In general, all methods perform well in terms of sensitivity except IRT, GPR and NPW. The rate of false alarm in most of the techniques such as acoustic emission, NPW, Vapour Sampling, Dynamic Modelling and DSP are high. Though many researchers have been working on alleviating these drawbacks, reducing false alarms in acoustic emission and DSP appears to be a challenging task as acoustic emission is highly sensitive to random ambient noise and the DSP approach mainly depends on instrument calibration accuracy. Besides, different circumstances such as pipeline corrosion, bending and blockage can easily lead to false alarms in DSP. Among all the reviewed methods, the Dynamic Modelling method shows high sensitivity in detecting the presence of pipeline leakage. However, the high complexity of the mathematical models involved and strict experienced personnel requirements are the key challenges of this method. With the help of recent advances in high performance computing and cloud computing technologies, the Dynamic Modelling will become more and more popular in the oil and gas industry.

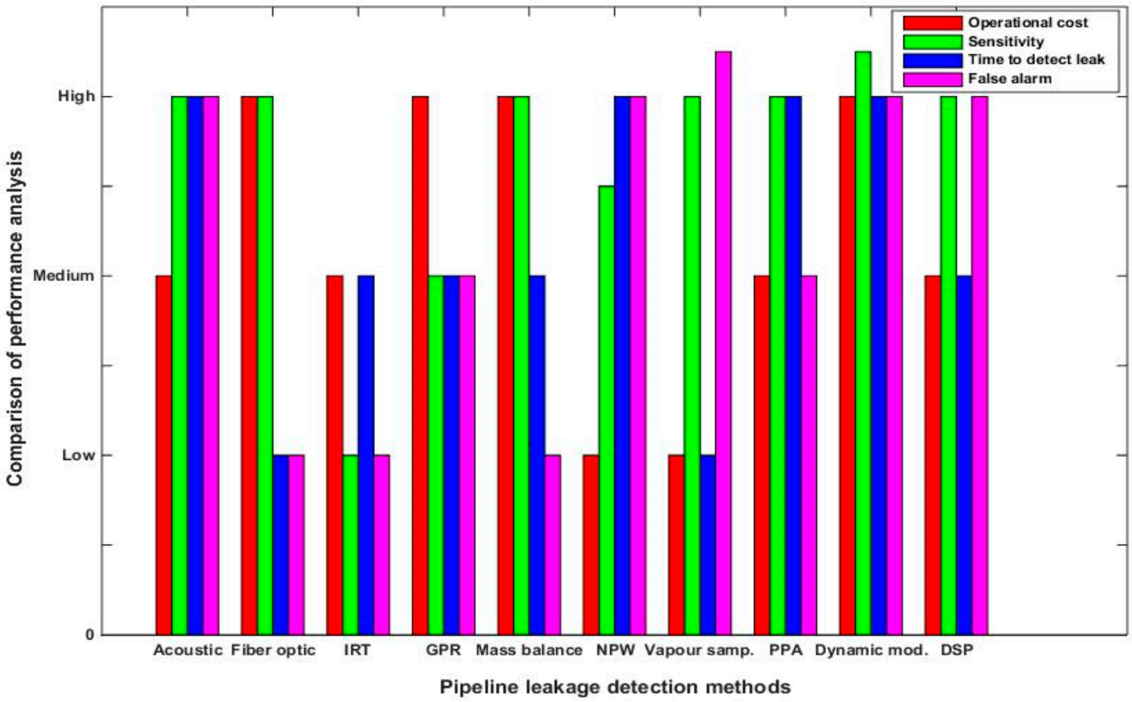

Figure 10. Three level performance analysis comparison

The performances of various pipeline leakage detection methods are compared using two-level performance analysis. System accuracy, system mode of operation, leak localisation, leak size estimation, ease of usage and ease of retrofitting are the criteria employed to evaluate performance of the reviewed methods using yes or no, high or low, and steady or transient state or not applicable (indicated by "—") scale. Table 3 shows a summary of the comparison. The study shows that none of the methods satisfies all attributes as they all varies in merits and critical shortcomings. For example, the system based on Infrared Thermography proved to be better in terms of system accuracy, leak localisation, easy usage and easy to retrofit. However, estimation of the leakage rate is difficult with the use of this method. Similarly, almost all methods satisfy easy to retrofit, or upgrading criterion except the Fibre Optic Sensing method, where a point of breakage can lead to total system failure thereby requires total sensor replacement. System accuracy is also an important criterion to evaluate the performance of a pipeline leak detection system. Although some of the methods perform better in regards to this criterion, system detection capability also depends on other factors such as instrument calibration, the quality and quantities of the instruments used.

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Table 3. Two-level performance analysis comparison

Methods	Performance comparison metric					
	System accuracy	Leak localisation	Leak size estimation	Ease of usage	Ease of retrofitting	Operational mode
Acoustic Emission	High, but sensitive to random noise	Yes	No	Yes	Yes	_
Fibre Optic Sensing	High	Yes	Yes	Yes	No	_
Vapour Sampling	Depend on sensing tube closeness to spill gas	No	No	Yes	Yes	_
Infrared Thermography	High	Yes	No	Yes	Yes	_
Ground Penetration Radar	Low	Yes	No	Yes	Yes	_
Fluorescence	Low	No	No	No	Yes	-
Capacitive Sensing	Low	No	N	Yes	Yes	-
Mass-volume Balance	Low, Depend on instrument calibration and leak size	No	Yes	Yes	Yes	Steady state
Negative Pressure Wave	Low	Yes	No	Yes	Yes	Steady state
Pressure Point Analysis	Low	Yes	Yes	Yes	Yes	Steady state
Digital Signal Processing	Depend on leakage size and sensor used	Yes	No	Yes	Yes	Stead state
Dynamic Modelling	High, Depend on pipeline stability and mathematical model	Yes	Yes	No	Yes	Both steady and transient state

6. Guideline for Pipeline Leakage Detection Method Selection

As mentioned in the previous sections, there are various methods and mechanisms for pipeline leaks detection and localisation. However, the applicability of each method varies considerably depending on pipeline operating conditions, pipeline characteristics and medium to be detected. For instance, detection of leakages in surface, underground or subsea environments can be attained through the use of the approaches such as fiber optic cable, fluorescence and interior methods. While GPR can only be applied for the underground pipeline networks. Some methods are applicable for all types of hydrocarbon fluid including oil, gas and water. However, only specific type of hydrocarbon fluid can be detected in some methods. In order to provide guideline in selecting method appropriate for a particular scenario, Table 4 illustrates major available leak detection techniques and guideline for the selection. The information is based on review works on the literature and information provided by report of Joint Industry and Project (JIP) offshore leak detection [44]. “Local coverage” refers to the small area within the vicinity of the sensor. While ”Area coverage” means that sensor can cover a large area but not entire field coverage.

Table 4. Summary of the guide for method selection

Methods	Operating environments	Sensor coverages	Hydrocarbon fluids
Acoustic sensing	All	Local coverage	All
Fibre optic sensing	All	Local coverage	All

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Vapour sampling	Subsea	Local coverage	All
Infrared thermography	All	Local coverage	Oil and gas
Ground penetration radar	Underground	Local coverage	Water and gas
Fluorescence	All	Local coverage	Oil
Capacitive sensing	Subsea	Local coverage	All
Spectral scanner	Surface	Local coverage	Oil
Lidar system	Subsea	Local coverage	All
Electromagnetic reflection	Surface	Local coverage	Oil
Biological methods	Subsea	Local coverage	All
Interior methods	All	Area coverage	All

7. Research Gaps and Open Issues

Based on the various reviewed pipeline leak detection methods, research gaps and future research direction are identified in this section. The performance of pipeline leakage detection generally varies between the approaches, operational conditions and pipeline networks. However, guidelines set by American Petroleum Institute (API 1555) such as sensitivity, accuracy, reliability and adaptability [85] must be met before we can consider leak detection systems suitable for production solutions. Moreover, leak localisation and estimation of the leakage rate are also important as they will facilitate spillage containment and maintenance at the early stage to avoid serious damages to the environment. The simplest way to achieve this goal is through deployment of vast number of leak detection sensors in a sensor network between the upstream and downstream of the pipeline. By doing so, it will easy to isolate the leak position and thus improves the ability to track which of the sensor acquires anomalous information in sacrifice of high implementation cost.

Remote monitoring of oil and gas pipeline networks using wireless communications technology provide benefits of low cost, fast response and ability to track the location where leakages occur. However, to attain trademark performance in monitoring pipeline remotely some of the design issues that require research attentions include sensing modality, sensing coverage and leaks localisation. As mentioned in the previous sections, several sensors are designed for monitoring pipeline leakages using different sensing modality. Usually, sensors are deployed for monitoring steady-state condition where physical pipeline context is expected to remain stable over the years. Variation in physical parameters of the pipeline operation such as vibration, temperature, pressure *etc.* are expected to be detected and communicated to reveal the incidents of anomalies. Leaks can only be accurately detected if the incident is within the vicinity of the monitoring sensors and thus accuracy of leak detection systems becomes questionable if the leaks are not within the receptive fields of the sensors. Sensors deployed for remote monitoring of pipelines are employed to perform both functions of sensing and communications. However, the challenge of how to cover a monitoring region efficiently and relay the obtained measurements to their neighbouring nodes is also challenging in wireless sensor network (WSN) which its impact becomes severe on the network performance. There are many issues in designing optimal WSN particularly for pipeline monitoring. These issues include: (i) self-organisation, (ii) fault-tolerance, (iii) optimal sensor node placement, (iv) sensor coverage, (v) energy saving routing, (vi) Energy harvesting and so on.

During the lifetime of the sensor network some of the deployed sensor nodes are expected to experience hardware failure and the network is not be able to cope with the failure. This will limit the effectiveness of the whole network. The operation and performance of WSN is largely dependent on optimal node placement as communication is required among the sensor node to transmit acquired data. Besides, sensor placement also influences the resources management such as energy consumption in WSN [151], while the energy consumption influence network lifetime [152]. In that case, sensor placement in pipeline monitoring attracts attention of further research. The development of self-organisation strategy has become an important research issue in WSN. Sensor nodes are smart enough to autonomously re-organise themselves to share sensing and data transmission tasks when some nodes fail. Although, the issue of coverage problem has been addressed in the literature [153-155]. Some of these studies proposed methods for achieving high sensor coverage [156-158], while

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development of analytical model and optimisation approaches for WSN coverage was proposed in some studies [159-161]. However, development of simple but realistic models for analysis and optimization still remains as a challenging research questions. Since a high percentage of pipeline systems are made up of underground and underwater pipelines networks and the power required for real-time sensing and data communications in such environment is demanding. Batter replacement of sensor nodes in these settings are expensive or infeasible for large sensor networks. In order to achieve long-lived network under these energy constrained environment, different energy consumption minimisation methods such as low energy adaptive clustering hierarchy [162], in-network processing [163], and sleep mode configuration [164] have been applied. Energy can also be harvested from pipeline surrounding resources such as fluid flow, pipe vibration, pressure and water kinetics using piezoelectric transducers Although great improvement has been observed in research development of wireless sensor network technology, efficient and reliable energy storage and generic plug and play energy harvesters from multiple sources remain open research challenges.

Leak localisation is very essential in pipeline monitoring as it will speed up the repair process. Different method of defect localisation in pipeline have been proposed [165-167]. The performance of these techniques, however, varies in terms of accuracy, degree of complexity and operation environments. Mobile sensor nodes with built-in Global Positioning System (GPS) have been successfully deployed to determine and report the geographical location of the pipeline leakages. The use of mobile sensor nodes in pipeline environment is essential as it can enhance coverage and recover the network from failure which partitions the whole network into multiple disconnected subnetworks. However, the cost of implementation of these sensor nodes with the GPS capability is extremely high. Besides, it may be difficult for GPS signal to penetrate the metal or concrete walls which protect the pipelines. If all sensor nodes are static, their locations are marked using GPS and stored permanently in a map in the deployment phase. Leaks can then be localised based on the known locations of reporting sensor nodes. On the contrary, Scalability of the pipeline leakage detection sensor network is another research challenge when the coverage of the pipeline network is huge. In this regard, localization techniques with a satisfactory performance will be a welcome addition to the leak detection mechanisms.

It is important to detect the valid leak and reduce the number of false positives alarms so that the pipeline leak detectors can attain acceptable accuracy. All leakage detectors are based on inference based on evidence acquired from sensors. [168]. The input evidence signature is usually noisy or error prone. The noise is in general random in nature and its underlying probability distribution is unknown. The source of the noise comes from inaccurate system measurement, instruments calibration, system modelling, data processing, feature extraction as well as communications. For example, in acoustic emission leak detection method data acquired using acoustic sensor is usually inherited with noise disruption as well as signal attenuation phenomenon. In order to reduce the effect of this noise, certain design requirements for signal filtering must be met. Effectiveness of some of the signal filtering algorithms such as Savitzky-Golay, Ensemble, Applet [169] can lessen the degree of signals distortion to acceptable level. An autonomous system which can detect, locate and quantify the rate of leakage with the capability to manage a large amount of acquired data is essential for planned and unplanned leak incidents. Advanced data visualisation tools will definitely help in showing the state of flow activities for decision making in leak detection, localisation and characterisation, and pipeline maintenance. In addition, data driven self-testing incidents analysis and other offline performance validation will also enhance the system flexibility.

The subsea industry activity has been continuously growing which has made the sector to be a truly global industry with the industry operation amounting billions of NOK in turnover [170]. However, pipeline leakages remain one of the major challenges in this sector [171] although various efforts have been made to guarantee early detection of leakages in the subsea pipeline. In [150], computational fluid dynamics modelling was devised to describe underwater gas release and dispersion trajectory. The challenges of this approach are that sea wave can easily alter the gas dispersion movements and in the event of large leakages, the gas release rate and dispersion trajectory could be arbitrarily. The mechanistic modelling of detection pipeline leak at a fixed inlet

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rate presented in [24] provides insight for monitoring hydrocarbon parameters. However, the algorithm is deprived because the external condition that can easily lead to subsea pipeline instability in a subsea environment was not taken into consideration. The updated information about the internal flow condition as well as pipeline integrity that are independent of the weather and sea conditions is needed for innovation. Moreover, experiment leak scenarios as a function of leak opening size in the laboratory and data processing in a way suitable to establish signals indicating hydrocarbon spillage will provide benefits in designing functional basis for leak detection.

In general, the aim of future pipeline monitoring is to design a real-time intelligent pipeline leak detection and localisation system for subsea pipeline networks. The effect of environmental factors, in particular, hydrodynamic forces due to oblique wave and current loading on subsea pipeline still require further research study. Extensive simulation and laboratory experiments are conducted to study the effects of leakage parameters, like size and shape, to the flow mechanism and validate models. Numerical simulation of fluid flow in pipeline using computational fluid dynamics (CFD) has proved to provide better understanding of pipeline internal flow and the conditions of pipeline leaks in various scales thereby reduce the cost in experimental study. However, high computational complexity remain one of the major drawbacks of CFD. Further research effort is still required to optimise and/or parallelise CFD solution algorithms in terms of computation and memory resource constraints.

8. Summary and Conclusions

This survey paper provides a rudimentary reference to guide readers in determining appropriate leak detection technology for a particular setting. In this paper, a comprehensive survey of various available pipeline leakage detection and localisation methods was carried out. A summary of what has been demonstrated to date is presented, along with research gaps and open issues that require attention in this research domain. A wide variety of pipeline leak detection approaches was reviewed and grouped into three different categories. The first category is the exterior method which involves the use of specially designed sensing systems to monitor the external part of the pipelines. The methods considered in this category includes acoustic emission sensor, fibre optic sensor, vapour sampling, infrared thermography and ground penetration radar. In the second category, the visual methods of detecting leakages in the pipeline which include trained dogs, experienced personnel, smart pigging or helicopter /drones/ROVs/AUVs were discussed. The interior method of detecting leakage using parameters associated with hydrocarbon fluid such as mass-volume balance, negative pressure wave, pressure point analysis, digital signal processing and dynamic modelling were presented in the third category. We then performed a comparative analysis using various performance requirements based on the American Petroleum Institute (API) guide [4, 85]. Based on the analysis, it can be concluded that each technique shares some merits and drawbacks. For example, most of the interior methods are sensitive to small leakage especially if the point of leakage is close to the sensing devices, but they are more prone to false alarms as they can easily be affected by environmental noise. Mass-volume balance and numerical computation model exhibits good performance for high flow rate, multiphase flow and subsea pipeline networks. Finally, we discussed the research gaps and open issues in pipeline leakage detection, characterisation and localisations. We observe that despite having invested a considerable amount of research effort in pipelines leak detection and localisation systems, various gaps are required to be filled before a reliable real-time leakage detection in the pipeline can be fully achieved.

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