Abstract

Condition monitoring in the water distribution network and sewerage pipelines is one of the primary concerns for water utility companies. The impact of complex interconnected parameters on pipe deterioration mechanisms, lengthy water transmission networks and resource utilisation makes maintenance procedure more challenging. Various condition monitoring techniques for underground water pipes are in practice by water utility companies. High resolution cameras, electromagnetic waves, laser radiation, ultrasonic waves, acoustic sensors, eddy current and thermal profiling methods are used for condition assessment. However, these technologies also have limitations depending on pipe material, size of pipe, types of defects, environmental factors, size of pipe network, water pressure and flow rates. The current review includes a wide range of condition monitoring techniques for water pipelines and also highlights key features and limitations of emerging techniques.

Keywords: leakage, water pipelines, condition monitoring, acoustics

1. Introduction

Water is an essential element to keep human life alive on the planet. A significant amount of clean water is being wasted in distribution networks before reaching homes and industrial properties. Global estimate of water loss in water distribution network is equal to 346,000 million liters per day [1]. Water companies manage a huge water distribution network consisting of 346,455 km of pipes including 24 million connections to properties in England and Wales alone [2]. Leakages in sewer pipes cause serious threat to the ecosystem and public health. The length of sewerage pipes in the UK is around 568,708 km [3]. Wastewater can be transmitted down the food chain, contaminate the drinking water, sea, river, surface water and air [4].

Most of the water pipes are buried under the ground and the deterioration mechanism is affected by various factors including the material, climate, cathodic protection, age, pressure zone and other intrinsic factors making it difficult to understand the failure mechanism. An extensive review on pipe failure mechanism affected by intrinsic, operational, and environmental factors has been discussed [5]. Factors are often interconnected and accelerate the pipe deterioration mechanism. However, some factors have a great influence, depending on pipe material and mode of failure. The implications in the detection of water leaks result in a huge amount of repair cost and water waste.

A wide range of condition monitoring techniques for water pipe networks are available. Most of the non-acoustic techniques directly assess the structure of pipe for any possible defects by applying electromagnetic waves, ultrasonic waves, eddy current, thermal profiling and visual monitoring methods. These techniques can provide more insights for the presence of the types of defects and leak size in the pipe. Defects in the water pipe cause water leakage and generate noise signals at certain frequencies. Acoustic techniques allow condition assessment of the pipe by monitoring the leak noise using accelerometers, hydrophones or microphones. The module that contains various sensors, memory unit and communication system can be referred as a sensor node. Low power sensor nodes and Internet-of-things (IoT) can provide an adequate way to cover huge water distribution networks and sewerage pipes.

Condition monitoring through leak noise detection can be characterised in three stages as identification, localisation and pinpointing (ILP) approach. The identification stage refers to determining the existence of leak in the water pipe. The localisation stage refers to detecting the segment of pipe where the leak exists. The pinpointing stage refers to finding the precise location of a leak in a water pipe. Several emerging techniques have been introduced in last two decades that can be divided into two categories, such as static leak detection systems and dynamic leak detection systems. Static systems are based on deployment of sensors on hydrants and valves in the water pipe network. Signals are continuously monitored and transmitted for identification, localisation and pinpointing of pipe leaks. Meanwhile, dynamic leak detection systems perform inspec-
tion of suspected leak in the pipe through floating or moving devices such as crawler or mini-robotic systems [6].

Common challenges in Water Pipeline Monitoring (WPM): The observation of distress indicators and inferential indicators provide partial evidence or potential existence of defects in the pipe. The impact of environmental conditions and variation in the properties of pipe material with ageing makes it challenging to quantify the pipe deterioration mechanism. Leakage of the water pipes can also cause water pollution that requires skilled professionals for maintenance. Installation and replacement of electronic devices may require turning off the water supply. The water companies covering huge water pipe networks often deals with false alarms and inaccurate pinpointing of leak that results in significant increase in maintenance expenditures. High processing capabilities are required in applying complex algorithms such as digital signal processing or image segmentation for efficient identification of leaks.

This review article has the following key contributions:

- It covers fundamentals of a wide range of WPM techniques, leading to recent research findings and system development specific to the technologies.
- State-of-the art emerging solutions commercially available and in practice by water industry are discussed. A comprehensive table for emerging WPM technologies is provided that highlights the key features and limitations.
- Major challenges in the application and development of more efficient WPM systems are also discussed for future research and development.

This article is divided into four sections. The introduction section emphasis the fundamentals of water leaks and common challenges encountered by water industry. A wide range of WPM techniques are listed in the second section of the article. Most of the state-of-the-art emerging WPM systems commercially available are described in the third section. Major challenges in the condition monitoring systems for water pipelines are highlighted in the fourth section.

2. WPM techniques

The monitoring of pipe infrastructure is often based on limited available distress indicators. Multiple interconnected parameters that provide physical manifestations of pipe deterioration mechanisms are acquired to make a direct or indirect assessment. The direct method involves non-destructive, visual, manual, or automated inspection such as visual inspections, electromagnetic techniques, ultrasonic techniques, radiographic techniques, and thermographic techniques. While the method of inspection through flow rate, pressure zone and other inferential indicators fall in the category of indirect techniques. Those are corrosion monitoring using linear polarisation resistance method, soil characterisation and close interval survey. Inspection techniques are applied depending on the type of material and geographical location of pipe infrastructure [7]. Technologies that are applied for the inspection of water pipes are listed in the Figure 1.

2.1. Acoustic techniques

A leak in water pipes causes vibrations that induce hissing noise (an acoustic signal) at certain frequencies, depending on the pipe material. Leak-induced noise signals can be recorded using hydrophones, accelerometers, or digital microphones. Various methods are applied to listen to the leak-induced noise, so the leak can be detected, located and the pipeline repaired.

2.1.1. Listening stick

One of the most common and simple tools to locate the underground leak is the listening stick. Noise signals generated by leak is transmitted through stainless steel stick to hollow wooden earpiece with resonant cavity as shown in the Figure 2. Listening sticks are low cost, highly portable and easy to use. Distortion in sound resulting from background noise reduces the quality of leak noise when listening, therefore electronic amplifiers and filtering techniques are applied to enhance the quality of leak noise. Listening sticks are commercially available in around 4’ or 5’ length [8].
2.1.2. **Correlator**

A correlator is used to pinpoint the location of the leak by listening to the leak noise signals. The synchronised acoustic sensors such as accelerometers or hydrophones are deployed across the suspected pipe as shown in the Figure 3. The synchronisation is commonly achieved with radio frequency (RF) signals [9]. Cross-correlation is applied on recorded noise signals to find the lag between the signals. The value of lag, total distance between the acoustic sensors and sound velocity of pipe material is used to determine the leak location. The performance of the correlator is highly influenced by the pipe material and background noises [10, 11].

2.1.3. **Remote loggers**

Water utility companies deploy acoustic loggers at remote locations across the water distribution network. The information is transmitted to base station using various communication channels such as SMS, GPRS or 3G/4G networks. Alarms are triggered for leak engineers/maintenance professionals in case of presence of leak noise. The major challenges for water utilities when applying this technology is the coverage of huge pipe infrastructure and effective management of large volumes of false alarms. The distributed frequency spectrum depending on pipe material, and background noises that distort the vibration signals are major factors for causing the challenges [12].

2.1.4. **Transient wave**

In transient wave technique, a series of transient waves are generated by changing the flow conditions through pumps, valves, or any transient wave generator that propagates through the pipe [13]. These transient waves are acquired to analyse the pipe for potential defects or anomalies. There are various methods of generating transient waves, each of which come with their own advantages and disadvantages that impact performance of the system and deployment mechanism. A sudden and complete closure of an inline valve is a simple and common method [14]. However, the smooth wave fronts with limited bandwidth could limit the accuracy of the system. Moreover, sudden closure of the valve can result in high pressure that could potentially damage the pipe network. ‘Oscillations of an inline valve’ is a time-consuming and complex method to generate stable oscillatory flow for each frequency [15]. While in PPWM, generated transient waves can be controlled to keep within safe limits [16]. PRBS method has wide bandwidth for high spatial resolution and small amplitude within safe limits for the pipe [17]. ‘Underwater electric spark-based generator’ produces very sharp transient waves with short wavelength that enhance the spatial resolution. However, the amplitude and bandwidth of these waves cannot be fully controlled [18]. Piezoelectric wave generation method is based on producing transient waves with small amplitude by using a piezoelectric actuator. Compact design and easy to transport are the key advantages of the piezoelectric wave generator [19].

2.1.5. **Sonar profiling**

Sonar profiling is an acoustic technique to detect objects underwater using sound waves. In water pipeline monitoring system, sonar profiling provides information regarding submerged deformation, debris and defects. It can be divided into active sonar and passive sonar systems [20]. In active sonar, the acoustic signal is generated by the transducer and the echo of the reflected pulse from the object is monitored. The time taken by the acoustic pulse to return is computed to estimate the distance between the transducer and the object. Passive sonar does not emit any signal however, it detects the signals emanating from the objects in sub-sea environment. Active sonar is utilised for maintenance and monitoring of underwater pipelines. Sonar profiling can be operated at different frequencies depending on the application requirement. High frequency in sonar profiling provides high resolution, however the high frequency attenuates resulting in reduced penetration capability. Low frequency
Side Scan Sonar (SSS) and multi-beam bathymetry are two active sonar profiling techniques that can be used to acquire information regarding the shape and locations of pipelines. SSS is also called side imaging sonar or bottom classification sonar when used to obtain the image of large sea floor area. Certain types of defects in the pipes can be detected using SSS technique including free spanning, cracks in concrete coating and pipe walking. SSS performs better on even surfaces as compared to uneven surfaces. The performance of SSS technique in terms of image resolution can be improved with the efficient probabilistic and geometric approaches [20, 22]. Forward looking sonar is designed and configured to visualise the frontal view, and it is also capable of locating and extracting the path of pipeline through small particles and turbulence [23].

Sonar profiling techniques provide an appropriate method for the monitoring of pipelines in subsea environmental conditions. However, the reliability and robustness can be improved by incorporating more enhanced imaging algorithms and integrating the sensors such as doppler velocity log, an inertial measurement unit and field gradient sensor [23].

2.1.6. Impact echo

Impact echo monitoring technique can be used to investigate various defects including delamination, cracks, honeycombing and debonding by monitoring the impact-generated stress waves. Low frequency waves are generated that propagate through the pipeline and bounce back from the defects in internal and external surfaces, as shown in the Figure 5. Impact echo is based on low frequency and long wavelength stress waves that distinguishes it from traditional ultrasonic monitoring techniques [7]. Only one side of the object is required to perform impact echo monitoring and it is also applicable on paints, tiles and coatings. Impact echo technique is typically applied to the various materials including stone, wood, ceramics, concrete, plastic and masonry materials.

The analysis of reflected waves is performed in frequency domain, which could become complicated due to embedded items in the structure. Impact echo systems are commercially available [24, 25], however no significant work has been reported for the monitoring of water pipelines.

2.2. Visual techniques

2.2.1. CCTV monitoring

Closed-Circuit Television (CCTV) is one of the well-adopted direct method for the monitoring of sewerage pipe interior. The system consists of a high-resolution camera mounted on a crawler robot that travels through the pipe while capturing images as shown in the Figure 6. The system is connected to a computer system to transfer image files for post-processing. CCTV monitoring systems could be remote or manual, have iris control and be available with directional illumination capabilities. Panorama optical scanner is widely used CCTV for pipe monitoring, and it can create 360° spherical images [26, 27].

Researchers have investigated several computer vision techniques to automate the process by developing a wide range of image features [28, 29, 30]. These image features should contain unique characteristics and be robust enough such that these features should help to differentiate the interested object from other objects even in the presence of background noise. Execution time for the computation methods applied to the image features is also one of the important aspects of visual monitoring application that needs to be improved to make the system sustainable in the real-world.

Several techniques are proposed to automate the detection process based on segmentation and feature extraction using image processing methods. Scale Invariant Feature Transform (SIFT) features of reference images are computed and stored in the database for comparison with new images [28]. The SIFT technique was further investigated in terms of shape contexts [29]. Artificial intelligence has gained significant momentum to solve the computer vision problems. Some famous AI algorithms for computer vision are Fuzzy Inference System (FIS), genetic algorithms, Neuro-Fuzzy System (NFS), Artificial Neural Network (ANN), K-mean clustering and Support Vector Machine (SVM). A novel approach has been introduced to extract the videos for the sewer pipe using 3D-SIFT and the pipe defects are classified by applying One-Class Support Vector Machine (OC-SVM) [30].

Convolution Neural Network (CNN) has been widely used in image classification. Researchers have proposed various modifications in CNN making it more robust in object detection based on Region of Interest (RoI), Region-based (R-CNN), faster R-CNN, fast R-CNN, You Only Look Once (YOLO), SPP-net, and Single Shot Detector (SSD) are proposed modified CNN algorithms [31, 32, 33, 34, 35].
2.2.2. Laser scanning

Laser scanning is also one of the visual monitoring techniques widely applied for condition assessment of sewerage pipes and water leak detection in underground tunnels as shown in the Figure 7. In laser scanning methodology, Terrestrial Laser Scanning (TLS) is the most significant technique to acquire 3-dimensional geometric information with flexibility, high density and high precision surface topography [40]. Laser pulses bounce off from scanned objects are captured and transformed to apply data processing algorithms. The intensity data is affected by many factors and some factors such as laser divergence angle, laser wavelength and laser power are related to the TLS sensor itself. While the incident angle, distance and physical characteristics of the surface are related to scanned objects [41]. TLS method can even work fine in the absence of external illumination, and it is also considered a suitable option for underground monitoring applications [42]. There are various commercially available LiDAR sensors used for TLS technique in wide range of applications [43, 44, 45, 46].

The intensity data measured by the TLS is significantly distorted by multiple variables, including distance effect and incidence angle. The distance effect occurs due to the gap between the centre of the scanner and the scanned points [41]. An intensity correction method has been proposed using piecewise fitting approach to eliminate the distance effect and overlap-driven adjustment approach to eliminate the incident angle effect. Surface roughness parameter of the scanned object is also considered for incident angle effect using oren–nayar model [47]. Feasibility of proposed approach has also been experimented for water leakage detection in underground tunnels. Water leakage regions are well extracted as compared to RGB images, and the influence of tunnel appendages are also eliminated from water leakage detection [48].

Visual monitoring techniques provide an effective way for condition assessment of the pipe interior. However, these techniques also require high processing power, data storage and high resolution cameras or laser scanners.

2.3. Electromagnetic techniques

2.3.1. Magnetic flux leakage

In Magnetic Flux Leakage (MFL), large magnets are used to generate a saturated magnetic field around the ferrous pipe. The distribution of magnetic flux is observed to identify the loss of metal on pipe surface or leakage as shown in the Figure 8. The pipe is considered in a better condition if the distribution of the magnetic flux is homogeneous. While the loss of metal on the pipe surface or leakage will have an impact on magnetic reluctance that will alter the homogeneous distribution of magnetic flux [49].

There are two methods to apply MFL that are single sensor-based method and multi-sensor-based method. Defects in single sensor-based technique are characterised on one dimensional space that provides relationship between defects and features of MFL information. An algorithm has been proposed to estimate the defects in two steps [50]. In the first step, image processing approaches are employed to evaluate the location, orientation, and number of defects. In second step, signal processing algorithms are applied on radial flux to estimate the widths of defects. MFL information is further enhanced by applying Self Quotient Image (SQI) approach and the Discrete Cosine Transform (DCT) approach is applied to locate the defects [51]. A Visual Transformation Convolution Neural Network (VT-CNN) approach is proposed to detect the defects more efficiently by applying visual transformation according to the characteristics of the MFL information [52]. Single sensor-based techniques provide limited information about defects in many cases. Meanwhile, the multi-sensor-based techniques provide more comprehensive information regarding the distribution of magnetic field [53]. Measurements are recorded from multiple sensors and data fusion is performed to improve the efficiency of defects characterisation [54]. Features of magnetic field are fused, and a machine learning algorithm is applied to evaluate the model [55, 56, 57, 58]. A multi-sensor data fusion framework is proposed to better estimate the spatial distribution of magnetic field, and improved conditional Generative Adversarial Nets (icGANs) are designed to enhance MFL information [59].

MFL technique is one of the effective and mature technologies to inspect internal and external defects with minimal data processing. However, it is not well suited for defects which are axially oriented, and the application is limited to metallic and concrete pipes [60].

2.3.2. Pulsed eddy current

An eddy current is induced in the conductive material by the changing magnetic field. It can be used to detect surface and subsurface defects in pipe. Pulsed Eddy Current (PEC) monitoring method provides an effective way of estimating wall
PEC method uses a transmitter coil that generates rectangular shape eddy current with positive and negative pulse as shown in the Figure 9. The receiver coil records the strength of magnetic field, which depends on wall thickness [61]. PEC monitoring is applicable to both insulated and non-insulated steel pipes. Research in PEC method has been focused on enhancing the performance of probe and feature extraction of detected signals [62]. A differential probe has been proposed that includes an excitation coil and two Hall sensors. The results have shown the potential to determine wall thinning defects in an insulated pipeline [63]. A Giant Magneto-Resistive (GMR) sensor-based probe is also used for evaluation of material thickness [64, 65]. Transient Eddy Current Oscillations (TECO) technique is introduced to estimate the thickness of stainless-steel material by identifying three features including zero crossing, envelope and energy in the magnetic field signal [66]. The distance between object/specimen and testing coil is referred to as lift-off. A signal is generated as the probe is moved over the object/specimen. The magnitude of the signal is a function of lift-off and several other parameters. The TECO technique is further investigated for non-magnetic stainless steel and lift-off point of intersection (LOI) is used to solve the false indications that happens due to lift-off variations during the process of thickness measurement [67].

The Decay Time (DT) approach is proposed based on highly sensitive Magneto Resistive (MR) sensor [68]. DT is linearly related with the conductivity property of materials which allows this approach to estimate conductivity from transient response of PEC measurements. DT approach is also less sensitive to lift-off variations. The square wave in PEC method has drawback of spectrum dispersion and low energy utilisation. Therefore, a Frequency-band-Selecting Pulsed Eddy Current (FSPECT) technique is proposed and the LoI and zero crossing time features are explored. The results have shown improved performance of FSPECT in terms of estimating the thinning defects of local wall [62].

PEC monitoring has been deployed in a wide range of industrial applications including oil, electric power, gas, petrochemical plants and aerospace. However, PEC monitoring technique is not applicable to polyethylene pipes.

2.3.3. Remote field eddy current

Eddy Current Testing (ECT) method has several advantages including fast speed, low cost, high sensitivity and low cost. This methodology is only limited to detect surface or near surface defects. Remote Field Eddy Current (RFEC) overcomes the limitation in ECT and provides the capability to detect deeper defects [69]. The RFEC monitoring method contains exciter coil and detector coil as shown in the Figure 10. The coil is excited by applying an alternating current signal at low frequency. The interaction between excited coil and detectors is divided into three zones: direct coupled zone, transition zone and remote field zone. In the direct coupled zone, the excited coil generates a magnetic field that interacts directly with the wall of the pipe and produces a concentrated eddy current. In the transition zone, the magnetic flux induced by the eddy current interacts with the magnetic flux induced by exciting coil. In a remote field zone, the interaction is negligible between excited coil and detector coil. There is a direct path of magnetic field between the exciter coil and detector coil inside the pipe. The direct path is affected by circumferential eddy current gen-

Figure 8: Magnetic flux leakage

Figure 9: Pulsed eddy current
erated in the conducting pipe wall. The indirect path of the magnetic field is radially outward through the pipe wall. Magnetic fields from direct and indirect paths re-diffuse through the pipe wall and produce dominant impact at the remote field zone. The magnitude and phase of the magnetic field in the indirect path will change due to any disruption [60].

Figure 10: Remote field eddy current

Dual-coil sensing coils are introduced in the RFEC technique to overcome the complications in detection of joint casings by applying filter to cut off the signal induced by the wall’s proximity [70]. A multi-coil sensor system is proposed for the RFEC technique by applying Window Multi-Frequency (WMF) algorithms. Finite element simulation in 3-D is then performed to investigate the defects [71, 72]. Researchers are also investigating the combination of MFL and ECT to take advantages of both techniques [73].

There are two primary challenges in RFEC technique. The first challenge is the weakness of detection signal at RFEC probe and the second challenge is the huge size of RFEC components [69, 74]. The performance of ferromagnetic shielding is also investigated to improve the sensitivity, minimise the impact of any nearby ferromagnetic objects and reduce the interference on sensor [74]. The results have shown that the distance between exciter coil and detector coil can be reduced with shielding plate and the ferromagnetic ring outside the ferromagnetic pipeline has shown improved results in signal detection.

Although the investigation has been carried out to overcome the limitations in signal detection and size of RFEC components. There are still limitations in implementing the structure for monitoring in underground pipelines.

2.3.4. Broadband electromagnetic

Conventional eddy current technique applies the single frequency signal. However, the Broadband electromagnetic (BEM) monitoring methodology covers a large range of frequency spectrum ranging from 50 Hz to 50 kHz [75]. The alternating magnetic field is generated by applying an alternating current to the surface of the pipe. Voltage is produced across the metallic pipe wall due to the magnetic field. An eddy current is generated in the pipe wall, which results in generating a secondary magnetic field. Thickness of the pipe wall is estimated based on phase delay and signal attenuation of the secondary magnetic field. BEM monitoring can estimate the thickness of pipe, locate broken wires in prestressed concrete cylinder pipes (PCCP) and quantify graphitisation in ferrous material. BEM systems are primarily employed on water mains for condition assessment. Commercially available hand-held BEM tools are also available to monitor corrosion pits. BEM technique is only applicable for ferrous materials [76].

2.3.5. Ground penetrating radar

Ground Penetrating Radar (GPR) technique uses electromagnetic field to detect variations in the material. Short electromagnetic pulses are emitted from radio spectrum and reflected signals from the subsurface of material are recorded as shown in the Figure 11. A magnetic field is applied on lossy dielectric material to probe the subsurface. There are two commonly used modes of measurement in the GPR technique. In the first mode of GPR measurement, the scattered or reflected magnetic field is detected to create profiles. While in the second mode of GRP measurement, the magnetic waves bouncing back from material is used to create profile. GPR profiles generated for the inspected pipelines are investigated for irregularities that provide information regarding water leakage [77].

Figure 11: Ground penetrating radar

GPR system does not require any close contact with components that are connected to the pipeline, like valves and hydrants. GPR can operate at a wide range of frequencies that makes it suitable to select an appropriate frequency depending on scale and size of material to be inspected. GPR technique also allows revealing the internal condition of subsurface with high resolution [78].

GPR technique is considered a time-consuming technique, and it is difficult to get accurate location of water leakage [79]. Therefore, researchers have attempted to combine the advantages of GPR and Infrared (IR) technology to detect and locate water leaks more efficiently. A multi-tier method is proposed to locate the buried pipes first using GPR technology and then apply IR technology at second stage to detect actual leaks [80].

GPR and EM techniques are applied on clay dam to investigate the leakage by taking advantage of integrated results [81]. The performance of GPR method is analysed on different type of soil and pipes [82]. Multi-band frequency is applied on PVC
and iron pipes buried under clay and sand to investigate which pipe and sand will result in more efficient reflection of EM waves. The higher frequency results in better resolution, however the depth penetration is low. Power reflectivity for PVC pipe is lower than compared to iron pipe and resolution of radar gram is better for both pipes at sand as compared to clay.

GPR technology is a well-established technique for the monitoring of buried assets [83]. However, there are several factors that limit the performance of GPR technique for underground water pipe monitoring. The scattering of signals in heterogeneous conditions such as rocky soils and change in response depending on type of soil and pipe material, water contents and density impacts the performance of GPR technique [84].

2.4. Ultrasonic techniques

2.4.1. Guided wave ultrasound

Guided Wave Ultrasonic (GWU) monitoring technique as shown in the Figure 12 employs guided acoustic waves that propagate through the structure for a long distance (up to hundreds of meters in some cases). The names of ultrasonic waves depend on the type of structure and how energy waves are guided through the structure. Torsional waves, longitudinal waves and flexural waves are three modes of guided waves propagation as shown in the Figure 13. Torsional waves propagate via shear motion parallel to the circumferential direction, and also propagate in the pipes filled with water. While longitudinal waves propagate via compressional motion in axial and radial directions, and these waves cannot propagate in the pipes filled with water [85, 86].

The generation of non-linear features due to the mixing of material non-linearity and torsional guided waves in the pipe structure at low frequency is investigated [88]. One of the major pipe defects is the damage caused by external loading. In-plane shear piezoelectric wafers are capable of sensing the shear deformation in flexural mode guided wave due to the bend. The approach based on conversion mode and in-plane shear piezoelectric wafer is proposed to determine the presence and direction of bend [89]. The reflected echo signals from minor damages in the pipe structure may be combined with high noise due to complex features in the propagation of guided ultrasonic wave. Stochastic resonance technique can significantly improve the Signal-to-Noise Ratio (SNR) of weak signals. A novel detection system is developed based on stochastic resonance of guided ultrasonic waves and du**ffling oscillator to detect minor damages in the pipe structure [90]. A time-frequency domain reflectometry technique is also proposed to improve the sensitivity of GWU monitoring [91].

GWU monitoring is a very promising technique to inspect the small leakages in the water pipeline. However, the geometry of the pipe, valves and welded supports in the pipe structure impacts the testing range of GWU technique [92].

2.4.2. Discrete ultrasound

Discrete ultrasound monitoring technique transmits short wave at high frequency to the material being inspected through a couplant as shown in the Figure 14. There are various techniques to generate the wave including electromagnetic acoustic transducer, piezoelectric ceramics, laser, magnetostrictive sensor and piezoelectric polymers. The sensor is calibrated with known thickness of the material. The transmitted waves reflect from the back wall of the material. Distance travel by the waves is computed by using velocity of wave propagated in the material and transition time [60].

Three primary components of the system are pulser, transducer and display unit. The pulser drives the transducer to generate high frequency ultrasonic waves. Part of the transmitted waves reflects in case of any object in the path. The reflected
waves are recorded and converted into electrical signals to extract the useful features including location, orientation and size. There are A-scan, B-scan and C-scan type of displays for ultrasonic display system. A-Scan provides time domain plot: a 1-dimensional information along the path of the ultrasonic beam. B-scan provides cross-sectional view of the object or pipe, and C-scan provides a 2-dimensional or 3-dimensional map of the pipe or object [93].

2.4.3. Phased array technology

Phased array monitoring technology consists of an array of individually wired, time shifted and pulsed sensor elements. Virtual sensor arrangements can be organised in the form of linear array, 2D array and in more complex forms. Phased array technique also allows transmitting sound beams in different directions and with different characteristics of ultrasonic beam. Steering angle, beam width and focal depth can be controlled using phased array technique [94, 95]. Polyethylene (PE) material pipes are well adopted for water and gas pipework. Condition monitoring of PE pipes is a challenging process because of frequency attenuation and low velocity. PE butt fusion joints have been investigated using phased array ultrasonic technique to detect flat bottom holes. Phased array technique has shown promising results to detect all sizes of flat bottom holes with high accuracy, except the area that is not within the coverage area of the technique [96].

The wave ultrasonic transducers can be deployed on a robot or crawler to monitor the condition of the pipe from inside and find the area of interest. However, the injection of enough ultrasonic energy to minimise the attenuation in concrete and polymer pipes, reproducibility of the results with variable pipe/surface conditions and quality of coupling between pipe wall and transducers are the key challenges. Future developments can be expected in this area [97].

2.5. Radiographic technique

Radiographic monitoring technique consists of a radioactive source and detector film. The radioactive source is either X-ray or gamma ray that is applied on the material or object to examine. Radiation penetrates through the material and any differences in the density detected on the film indicates imperfections. Several imaging techniques are available in radiography including Computed Radiography (CR), Digital Radiography (DR), Film Radiography (FR), Computed Tomography (CT) and Real Time Radiography (RTR) [98].

Radiography technique is sensitive to corrosion, thickness, and density changes of material. This technique is capable of inspecting complex structures, including surface and subsurface defects. There could be different configurations in radiography technique to inspect water pipelines depending on the position of radioactive source as shown in the Figure 15. One of the convenient configurations is to position the radioactive source outside of the pipe and film detector on the opposite side. The radiation penetrates through both pipe walls and fall onto the film detector. Multiple exposures are required in double pipe wall to capture a complete image of the pipe. There are further two categories in double wall technique, including Double Wall Single Image (DWSI) and Double Wall Double Image (DWDI). The second configuration is to position the radioactive source inside the pipe and the film detector is wrapped around the pipe wall. This configuration is applied where pipe bore can be accessed. This technique is referred to as Single Wall Single Image (SWSI) as radiation penetrates through pipe wall once [99].

Radiography sensitivity is affected because of the interaction of transmitted radiation with water. Researchers have attempted to improve the radiographic sensitivity by controlling the scattered radiation to optimise the radiographic screen [100]. However, this approach was only experimented with specific thickness of pipe wall and still water.

The segmentation algorithms on welding zones also has significant impact on the quality of image and target shape of the object. Various segmentation algorithms have been proposed to improve the quality of image of pipe under monitoring [101, 102]. These conventional algorithms could perform rapid monitoring however, the results from segmentation are not very efficient. The performance of segmentation algorithms is improved by taking advantage of advanced computing capabilities. An efficient segmentation algorithm is proposed for welding zone in cooled-water pipes based on boundary infor-
mation from radiographic images [103]. Improving the quality of radiographic images is the primary focus for researchers, since it will help to minimise the efforts of taking multiple shots and reduce the number of required components.

2.6. Thermographic technique

In thermographic monitoring, a heat source is applied to the object to be investigated, and the infrared camera is used to capture the thermal energy emitted from the object as shown in the Figure 16. The released thermal energy is converted into the image to observe the heat emission. The small variations in temperature on the image enables the identification of the existence of defects in the object [104]. Thermography monitoring allows the inspection of large areas in a short amount of time. It also offers non-contact monitoring without affecting the production process, and results are easy to interpret. Active thermography and passive thermography are the two basic types of thermography monitoring techniques. In active thermography, an external heat source rapidly heats the object, and the decay rate of temperature is monitored to identify the flaws. Passive thermography involves pointing the camera at the object to capture a thermal image [105]. Active thermography techniques can be applied to estimate the remaining quantity of water in steel pipes [106].

Active Microwave Thermography (AMT) is an advanced technique to evaluate the defects in the material. AMT utilises microwave excitation to heat the object, and the thermal profile of the object is subsequently monitored using infrared cameras [107]. Microwave excitation has several advantages compared to conventional thermal excitations, including focused and selective heating [108]. The water exhibits high absorptive property to electromagnetic energy within the range of microwave frequency [109]. Therefore, AMT technique has a strong potential to locate and estimate small volumes of water ingress [110]. It can also be applied to detect and characterise corrosion in pipes [111]. A vision-based monitoring technique for leakage detection in chemical plants is proposed. The motion pattern of leakage drops is repetitively observed using IR video. Kalman filter is applied for the detection of motion patterns of drops to identify the leakage in the process plant [112]. Thermography monitoring technique is a robust technique for small leakage detection. However, the environmental factors needed to be considered during the monitoring process to obtain better results [105].

2.7. District metered area

Water utility companies in the UK have installed flow meters and valves at strategic points on water pipeline infrastructure. This process breaks down the pipeline network into zones, which are referred to as District Metered Area (DMA). Water supply and leaks are monitored and managed by the water utility companies based on DMA. This approach allows controlling the water pressure and prioritise the leak maintenance strategies. The effective and efficient water leak management requires sophisticated data analysis techniques and capabilities. The cost of deployment for DMA technique is an important factor to consider. Apart from data loggers and flow meters, the replacement of valves may be required. Consistent monitoring of the components is also required from the workforce to avoid any misleading data.

The primary focus of research is to design effective decision-making algorithms based on patterns. The concept of virtual DMA and classification based on machine learning approach is proposed to enable water utility companies to perform the best quick response strategy [113]. The development of an optimised design of DMA in multi-criteria decision analysis is a challenging task. Optimisation of DMA design using Self-Organizing Map (SOM), Community Structure Algorithm (CSA), modified k-mean clustering and fuzzy analytic hierarchy process are also available in literature [114, 115].

2.8. Linear polarization resistance

The corrosion rates of metal structures can be monitored by using Linear Polarisation Resistance (LPR) technique. A small voltage is applied to the metal object and flow of corrosion current between anodic and cathodic half cells is measured by LPR probes. An LPR sensor is shown in the Figure 17. The interaction of electrolyte solution with metal results in an electrochemical reaction that generates a weak electrical current, which is directly proportional to the rate of corrosion. The resistance of the material to oxidation process during the application of an external electrical potential is referred to as polarisation resistance, which is inversely proportional to the corrosion rate [116]. 

Researchers have attempted to develop a field-probe that could potentially generate LPR measurements for ductile iron
pipe to monitor the corrosion rate [117]. Corrosion phenomena have the most significant impact in the biological contamination of water that degrades the quality of water. The water distribution system made of carbon steel in Cracow has been investigated online using LPR monitoring method to determine the impact of environmental factors [118]. Environmental pollution in the form of run off from agriculture and acid rain has shown significant impact on corrosion of the water distribution system.

The LPR technique provides a viable solution for the estimation of corrosion rates. It can be incorporated in remote sensor nodes however, the LPR technique provides localised results that need to be extrapolated for lengthy sections of pipes. It also requires establishing a relation between corrosion rates and LPR for various pipe materials [119].

2.9. Soil characterisation

Soil characterisation is another indirect monitoring technique to estimate the degradation of buried pipes. Soil samples are collected from locations closer to the pipe for in-situ testing or lab characterisation. There are a number of parameters in soil characterisation as shown in Table 1 that can be considered for the assessment of the buried pipe [7, 120, 121]. Soil characterisation of the surrounding soil of buried pipeline allows the maintenance professionals to take protective measures to prevent or stop any loss of containment [122].

2.10. Close interval survey

Close interval survey is also known as potential gradient and pipe-to-soil surveys. CIS is the measure of potential difference between the pipe and surrounding ground surface, as shown in the Figure 18. This monitoring technique is used to assess the efficiency of the Cathodic Protection (CP) system installed on buried pipes [124]. There are three basic types of CIS techniques including ‘on/off potential survey’, ‘depolarized potential survey’ and ‘on potential survey’ [125].

- In on/off potential survey, the CP system is switched on and off, while monitoring the potential difference between the pipe and the surrounding surface.
- In depolarized potential survey, the CP system is switched off to stabilise the pipe-to-soil potential before measuring the potential difference between the pipe and the surrounding surface.
- In on potential survey, the potential difference between the pipe and the surrounding surface is measured at regular intervals during the normal operating mode.

External corrosion direct assessment (ECDA) is a structured process that allows assessment to ensure the integrity and safety of pipeline infrastructure [126]. CIS is one of the essential tools in ECDA process to evaluate the efficacy of installed cathodic protection systems of underground and submerged pipelines to certify the NACE SP0169 specified standards [127].

3. Emerging WPM techniques

Several state-of-the-art emerging WPM techniques have been developed in the last two decades. These WPM systems can be characterised into static and dynamic systems as shown in the Figure 19. In static systems, sensor nodes are installed on the critical points and measurements are recorded in stationary mode. In dynamic systems, the sensor node either floats through the pipe or it carried through the pipe using a robot or crawler. Mobile sensor nodes float through the pipe while recording measurements as shown in the Figure 20.

Static systems are usually easy to deploy and applicable to most of the cases in real-world scenarios. However, the performance could be affected by background noise and pipe materials. The performance of dynamic systems has minimum impact from background noise and material of pipe however, these systems are hard to deploy and applicable to limited cases in real-world scenarios. A list of state-of-the-art WPM systems with corresponding methodology, features and limitations are listed in Table II.

![Figure 18: Close interval survey](image)

![Figure 19: Emerging WPM Techniques](image)
Table 1: Parameters for soil characterisation

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Soil resistivity</td>
<td>It is the resistance of soil to conduct electric current. High soil resistivity implies low corrosion rates.</td>
</tr>
<tr>
<td>2</td>
<td>pH value</td>
<td>It determines how acidic or alkaline is the soil. Alkaline soil can result in high corrosion rate of metallic pipes, while acidic soil can be correlated with deterioration of ferrous and cementitious assets.</td>
</tr>
<tr>
<td>3</td>
<td>Redox potential</td>
<td>It determines the soil aeration that identifies the conditions for microbial induced corrosion phenomena.</td>
</tr>
<tr>
<td>4</td>
<td>Sulfates</td>
<td>The reaction of sulfates with cementitious materials produces ettringite and gypsum that accelerates the cracks and pores in the concrete.</td>
</tr>
<tr>
<td>5</td>
<td>Chloride content</td>
<td>Chloride ions act as electrolyte in moist soil which reduces the soil resistivity and low soil resistivity accelerates the corrosion rate.</td>
</tr>
<tr>
<td>6</td>
<td>Moisture content</td>
<td>It estimates the soil saturation. Moisture in soil act as an electrolyte that results in corrosion phenomena of ferrous pipes.</td>
</tr>
<tr>
<td>7</td>
<td>Shrink/swell capacity</td>
<td>It is the capacity of clay minerals to swell when wet and shrink when dry. High shrink/swell capacity indicates high failure rate due to stresses imparted by the soil.</td>
</tr>
<tr>
<td>8</td>
<td>Buffering capacity</td>
<td>It is the capacity of the soil to resist the variation in pH in certain acidification.</td>
</tr>
<tr>
<td>9</td>
<td>Contaminants</td>
<td>Higher levels of acidic contaminants can lead to environmental stress cracking of polymeric materials.</td>
</tr>
<tr>
<td>10</td>
<td>Soil compaction</td>
<td>It indicates surrounding sediments and trench filling.</td>
</tr>
</tbody>
</table>

3.1. Static systems

3.1.1. MISE-PIPE

MISE-PIPE is a WSN pipeline monitoring system that utilises magnetic induction technique for wireless transmission [128]. It contains various types of heterogeneous sensors that are located inside and outside the pipeline infrastructure. The cluster of sensors consists of two layers, including the hub sensor layer and the in-soil sensor layer. The hub sensor layer contains acoustic sensors and pressure sensors that are located inside the pipe. The in-soil sensor layer contains various types of soil property sensors that are located outside the pipeline. The pressure and acoustic sensors locate the leak and act as the cluster heads. The in-soil sensors help to improve the accuracy of the system and act as the cluster members. The cluster members transmit the measurements to the cluster heads, and the cluster heads transmit the data to the base station. The deployment of MISE-PIPE system in in-field monitoring has not been found in literature.

3.1.2. PipeNET

PipeNET is a sensor network-based WPM system which is developed to detect, locate and identify various complex anomalies in pipelines infrastructure [129]. PipeNET architecture contains sensor node, gateway and backend server. The sensor node consists of various sensors including hydraulic sensors to monitor the water pressure, pH sensor for water quality and accelerometers for vibration detection. The measurements from sensors are collected at high sampling rate. The sensor node is responsible for data acquisition and transmission to the gateway through Bluetooth. The gateway communicates to the backend server through GPRS modem to transmit data for further analysis. The acquired data is analysed by applying various algorithms including wavelet transform, cross-correlation function and pattern recognition.

3.1.3. LeakFinder

LeakFinderRT system comprises accelerometer and hydrophone acoustic sensors, and they are connected to the wireless transmission system. Accelerometers are prone to background noise, therefore better SNR is achieved by using hydrophones. Leak in the pipe induces distinctive vibrations and sound signals. Accelerometers monitor the vibration signals, while hydrophones listen to the sound signals. The cross-correlation function is computed for the two leaks signals to estimate the time lag [130]. In LeakFinderRT system, the enhanced correlation function is computed by applying the inverse fourier transform on cross-spectral density. High resolution of narrowband leaks can be obtained through enhanced cross-correlation function. It is also useful for multiple leaks, small leaks and the environment with high level of background noise [131]. However, the information regarding size of the leak is not available and the performance of the system is highly influenced by the pipeline configurations.

A more advanced version of LeakfinderRT introduced by Echologics is LeakFinder-ST with better signal processing algorithms and low electronics noise. It provides more accurate
location of leak by estimating the speed of sound waves in the water pipes and low noise interference enables it to detect the quiet leaks [11]. LeakFinder-ST is applicable to multiple type of pipe materials and provides rapid correlation time. AQUASCAN is another leak noise correlator commercially available [132].

3.1.4. Permalog

There are various instruments offered by Halma Water Management for water leak detection including PermaNET SU, PermaNET+ and PermaNET. These correlator noise loggers comprise leak noise sensors with telemetry technology. Once the leak is detected, secondary parameters can be used to locate the position of the leak. The noise loggers usually operate during the night due to low background noise and high pressure. These noise loggers can be installed semi-permanent or permanently as well. They are durable, robust and specifically designed for easy installation at more challenging areas [133].

3.1.5. SmartPipe

SmartPipe is a multi-modal Underground Wireless Sensor Network (UWSN) system that generated pressure profile of water flow in the pipelines. The leaks can be identified by analysing the variation in pressure profile. Force Sensitive Resistor (FSR) sensor technology is used to monitor the pressure. Conventional pressure sensors require access to inside the pipeline. However, an FSR sensor with high Young’s modulus is adhered to the outer surface of pipe with a clip. The architecture of SmartPipe contains sensor node, master anode and base station for post-processing. The sensor node is responsible for the collection of FSR sensor measurements, and a transmitter inside the sensor node transmits the data to the master node through RF signals. The master node communicates with the base station through internet connection or local RF connection. SmartPipe is a non-intrusive technique and allows easy installation of the monitoring system [134].

3.1.6. FIDO AI

FIDO AI is the only state-of-the-art Software-as-a-Service (SaaS) solution for water leak detection based on differential analysis and machine learning algorithms. FIDO AI is a sensor agnostic technique that does not require any modifications in the existing pipeline monitoring system. FIDO Tech Ltd hosts FIDO AI SaaS platform and it can be accessed through REST API or web service. All types of kinetic and audio files are compatible with FIDO AI. It does not require special skills to utilise the FIDO AI agnostic tool. Professionals can upload the input file to get instant results regarding the existence of leak to avoid dry digs. FIDO AI has been tested in-field for complex real-world scenarios, and it has achieved a high accuracy in reduction of false positive alarms. It is a fully scalable, instantly deployable and easy to use monitoring system [135].

3.2. Dynamic systems

3.2.1. PipeProbe

PipeProbe is a mobile sensor system which is designed to map the hidden pipelines. The pressure and accelerometer sensors are encased in a capsule. The pressure of water indicates the height of the pipeline, and the accelerometer provides information regarding the geometry of the pipeline. A capsule floats through the pipeline with the flow of water and records measurements into a memory for post-processing. The capsule can be inserted for multiple trips to improve the accuracy of mapping. This technique does not require accessibility to the surface of pipelines for deployment. However, the accuracy decreases for lengthy pipelines [136].

3.2.2. TriopusNet

TriopusNet is a mobile sensor network system that provides an automated mechanism for deployment and replacement of sensor nodes inside the water pipe. The replacement sensor node is released from a centralised repository which is located at the source of the water pipe. The sensor nodes in TriopusNet system consist of a wireless sensor mote, a motor to drive mechanical arms, gyroscope and pressure sensors. Deployment algorithm is executed to monitor the network connectivity, sensing coverage and determines the location for node deployment. TriopusNet system extends mechanical arms for latching the sensor node for deployment. It can also perform replacement of sensor in case any sensor node fails. The replacement algorithm is executed to replace the failed sensor node with a fresh sensor node from the repository. Measurements from gyroscope and pressure sensors are used for localisation. Although, the experimental study has been performed to evaluate the feasibility of the TriopusNET system. Future extensions are required to overcome the challenges for real-world deployment [137].

3.2.3. Sahara

The Sahara system comprises a hydrophone tethered to the cable, which listens to the leak noises as it floats through the pipe using a small parachute. These leak noises are distinctive acoustic signals generated by the leaks in pipe joints, steel welds or walls. Monitoring using Sahara system can be applied while water pipelines remain in-service. The Sahara system is connected to the control unit, and it also contains a light sensor and camera to provide real-time visual monitoring. It allows inspecting wall thickness of metal pipes, visible defects, leaks and gas pockets. The Sahara system is an intrusive technology and requires extra effort depending on bends and flow rates [138].

3.2.4. SmartBall

SmartBall contain a range of acoustic sensors including ultrasound transmitter, accelerometer, temperature and magnetometer sensors. The monitoring of water pipes is performed by floating the SmartBall through the water pipe. It can detect the water leaks and air pockets in pipe with diameter equal or greater than 8 inches. The sensor suite including power source and other electronic components are enclosed in an aluminium alloy core. The core is encapsulated with a protective outer foam shell, which minimises the impact of noise while traversing the water pipe. The size of the outer sphere depends on the diameter of the pipe and flow conditions. SmartBall continuously records the acoustic measurements while floating through
the pipe, and it also emits an acoustic pulse after every 3 seconds for localisation. A SmartBall acoustic receiver is designed to keep the track of the SmartBall [139, 140].
<table>
<thead>
<tr>
<th>No.</th>
<th>System</th>
<th>Year</th>
<th>Features</th>
<th>Limitations</th>
<th>Implemented on existing infrastructure</th>
<th>Challenges</th>
<th>Success</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MISE-PIPE</td>
<td>2003</td>
<td>MISE-PIPE detects and locates leaks based on sensors located inside and outside of pipelines. Long operating lifetime in harsh underground environments. Installation of relay coils required significant human effort. Placement of small relay coils installed inside the pipelines is challenging due to installation of magnetic induction waveguide technique.</td>
<td>Installation of sensors required. Magnetic induction waveguides are sensitive to high background noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of gate-way nodes inside the pipelines.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of magnetic induction waveguides.</td>
</tr>
<tr>
<td>2</td>
<td>PipeNet</td>
<td>2004</td>
<td>The system is composed of sensors, acoustic sensors, and soil property sensors.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>3</td>
<td>LeakFinder</td>
<td>2004</td>
<td>The system includes sensors for pressure and temperature monitoring.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>FIDO AI</td>
<td>2019</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>7</td>
<td>PulsarPro</td>
<td>2004</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>8</td>
<td>Sahara</td>
<td>2004</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>9</td>
<td>Sahara</td>
<td>2004</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>10</td>
<td>SmartBall</td>
<td>2004</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
<tr>
<td>11</td>
<td>RAMP</td>
<td>2004</td>
<td>The system includes sensors for pressure and water level monitoring.</td>
<td>Installation of sensors on existing infrastructure is challenging due to the need for human intervention.</td>
<td>Deployed on existing infrastructure</td>
<td>Challenges due to installation of relay coils required significant human effort.</td>
<td>Susceptible to low-frequency non-leak noise, resulting in false alarms.</td>
<td>Deployed on existing infrastructure is challenging due to installation of gate-way nodes inside the pipelines.</td>
</tr>
</tbody>
</table>
SmartBall monitoring is applicable to all type of pipe materials and can be applied while the pipelines are in service. Pure technologies have reported that it can detect water leaks less than 0.1 gal/hr at high pressure and minimum level of ambient noise. However, it cannot be applied to the pipelines with water pressure more than 400 psi and an extra effort in moving the instruments is required to inspect lengthy pipelines.

3.2.5. RAMP

RAMP is a radio frequency identification based autonomous maintenance system for Pipelines (RAMP). This technique is a combination of sensing, robotic and Radio Frequency Identification (RFID) technologies that provides a proactive monitoring and maintenance system. RAMP technique consists of three major components including RFID tags, mobile sensor and robot agent. RFID tags are used to provide incident and location information to the mobile sensors. The mobile sensor has various sensing capabilities including chemical, visual, sonar and pressure. The mobile sensor integrates multichannel RFID reader/writer to communicate with multiple-channelled redundant array of independent RFID tags. Robot agent provides detailed monitoring and maintenance services based on information obtained from mobile sensor. RAMP is a scalable, customisable, and economical solution for various pipeline applications. However, there are many features within the system that could be further improved, such as real-world implications in robot agent and developing buoys for mobile sensors [141].

4. Conclusion and recommendations

There are several challenges in the existing condition monitoring technologies for water distribution network. Some key challenges are highlighted in the current section that needs to be addressed for future developments.

4.1. Acoustics

The complex mechanism of pipe failure modes and presence of background noise makes it challenging to identify leak noise signals. Acoustic noise loggers are installed to record noise signals and the signals are processed to differentiate leak signals from other noise signals. The similarity between leak and non-leak noise signals is a key challenge at the identification stage that results in false alarms. These false alarms increase the expenditure on maintenance and monitoring of the pipe network for water utility companies. Large size leaks are relatively easy to locate as compared to medium or small size leaks. The hidden information within the frequency range depending on pipe material and amplitude of noise signals can help to identify the size of leaks.

The correlation is one of the techniques used for localisation of leaks between the known locations of data loggers. Location is computed using time difference between the arrival of leak noise at data loggers. The accuracy of localisation depends on three important factors that are synchronisation between the loggers, computation of time difference between the noise signals and speed of sound in the pipe material. Time difference is often computed with cross correlation technique which requires sophisticated filtering. The mathematical relation also takes speed of sound as input argument to compute the distance of the logger from the leak. Ageing of pipe and change in temperature [142] does impact the material properties, thus changing the speed of sound. In another case, locating a leak on a section of pipe where two different type material are connected will have variation in speed of sound. Design and development of an appropriate technique is required to find the speed of sound in the pipe before applying the correlator.

4.2. Visual technique

The visual monitoring system requires a moving camera inside the pipe with a crawler or manually with wire. The size of the visual monitoring system and geometry of the pipe can also restrict or limit the movement. In most cases, the design of the visual system cannot be inserted into the pipe due to the dimensions of the hydrant. Another major challenge is the requirement of large memory storage for high resolution imaging data. Machine learning algorithms can automate the process to only store suspected area of the pipe for further investigation. This requires comprehensive data sets for various types of defects in pipe infrastructure to design more robust models. Moreover, existing models are designed for sewerage pipes, and they need to be extended for clean water pipes.

4.3. DMA technique

The water leak management in the DMA technique is based on data acquired from flow meters and other monitoring components. Water utility companies require huge investment in the installation of components and replacement of valves. Expanding the DMA network also increases the processing of data in the decision-making process for optimal and quick repair. Although optimisation in design of DMA and algorithms for making efficient decisions are presented in the literature, however, there is still room for further investigation for optimisation. Identification of optimal valves and flow meters without compromising on critical location is one of the important factors to consider for optimisation of DMA technique.

4.4. Internet-of-Things

Emerging WPM techniques take advantage of IoT to cover huge water network. These WPM techniques adopt sensor placement strategies based on type of sensors and IoT architecture. Sensors could be installed above the ground and under the ground to detect multiple interconnected parameters. Wireless communication and recharging devices under the ground becomes more challenging.

Signal attenuation referred to as path loss is the primary concern for Wireless Underground Sensor Network (WUSN). In past few years, various cutting-edge models based on propagation loss, electromagnetic waves, magnetic induction, and acoustic wave have been proposed to overcome the path loss [143, 144, 145, 146, 147, 148]. These models can be integrated in sensor node architecture for WPM applications for...
better wireless underground communication. Memory management and power consumption in IoT based systems are the most important factors that need to be considered in development of WPM systems. Efficient memory management and low power consumption can be achieved with intelligent data compression algorithms. Usually, data from sensor nodes is stored temporarily in the memory unit of the sensor node and transmitted to the base station for real time monitoring. An appropriate data compression algorithm can be applied to optimise the data so that it consumes less memory for storage and similarly, less power is consumed in transmission of optimised data. To the best of our knowledge, no study has been found in literature which has an emphasis on data compression specific to WPM systems.

Improvement in processing capabilities of hardware can also enhance the performance of WPM systems. There is no significant attention has been given to the design and development of architecture of sensor nodes. Existing WPM systems are built on the Application-Specific Integrated Circuit (ASIC), DSP and Field Programmable Gate Array (FPGA) architectures. A System-on-Chip (SoC) based approach has also been proposed in literature [149]. However, a comprehensive study for SoC and IoT based architectures to evaluate the performance in terms of reliability, management, and power consumption for WPM systems is still scarce [150].

### 4.5. Dynamic systems

Dynamic systems can localise the water leak, and it can also be used for the mapping of unmapped pipelines. Complexity in leak localisation depends on geographic location, geometry of pipe and environmental conditions. Various state-of-the-art inspection systems have designed mobile sensor nodes that float through the pipe with flow of water for leak localisation. Lengthy pipes, application process and behaviour of water adversely impact the performance of the system. Locating the sensor while in operation inside the pipe is a challenging task. The geometry of the sensor node and flow rate of water determines the smooth floating of the sensor node. Launching and collection of the sensor nodes at the end hydrants requires human effort. Moreover, multiple connections of suspected pipe could result in losing the sensor node. Applying AI/machine learning algorithms to identify air pockets, leaks and bends can produce more accurate leak locations. Introducing more convenient launching and collection mechanisms would make dynamic systems more feasible.

## Acknowledgements

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