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Acoustic and ultrasonic techniques for defect detection and condition monitoring in water and sewerage pipes: a review

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Abstract

Condition monitoring for water and sewerage pipes is essential for the safety of the environment, energy conservation and human health. This paper focuses on the application of acoustic and ultrasonic techniques for the detection and assessment of leaks, blockages and defect in buried pipes. The review includes acoustic methods (below 20kHz) based on vibration sensing using accelerometers, hydrophones and fibre optic sensors, and ultrasonic methods (above 20kHz) based on the propagation of bulk and guided waves. Related data-driven, machine-learning techniques are also discussed. Typical arrangements of sensors are shown, explained and analysed in terms of their applicability to buried pipe networks. Commercial systems and state of the art research for the inspection of pipes made of a range of materials such as cast iron, PVC and concrete are critically assessed. This review also explores the future application of robotic autonomous do deploy these sensors in water distribution and sewerage pipes.

Keywords : *Acoustics, Ultrasonics, Ultrasonic guided waves, Water pipes, Sewerage pipes, Buried pipeline*

1 Introduction

Buried infrastructure, in the form of networks of pipes, is important to urban life and forms a vital part of many engineering structures for transporting fluids and gases. In the UK alone there are over 600,000 km of sewer pipes [1]. The US Environmental Protection Agency estimates that water collection systems in the USA have a total replacement value between $1 and $2 trillion. The EU has a similar value of buried water pipe network. These networks are aging rapidly and becoming more heavily used due to population growth, increasing demand for water and climate change. With an increased use of pipe networks comes increased chance of faults occurring and when they do occur their impact is greater. Therefore, safe and reliable techniques for condition monitoring and fault detection are required for the maintenance and targeted replacement of the pipe infrastructure.

The underground water and wastewater/sewerage pipe networks are challenging environments for sensing. The requirement for sensors in this environment ranges from measurement of internal geometry and operational parameters (e.g. flow), to blockages, leaks and the structural integrity of the pipe itself. The pipes are made from a disparate selection of materials including, various polymers (e.g. high-density polyethylene (HDPE)), cast iron, ceramic, concrete and masonry [2] [3]. Pipes of a different age are often made from different materials, where some of the older materials are now in poor condition. The topology of this system is very complex. It is full of connections, inspection chambers, hydrants, valves and pumps (see an example shown in Figure 1). Typically, some details of the networks are uncertain, particularly the location of discontinuities in the properties of the pipe. This uncertain and challenging environment often means that that no single sensor technology is suitable.

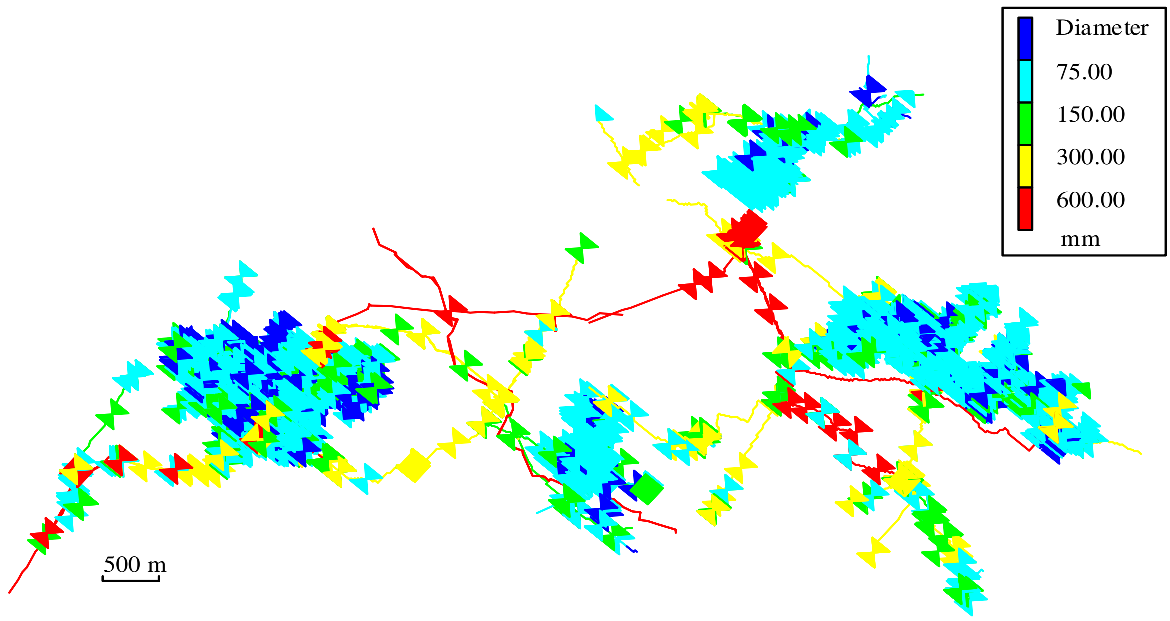

Figure 1. An example of the water distribution system in a small area of a town with different diameter (colour lines) and valves (pointing triangles).

The most common sensors in use today in underground water and wastewater/sewerage pipe networks are ultrasonics, passive and active acoustics, but other technologies such as CCTV, laser profiling, Eddy Current Testing (CET) and Magnetic Flux Leakage (MFL) are also used. This means that the pipe inspection engineer has a large toolbox of sensors and methods at their disposal to cover this wide range of needs [2] [3] [4] [5]. This paper reviews recent developments in acoustic and ultrasonic technologies and their application to the inspection of water and sewerage pipes. The review covers the use of accelerometers, hydrophones, fibre-optic sensors, bulk wave and guided wave sensors. These technologies have recently attracted a significant interest because of their high sensitivity, flexibility and speed to use in complex circumstances [2] [3] [4] [5]. We also explore the future potential of these technologies for use on autonomous robotic platforms.

A majority of acoustic sensors are still deployed and operated manually. Leak detection in water pipes is regularly performed by human inspectors who visit suspect regions to take manual measurements with listening sticks or to attach acoustic detectors to hydrants [6]. Blockages and structural damage in sewer pipes are often investigated by an operator working from a manhole with acoustic pulse reflectometry [7]. The need for human inspectors means that such measurements are expensive and time consuming. Typically, inspections are performed in response to a reported incident, such as a flooding, leakage or blockage meaning that only a tiny fraction of the network is covered by sensors at a time. A consequence of this responsive approach is that the opportunity for automated and condition-based maintenance is missed. Furthermore, the manual nature of the inspections means that they are relatively slow, not sufficiently pervasive and often subjective. There is a strong drive for water utility companies and municipal/government departments to move from reactive maintenance to predictive assessment and maintenance that can be achieved with advanced autonomous robotic systems [8]. Robotic sensing systems working in buried pipes have the opportunity to capitalise on recent advances in acoustic and ultrasonic sensing techniques. Although there have been reviews of pipe inspection technologies (e.g. [2]), there is still a limited understanding how these technologies can be adapted for autonomous sensing. Therefore, the purpose of this paper is to review the state-of-the-art acoustic and ultrasonic sensor technologies for water mains and wastewater/sewerage pipe networks and discuss their potential for being deployed on autonomous robots used for pipe condition assessment.

The paper is organised in the following manner. Section 2 reviews the existing acoustic inspection methods. Section 3 reviews ultrasonic methods using bulk wave and guided waves.

Section 4 is a summary of the applicability of the reviewed inspection methods and Section 5 is the conclusions.

2 Acoustic methods

A wide variety of acoustic techniques have been developed over the years for applications in the water and sewerage industries that include detection of leaks [9], blockages [7] and sediment depositions [10] as well as mapping the location of underground pipes [11]. These methods rely on sound waves with frequencies less than 20 kHz, i.e. waves generated in the audible frequency range. Acoustic sensing methods are non-invasive and allow inaccessible pipe sections to be inspected with minimal disturbance. Active sensing requires presence of a sound source and a receiver to measure the acoustic response of the pipe. Active sensing usually analyses the reflected waves that contain the information about the discontinuities of the pipe (e.g. blockages [7]). Passive sensing is used for leakage detection when signal generated by high-pressure fluid escaping from a perforated pipe is measured directly by a hydrophone or accelerometer [5]. The main content of the frequency spectrum generated by leaks in water pipes is generally below 1kHz with a peak around 100 Hz [2] [12] [13]. Passive sensing requires that the signal generated by the leak is stronger than the background noise, i.e. there is a sufficient signal to noise ratio (SNR) to recognise leak noise over other unrelated sources. For active sensing, the energy produced by the emitter should also be sufficient so that the signal can be measured over the background noise. This section reviews acoustic sensing techniques for condition assessment of water pipes using accelerometers (acceleration) and hydrophones (acoustic pressure).

2.1 Accelerometer sensing in water pipes

Acoustic correlators attached to hydrants have been used for more than three decades to detect and locate leaks from water pipes with commercial products (e.g. [14]) and lab prototypes [12] [15]. The location of water leaks is estimated from the peak in the cross-correlation function between the leakage signals measured by accelerometers at two different positions in the water pipe [5]. As shown in Fig. 2, if a leak exists in a pipe between two accelerometers attached to it at distances d_1 and d_2 from the leak, respectively, a distinct peak can be found in the cross-correlation function calculated using the accelerometer data. The time delay at which this peak is observed, τ, corresponds to the difference in the signal arrival time between the two accelerometers. The location of the leak can then be calculated using the time delay τ; the distance d between the sensing points, and the propagation wave speed c in the buried pipe by $d_1 = \frac{d - c\tau}{2}$.

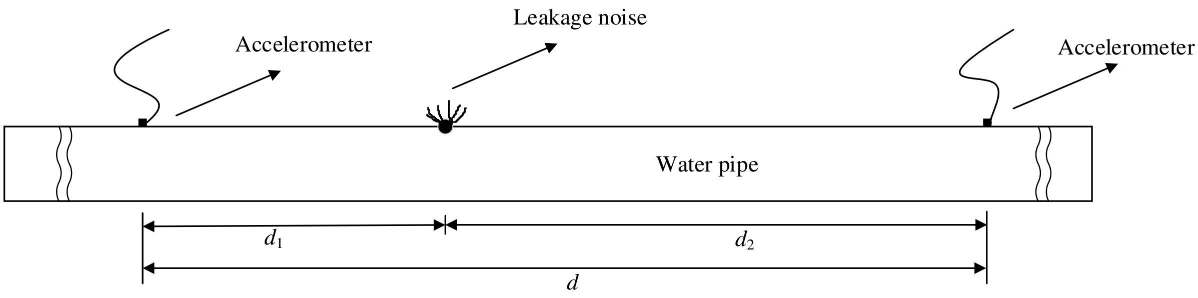

Figure 2. Cross-correlation leakage detection of water pipe using two accelerometers.

Cross-correlation based techniques can have less than 10 cm leak location error [2] in pristine metal pipes. In plastic pipes, rapid attenuation of acoustic waves associated with relatively large loss factor in pipe walls makes the problem of water leak detection more challenging especially for high frequency signals [2] [13]. [12] reports that the location error using acoustic correlators is less than 1m when the detection range is 20 meters for plastic pipes. Another fundamental challenge for the cross-correlation method in plastic pipes is that the wave propagation speed for plastic pipes is required as *a priori* which can be difficult since there are more uncertainties (i.e. type of polymer, effect from the surrounding media) than in metal pipes [12] [13].

Another method of using an accelerometer for damage detection and assessment in a pipeline system is based on pipe-flow interaction. It is observed that a sharp change in fluid pressure is always accompanied by a sharp change of vibration on the pipe wall at the corresponding locations along the pipe length [16]. Therefore, water pressure-monitoring can be transformed into acceleration-monitoring of the pipe surface and recent work shows that this can be achieved using low-cost Micro-Electro-Mechanical Systems (MEMS) acceleration sensors [16] [17]. However, these methods have difficulty in distinguishing pressure changes from a leak and those due to other transient sources (i.e. loops, valves and bends) [18].

Damage of water pipe walls (i.e. cracks or corrosions) can be detected using accelerometers measuring the change of vibration response characteristics of the pipeline structure, specifically its natural frequencies [19] [20] and mode shapes [21]. However, these methods have not been applied to real pipe networks to date. This approach also requires accurate information of the pipeline system and the changes due to defect can be swamped by the uncertainties in the boundary conditions such as external ground conditions. Furthermore, vibration response characteristics of a pipeline are global features that can similarly result from several defect types, positions and severities, making it challenging to determine a unique defect signature [18][22].

The above methods have potential to be used with autonomous robots which can measure the pipe wall acceleration from the inside of the pipe and at ranges (along the pipe) short enough to ensure a good SNR. Such robots could measure over a period of time and spatial span which would be sufficient to ensure high frequency resolution of spectral peaks and spatial resolution of the location associated with leak noise.

2.2 Hydrophone/microphone sensing

A hydrophone is an acoustic transducer capable of measuring sound pressure underwater and can be used for listening measurements in water pipelines. A tethered hydrophone that travels with the flow in a live service water pipe has been developed (e.g. Sahara [23] see Figure 3). A human inspector controls the hydrophone, listens to, and analyses the spectrum of noise in this pipe. In this way, a leak can be detected when the noise spectrum becomes comparable to that expected from a leak [2] [24]. With knowledge of the propagation distance, the ground can then be marked in the right location for excavation and/or subsequent pipe repair [25]. This technology enables leaks as small as 0.005 gal/min to be identified with a typical spatial location accuracy of 0.5 m (1.5 feet) [23]. At present, this technique requires an umbilical cable inside pipe, and it only works if there is a suitable access point in the pipe.

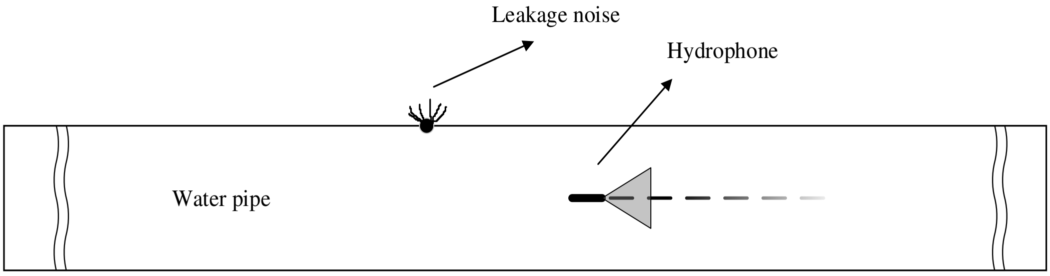

Figure 3: A typical *Sahara* pipe inspection system using hydrophone [23].

Using the signal correlation technique similar to that developed for accelerometers, leakage noise acoustic pressure measurements with two hydrophones can be used to estimate the location of the leakage. Compared with accelerometers, pressure response measurements by hydrophones are known to be more effective for low signal-to-noise ratio (SNR) situations particularly in plastic pipes [6] [12]. Higher SNR leads to a sharper peak in the correlation function calculated for sound pressure data and hence more precise leak localisation particularly when hydrophones are used in combination with accelerometers [6]. Research presented in reference [12] concluded that for large distances between sensors and high attenuation factors (i.e. plastic pipe) hydrophones offer the most accurate results (with <0.5 m error) compared to other sensors (i.e. accelerometers and geophones have <1m error).

Apart from using hydrophones to listen to steady state leakage noise, a transient-based methodology has also been studied for the detection of large defects. This method detects in-pipe defects from the hydraulic transient behaviour which is sensitive to the structure of the pipe. Wall perforations, poor joints, blockages and other discontinuities including junctions or diameter expansions cause transient wave reflections [26]. A leak in a pipeline system can also increase the attenuation of the transient pressure wave [26] [27].

A transient pressure pulse can be generated by the sudden closure of an initially open side-discharge. A pressure sensor located close to the valve can be used in the leak estimation process as shown in Figure 4(a). The leak can induce a distinct signal in the pressurized water system compared to the intact system. The transient signal decays more rapidly due to the leak induced damping, compared with the transient signal without leak as illustrated in Fig. 4(b).

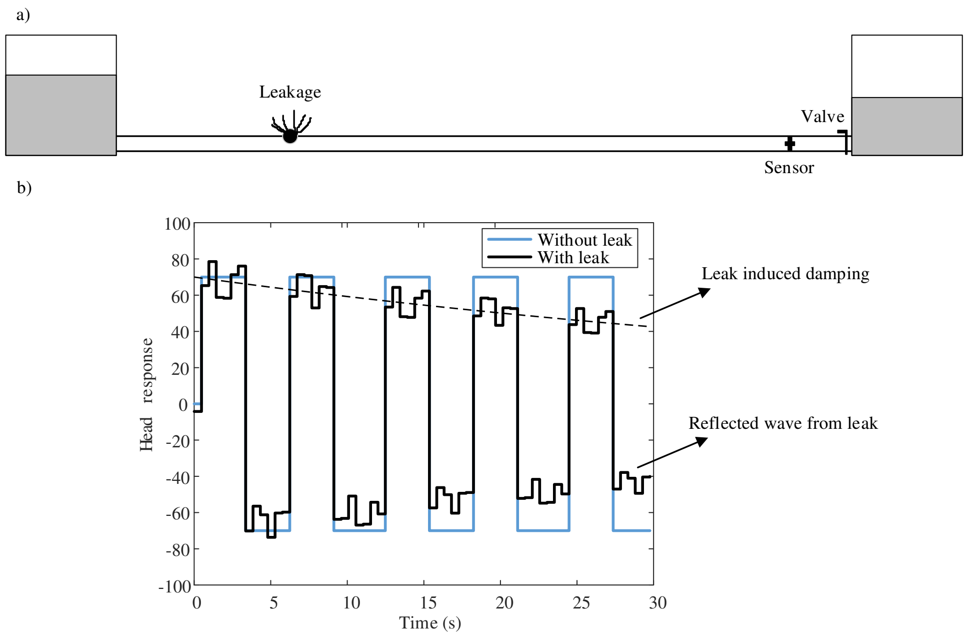

Figure 4: Transient-based method for leakage detection: a) configuration of the pipeline system measurement, b) transient wave in the time domain [26].

There exist many processing methods to detect the leakage using transient wave measurement. Inverse-transient analysis proposed in [28] can determine the leak size and location by minimizing the differences between calculated and measured water heads. This method has been improved over the years by optimizing the deployment of sensors and refining the hydraulic transient model [26]. The transient damping method [29] [30] is an alternative for leak size and location identification. It is claimed that the procedure can find leaks as small as 0.1% of a pipeline's cross-sectional area [26]. The efficacy of this method is demonstrated in laboratory studies with simple configurations and is yet to be used in real field testing. It is noted in [26] that the accuracy of this method can be influenced by several factors such as unsteady hydraulic friction terms (which are component dependent), and validity of linearizing head and flow into steady and transient components. Other methods based on time-domain reflectometry techniques [31] [32] and frequency response-based methods [33] [34] have also been studied by many researchers to identify leaks. More recent studies have explored multiple leak detection using more robust algorithms in the presence of background noise (e.g. matched field processing [35], compressive sensing [36] and machine learning methods [37]). However, most of these conventional and recent techniques were in carefully contrived hypothetical examples and heavily controlled laboratory trials which can be problematic in applications for complex systems under a wide range of conditions [26]. Therefore, the validation and assessment of the performance these technologies in real-field testing is important. The above sensing technologies are well suited for being deployed on autonomous robots operating from inside the pipe. These robots could carry hydrophone arrays or operate collaboratively to excite sound, record sound pressure and to process acoustical information coherently over the required temporal and spatial extents. Autonomous robots could move the sensors close to a defect to examine its acoustic response at a range where its effect is particularly strong and detectable in the presence of background noise and influences from other artefacts present in the pipe.

Similar to the application of hydrophone in water pipes, microphones can be used in sewerage pipes for blockage detection. Blockages can be localized according to the time delay of acoustic echoes measured by microphones [38]. The power reflection ratio and phase change measured by microphones can be also used to determine the geometry of a blockage in a sewerage pipe [7]. These methods could be conveniently applied to robots carrying loudspeaker and microphones to actively collect the reflected wave from blockages in sewerages. Similar to water pipe detection scenarios, autonomous robots could also move close to the defects (e.g. blockages) to enhance the signal to noise ratio and reduce the influences of complex and poor operating conditions (e.g. wave scattering caused by complex surface roughness [10]).

2.3 Fibre optic detection in water pipes

Fibre optic sensors have typically been installed as distributed sensors. They have been used extensively to assess the condition of pipelines (particularly leakage detection) due to their geometric flexibility, high sensitivity, and wide dynamic range [39] [40]. Fibre optic sensors are typically fixed to the surface of pipes to detect temperature, vibration and acoustic pressure via induced phase changes in the optical signal [41]. They have been used for leakage detection in pressurised water pipes and shown capabilities to detect small leaks [41]. Figure 5 shows three common ways in which fibre optic sensors have been installed in pipes for condition monitoring.

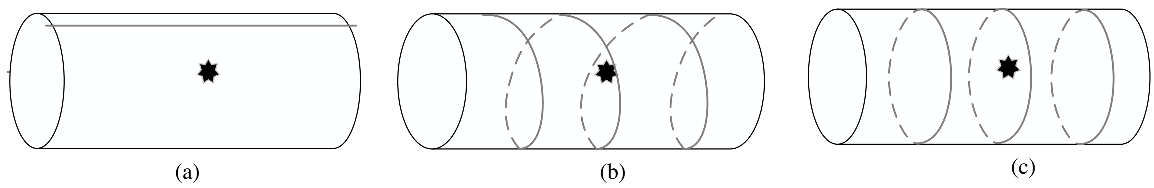

Figure 5: Three different ways mounting fibre optic sensors on the pipe wall surface: (a) axial wrapping, (b) helical wrapping, (c) loop or hoop wrapping.

A fibre optic sensor detects a change in the optical phase caused by pipe deformation when a sound wave propagates through it. Similar to accelerometer or hydrophone sensing, the leakage position can be identified from the amplitude of frequency spectrum of fibre optic phase measurement [39] [42] which usually has peaks near the leakage. The sensing element(s) can pinpoint the leakage location within 0.07m as reported in [43]. However, this technique has high installation costs and soundproof material needs to be added at the outer layer of the fibre to minimize the effect of external environmental noise [40]. Usually, fibre optic sensor systems are installed while the pipe is being constructed and it may be problematic when a section of the pipe is damaged and needs to be replaced. The fibre optic sensing method is highly sensitive in detecting the leakage noise and has low rate of false alarms and detection promptness compared with accelerometer or hydrophones [44].

From the robotic sensing point of view fibre optic sensing technology could be useful to help navigate robots to those parts of the pipe which are likely to develop defects. Robots could then potentially interrogate these defects with higher resolution and use the fibre-optic cable as a means of communication. In this respect, the two technologies complement each other well.

2.4 Data-driven methods based on acoustics

Data-driven techniques are used to identify the leakage or blockage of the pipe from data obtained through vibration or acoustic pressure measurement. These techniques require no specific knowledge about the pipe and formulate the challenge as a classification problem [45] [46]. The approach is divided into two stages: (i) generating a classifier from a set of measured vibration/acoustic data; and (ii) applying the classifier to predict the condition category (i.e. whether a problem exists or not). Many classifiers have been investigated based on measured acceleration signals (e.g. standard deviation by Martini et al. [47], and leak detection index based on the cross-spectrum density by Yazdekhasti et al. [18] [48]), and acoustic pressure signals (e.g. Singular Spectrum Analysis (SSA) by Cody et al. [49], and acoustic energy by Feng et al. [50]). Classification using machine learning methods have also been applied to a range of acoustical data through support vector machine (SVM) [49], k-nearest neighbours (KNN) [50], artificial neural networks (ANN) [51], multi-layer perceptron neural networks [52] and deep neural networks (DNN) [37].

Data-driven methods using machine learning techniques are still at the research stage. Most of the research into these methods used carefully contrived hypothetical examples or heavily controlled laboratory trials. The main disadvantage of a data-driven method was the requirement for a large amount of data to develop a robust classification or predictive model [45] [46]. Data uncertainty, particularly a non-stationary component in recorded data, will propagate to predicted values [45] [53] and affect the accuracy of detection. Furthermore, the designed fault identification system (e.g. leakage detection) will only be able to deal with faults that have been previously observed in the training data [45] [54]. One possible solution to this problem was using a mixed model-based data-driven approach (e.g. [54]) to improve the robustness of the detection system. This method [54] compared the pressure measurement with the estimations provided by theoretical models to obtain the residuals, and then apply a classifier (e.g. KNN) to the residuals to determine the damage location.

The fidelity of the above methods could be improved if longer-term, better quality data obtained through pervasive deployment of robots in pipes become available for better machine learning and condition classification. In this respect, autonomous robots provide a unique opportunity to collect big data from a pipe network of a representative size and over a representative period of time. These data could be tagged to provide high-fidelity training for a data driven model to be able to recognize a particular defect. This information could be dynamically updated and adopted for a data-driven pipe condition classification technique to be retrained provided these robots preside in pipes over a long enough period of time representative of a critical change in the system behaviour.

3 Ultrasonic methods

3.1 Bulk Wave

Bulk wave ultrasonic inspection for structures such as plates and pipes has traditionally been performed using single or multiple transducers [55] [56]. A typical configuration involves a single transducer (pulse-echo) or a pair of transducers (pitch-catch) that is usually attached to the outside of the pipe as shown in Figure 6(a)-(b). Ultrasonic bulk waves are most commonly generated by piezoelectric ceramics or polymers that require contact or a liquid or solid couplant. However, non-contact methods are available including lasers for non-conducting materials and electromagnetic acoustic transducers (EMATs) for conducting materials [2]. The bulk waves travel through the solid material as longitudinal or shear modes and reflect/scatter at a discontinuity such as a defect or backwall. The angle of the incident transducer and angle of the receiving transducer (if present) are selected to optimally detect the reflection/scattering from the feature of interest. For example, vertical cracks from the back wall of a plate/pipe can often be detected using a single transducer set at an angle to receive the strong reflection from the crack corner and smaller reflection from the crack tip. The proportion of the incident energy reflected from a defect depends on its size and type, e.g. a large air-filled crack results in a complete reflection, whereas a water-filled crack results in a partial reflection making it harder to detect [57] [58] [59] [60] [61] [62]. As the wave-packet propagates through the material the energy available for defect detection reduces due to a combination of spreading, attenuation and scattering from the microstructure. The reflected signals are then analysed to detect and to locate defects as well as to measure the material thickness [57] [63] [64] [65] [66].

Table 1 compares the bulk wave speed and attenuation in typical pipe materials used in clean water and wastewater pipes. These pipe materials present various challenges in terms of their ultrasonic bulk wave inspectability. These challenges are mainly due to the relatively high attenuation which is caused by the scattering from the microstructure of the materials and wave absorption, the latter being particularly important for polymer pipes. Pipes made of inhomogeneous materials such as concrete, clay and brick are rather difficult to measure ultrasonically due to a relatively high attenuation. These challenges can be overcome to some extent by reducing the frequency of the ultrasonic wave to hundreds of kHz, which inevitably increases the wavelength, compromises the spatial resolution of the measurements and complicates data analysis due to multiple reflections and interference. In contrast, metallic components have a lower attenuation which allows for higher frequencies (potentially several MHz) to be used.

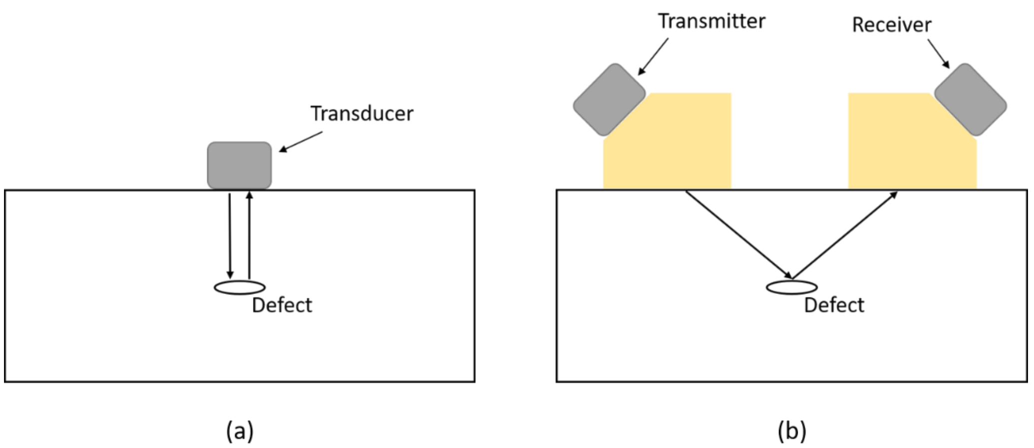

Figure 6: Schematic diagram of (a) pulse-echo and (b) pitch-catch ultrasonic bulk wave setup.

Table 1: Sound velocity and attenuation in typical water and sewer pipe materials [67] [68] [69] [70] [71] [72]. Low attenuation means less than 1dB/cm, medium is between 1-15 dB/cm and high is more than 15 dB/cm at frequency 5 MHz.

Material	Cast iron	Plastic (PVC)	Plastic (PE)	Concrete	Asbestos cement	Brick
Attenuation	Low	Medium	Medium	High	High	High
Longitudinal velocity (m/s)	4550	2400	1950	3700	2200	4200
Shear velocity (m/s)	2500	1060	540	3200	-	3600

There are 3 types of ultrasonic scans with bulk wave and types of displays commonly used in plate/pipe inspections (as illustrated in Figure 7):

- A-scan, or time domain plot: it provides 1D information on reflections along the direction of the ultrasonic beam. For example, Inductosense technology [73] uses A-scan for inspection of structures including pipes from their external surfaces. The advantage of this method is its simplicity where a single probe can be used.
- B-scan: it provides a 2D cross-sectional view by combining A-scans from multiple transducer positions (or multiple transducers). One axis of the cross-section is in the thickness direction, the other is typically axial or circumferential. Mentor UT (ultrasonic testing) with ultrasonic phased array flaw detector [74] is a commercial system using a phased array and is commonly used for B-scan of pipelines from the external surface to detect corrosion and measure wall thickness.
- C-scan: it provides a 2D map from the plate/pipe surface by extracting specific features from A-scans. In case of a pipe, the transducer is moved in both axial and circumferential directions. Tablet UT [75] is an example of a system that can produce A-, B- and C-scan images of pipes, again, from the exterior. This system can also be used to detect flaws, but it can also more accurately find defects such as cracks that are oriented unfavourably.

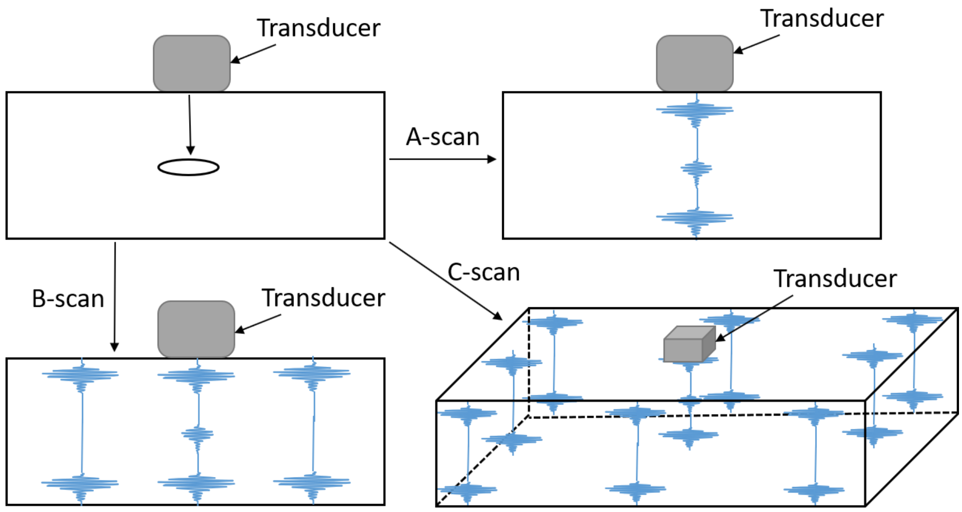

Figure 7: Schematic diagram of ultrasonic scans.

Ultrasonic inspection can be used to inspect pipes both externally and internally. External inspection is challenging as the pipe must be excavated and cleaned for inspection. However, ultrasonic bulk waves are used routinely for condition assessment of exposed pipelines in oil and gas industries. In these industries externally applied ultrasonics have been used in combination with high precision robotic manipulators to detect and characterise corrosion [76], cracks [77] and residual stresses [78] [79] in pipes, particularly in welded joints. In addition, research has also explored their use for assessing the condition of water and sewer pipes, but with a focus on internal inspection. Various commercial systems are available in the form of pipeline inspection gauges (PIGs) (shown in Figure 8) typically based on angled beam B-scan and C-scans. For example, the UltraScan CD inspection tool [80] uses a number of 45° shear wave transmitters and receivers arranged around the interior of the pipe circumference to detect cracks that are parallel to the axis of the pipe [3]. This is also an area of active research. Zhu et al. [81] developed and tested ultrasonic bulk waves for the condition assessment of buried plastic pipes in water distribution systems to assess void formation and critical loss of support in HDPE and PVC materials. They used a water coupled transducer with centre frequency of 10 MHz and detected machined grooves/slots (1 to 2 mm) in PVC plates (6 mm thickness). They also reported successful detection of major cracks in PVC and voids in both PVC and HDPE.

The most significant limitation of all these approaches is accessibility as the external measurements are often not possible at all locations. As the detailed ultrasonic inspections are time consuming and costly, they can only be undertaken infrequently. Furthermore, PIGs are not ideal for on-going monitoring as they are relatively large and need to be entered from one side to be captured from the other side. As a result, some temporary disruption of service during deployment is currently unavoidable. This issue could be resolved through the development of miniaturised robotics which deploy sensors and carry out measurements autonomously while the pipe remains live.

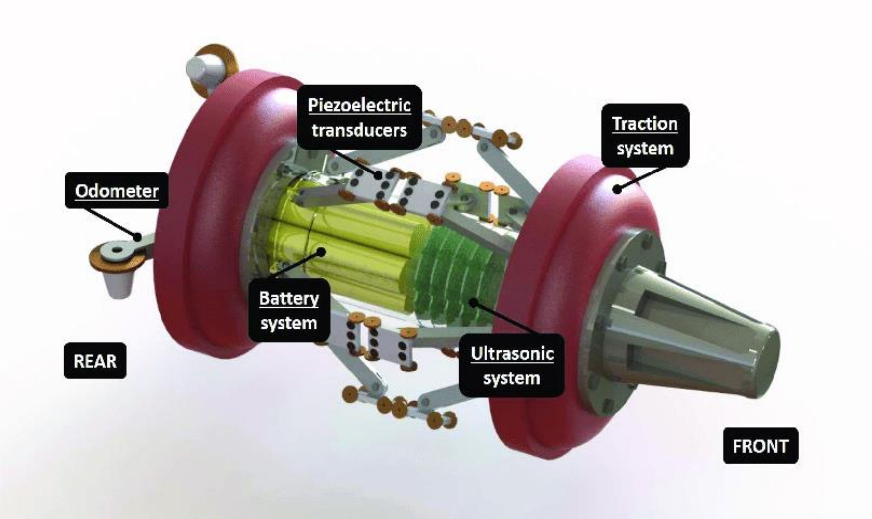

Figure 8: A schematic of an ultrasonic PIG [82]. Multiple transducers are arranged circumferentially to inspect the pipe wall as the PIG is moved through the pipe.

Other ultrasonic inspection methods include that developed by Hong et al. [83] who used nonlinear modulation between a low frequency pump wave (6-16 kHz) and a high frequency probe wave (155-165 kHz) to successfully detect various defects (lengths 0-35 mm and depths of 0-2.5 mm) in PVC pipes (53 mm diameter and 3 mm thickness). In general, despite these promising results, nonlinear techniques were shown to be extremely sensitive to other factors, such as coupling conditions [83] and have yet to find commercial applications.

Skjelvareid et al. [84] studied ultrasonic inspection in a cast iron pipe, which was originally part of a water network of the city of Skien in Norway. They proposed synthetic aperture focusing to extend the focal range of transducers and used a pulse-echo setup operating at 2.25 MHz frequency. They inspected four small drilled holes as point scatterers and showed their focusing technique extends the focal range and increases resolution of scatterers outside the transducer's original focal zone. As arrays are used widely in other industries, this is an area where we expect further progress in the coming years particularly in combination with the advance of autonomous robotics.

Many buried pipes are made of precast concrete (PCCP) that has a large bulk wave attenuation and noise due to backscatter from its heterogeneous structure [85]. Hence, getting the ultrasound energy to and from the defect remains challenging. As a result, the area inspectable in a concrete pipe by bulk wave ultrasonics or guided waves is smaller compared to metal pipes and the ultrasonic frequencies used must be lower, typically in the range of 50 to 200 kHz [72]. In 2012, Iyer et al. [85] evaluated the ultrasonic inspection and imaging systems for concrete pipes. They measured the through thickness resonance, which was 31.25 kHz in 60 mm thick concrete, and used this to determine the thickness. They also carried out an experiment on concrete slabs (60 mm depth) containing a hairline crack (~75 mm), crack (~75 mm), fracture (~75 mm) and a hole (~10 mm diameter) using a 250 kHz transducer and identified all four types of defects with C-scan imaging.

3.1.1 Phased arrays

Ultrasonic phased arrays are arrangements of individually connected transducers (or elements). Generally, the arrangement of the elements within the array are classified as 1D, 2D or annular [86]. The most common type of array in industry is a 1D linear array in which the array images a cross section of the pipe in the thickness direction. This type of array allows beam steering and focusing within a 2D inspection plane. 2D or mosaic arrays allow beam steering and focusing within a 3D inspection volume and annular arrays provide variable focal depths.

Hagglund et al. [87] have taken advantage of 32-element linear ultrasonic phased arrays of 2 MHz and 4 MHz central frequency with pulse-echo configuration for inspection of polyethylene (PE) butt fusion joints. They used pipe sizes of 220 mm to 450 mm outer diameter and reported successful detection of flat bottom holes of depth 40 mm and diameters of 1.5-8 mm. Rachev et al. [88] investigated the in-service inspection of large diameter pipes using PIG-mounted phased arrays and immersion scans from inside of oil pipes with a focus on detection and sizing the depth of axial surface breaking cracks. They studied the performance of plane wave imaging (PWI) [89] and total focusing method (TFM) [90] characterising cracks of 1-8 mm length in a 42” (~1.07 m) outer diameter and 10 mm thickness pipe.

Deploying bulk wave ultrasonic transducers on autonomous robots is potentially attractive because they can reach parts of the pipe which are not accessible from outside. These robots could move the transducer inside the pipe at relatively small and accurate steps to cover patiently an area of interest. There are real challenges here which are related to establishing good quality coupling between the transducer and pipe wall, injecting enough ultrasonic energy to overcome a relatively high attenuation, particularly in polymer and concrete pipes, and to ensure reproducibility of the inspection, given the variable surface condition. The deployment of this technology on robots deserves more research.

3.2 Guided ultrasonic wave techniques

Guided ultrasonic waves are sound waves that travel in bounded structures known as waveguides, and of relevance here they can be guided by pipes. Typically, a waveguide traps the propagating wave and allows this wave to travel long distances, i.e. several meters or even kilometres if the propagation conditions are favourable. Existing guided wave non-destructive testing systems were originally designed for use for an above-ground pipe inspection. Currently, these systems are used to inspect buried pipes filled with water, but the testing range is limited due to the significant attenuation of guided waves. As well as losses in the pipe materials itself, the energy of guided waves in buried pipes tends to leak into the surrounding soil resulting in a dramatic reduction in a test range [91].

In the typical experimental arrangement for a ground guided wave pipe inspection, several transducers [92] [93] are clamped in a circumferential ring on the external surface of the pipe (see in Figure 9) to detect a loss of the pipe wall material, i.e. corrosion or erosion. In order to achieve a long-range guided wave propagation (i.e. many tens of metres) operating frequencies below 100 kHz are common. Lowe and Cawley [94] [95] described a shorter range (typically less than 5 m) system using frequencies in the range 0.5-1.0 MHz. An infinite number of different wave modes (where a wave mode defines the shape of the propagating displacement field) can exist in any given pipe which means that coherent noise from the high-order modes can be a problem unless the excitation system is designed to excite a single mode at a suitable frequency. For example, a relatively low-order (i.e. low-frequency) guided wave with a simple mode shape (torsional or longitudinal) [92] [96] [97] [98] is used as it leads to reduced measurement complexity and long propagation distances in commercial systems. Piezoelectric (PZT) array technology [99] [100] has been developed to test a broad range of standard pipe diameters (e.g. 38.1 mm to 1.98 m [100]). The sensitivity of this system in typical above-ground oil and gas applications is in the region of 3−5% [101] [102] metal loss of the pipe wall cross-section.

For buried pipes, common commercial systems require the digging of a pit in order to gain access to the pipe exterior [91]. Then, the commercial transducer ring can be clamped to enable testing in each direction from this location at a maximum possible range as shown in Figure 9. Ultrasonic guided wave technologies as applied to buried water pipes and wastewater pipes has been reviewed in [2] [3] [103].

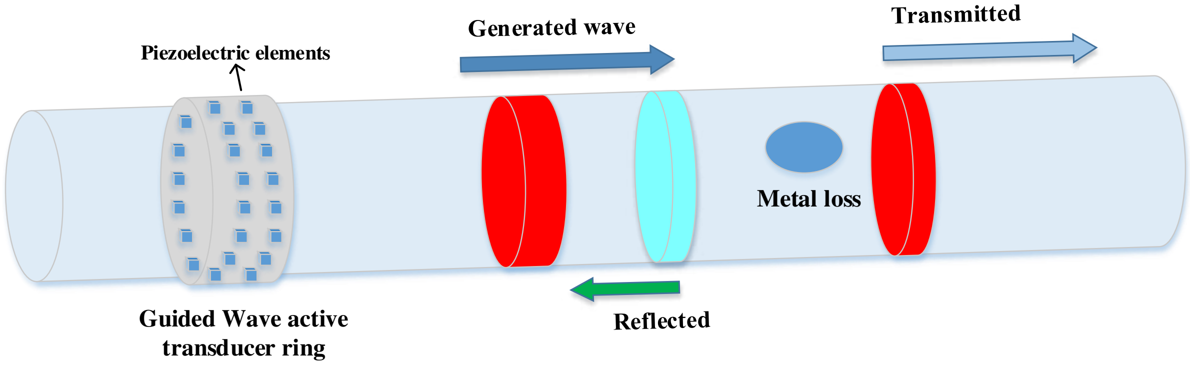

Figure 9. Illustration of guided wave testing on pipes

As well as the pipe material itself, the media both inside and outside the pipe has a dramatic effect on the guided wave propagation [104] [105] [106]. Rose et al. [107] showed both experimentally and theoretically that in the case of wave propagation in a 5 mm outer radius steel tube, external water loading leads to an increase mode attenuation. Lafleur and Shields [108] have studied the propagation of low-frequency axisymmetric wave modes in liquid-filled tubes. The experimental system consisted of a 313 cm long, 5.08 cm inner diameter, 1.27 cm wall thickness aluminium tube filled with water. A signal pulse at the centre frequency of 17 kHz was excited using a PZT transducer and this led to excellent experiment-theory agreement in terms of the phase velocity as a function of frequency (i.e. the dispersion curves) and this showed the effects such as liquid loading could be accurately modelled. Aristégui et al [105] addressed energy leakage by both longitudinal and shear waves which leads to very high attenuation rates when the pipe is embedded in a solid media. The experiment was carried out using a copper pipe having inner radius 6.8 mm and wall thickness 0.7 mm. Measurements in pulse-echo mode using a 250 kHz longitudinal transducer were used to excite longitudinal wave modes propagating distances between 0.8 and 2 m. Plona et al. [106] described a set of axisymmetric modes that are characteristic of the “fluid” cylinder inside the steel and a set of modes characteristic of the pipe-like structure (e.g. cylindrical shell) plus fluid outside the steel. The attenuation and dispersion curves were verified successfully using a PZT ring source (50-240 kHz) as transmitter and a movable ring receiver on a steel cylindrical shell with an outer radius of 9.53 mm and an inner radius of 7.94 mm. The case of external ground loading [109] was shown to reduce the amplitude of the guided waves and hence limit the inspection range. Alleyne et al. [110] showed a field test using at 21 kHz, in which corrosion on a 254 mm outer diameter steel pipe passing through an earth wall was found. The test operating range was 50 m (25 m in each direction) and the sensitivity of the inspection system reduced (compared to the over ground case) to about 10-15% cross-sectional loss because of the higher attenuation through the buried section. Demma et al. [111] reported a 203.2 mm outer diameter buried steel pipe under guided wave testing and suggested that the range of the inspection sometimes can be reduced to about 5 m on either side of the system due to limiting factors, such as the conditions of pipe, coating and soil. Lebsack [112] also introduced wave propagation through a 27-40 m buried pipe. The high attenuation of guided waves in buried pipes was shown to depend on the variable conditions of the pipe, coating, soil moisture content and soil type. Long et al. [113] [114] studied the attenuation of the fundamental non-torsional modes that propagate down buried iron water pipes. Whilst attenuation was not a key limiting factor in many metal tubes/pipes, it was high in the other common materials, e.g. HDPE [70] [115] [116], and concrete [117] [118]. Chan and Cawley [115] have studied the influence of material attenuation on the guided wave dispersion behaviour in HDPE plates. They chose a frequency range of 0.1-0.3 MHz in the guided wave experiments following bulk wave experiments at 2 MHz. A pitch-catch guided wave inspection was carried out on a 12.7-mm-thick HDPE plate at 137 kHz. Na et al. [119] used cylindrical guided Lamb waves to inspect the concrete–steel interface. In their experiments, the transducer–receiver arrangement on the concrete surface to excite guided waves at 50 kHz can be used for detecting interface delamination in 76.2 mm or 127 mm thick concrete.

At sufficiently high frequencies (i.e. short wavelengths) surface waves can exist on the internal pipe walls (often called a Rayleigh wave, or leaky Rayleigh wave, depending on the energy leakage into the surroundings). Yew et al. [120] demonstrated the use of Rayleigh waves for the detection of a surface-breaking crack (0.6 mm thickness slot) on an aluminium plate. Zerwer et al. [121] and Song et al. [122] examined the use of Rayleigh waves for the detection and sizing of surface-breaking cracks in concrete beams. The results showed that by combining information from Rayleigh wave dispersion and energy dissipation, it is possible to determine the location of surface-breaking cracks. However, the sensor coupling conditions on rough concrete surfaces limited the test accuracy and application of this technique.

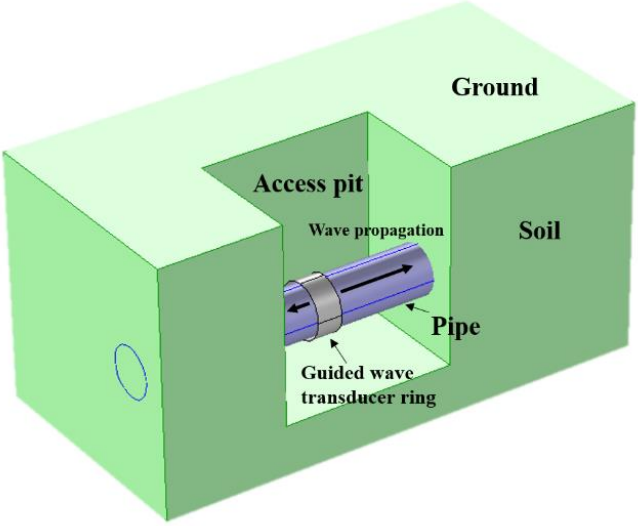

Figure 10. Schematic of guided wave testing on a pipe buried in soil

The air-coupled ultrasound was used by Kee and Zhu [36] [123] as a solution to the sensor coupling problem. Musolino et al [124] investigated Rayleigh waves to detect the presence of voids in masonry using one transmitter that generated a transversal (shear) waves in the frequency range 4-128 kHz and multiple receivers. They showed that this configuration allowed wave propagation up to 4 or 5 meters. The region under test can potentially be enlarged by using an array of transducers [125] [126] [127].

The available commercial guided wave systems for above ground pipe inspection can also be applied to water/sewer buried pipes. However, the high attenuation of guided waves in buried water pipes limits a test range and access to this system from outside is difficult or impossible. Clay and concrete sewers are laid 1-2 m long pipe sections with a very high attenuation at their joints. In this respect, a robotic sensor platform operating from the inside of the pipe could be ideal to deliver ultrasonic sensors to generate and record signals over a plurality of positions. Several autonomous robots could cooperate to regularly measure the spatial response of the pipe from which its condition could be reconstructed with high fidelity [9]. This mobile robotic ultrasonic guided wave transducer system could extend the testing range to potentially inspect the whole pipe network with guided waves. This system could excite guided waves through the fluid filling clean water pipes or via a mechanical contact with the surface of largely air-filled sewer pipes.

4 Accuracy of the methods to water and sewerage applications

For sewerage pipes, airborne acoustic waves have been extensively to localise and characterize blockages with a stated accuracy of the order of several centimetres over a range of 100 m [7] [50] [128]. The accuracy and performance of this method mainly depends on the ability to measure the temperature and cope with a relatively high attenuation caused by the rough clay and concrete pipe walls which is typically 0.1-0.5 dB/m [10].

Accelerometers, hydrophones, and fibre-optic sensors have been used in water pipes for leakage detection. For different pipe materials, the accuracy achieved by these sensors varies due to the differences in wave propagation conditions in the surrounding soil and uncertainties in the pipe thickness and material. The US EPA report [129] suggested that commercial leak correlators based on a pair of accelerometers can detect the location of a 10 mL/s leak in a cast iron water supply pipe and locate it to within several meters. A pair of sensitive hydrophones were reported to detect a 30 mL/s leak over a kilometre away [129]. The elastic waves in a plastic pipe wall attenuates much more quickly than in a cast iron [6]. Therefore, leakage signals that travel along the pipe-wall and are measured with an accelerometer can be less sensitive compared with signal travelling through the internal fluid and detected using hydrophones [12]. Therefore, accelerometers attached to a plastic pipe are unlikely to detect leaks which are further than 50-100 m away from a hydrant [9] [130]. FIDO technology [131] on their website claim the 92% accuracy of the detection using their sensors and AI algorithms.

Fibre-optic sensors installed on a length of water pipe can provide an effective sensing but also have the highest installation cost compared with accelerometers and hydrophones. The authors are unaware of any fibreoptic cable sensors installed permanently in the field and it is difficult to find any reliable figures for the range or accuracy of leak detection using fibreoptic cable. The accuracy of the fibreoptic cable sensing technology developed for sewer inspection by nuron Ltd. The company claim that their technology [132] is capable to monitor flow conditions with a 5 m resolution.

Ultrasonic transducers have been installed on PIGs [102] that can measure remaining wall thickness as well as cracking within a wide range of pipeline systems, including water and sewerage applications. Such PIGs use ultrasonic bulk waves and so the accuracy of the inspection depends on the pipe materials (speed of sound and attenuation) and geometry (thickness and diameter). For example the PIG described in [82] can move at speeds up to 2 m/s, taking measurements at intervals of 3 mm. For water applications, the ultrasonic transducers can be manufactured to measure the thickness of plastic pipes (e.g. PVC or PE) to millimetre accuracies using high frequencies, i.e. 1 to 5 MHz [102]. As they use the same frequency range, developments such as phased arrays can be expected to be directly transferable to water and sewerage applications. This would lead to the ability to produce high resolution volumetric imaging on the pipe-wall material. However, phased array also necessitates the need to transfer and process significantly more data.

Existing ultrasonic guided wave systems were originally designed for use for above-ground pipe inspection frequencies between 20 kHz and 1 MHz for long-range (i.e. many tens of metres) or shorter-range (typical 0.5 m) detection. The main application area has been in the oil and gas sector where the pipes are made of mild steel and external access is often possible. The sensitivity of this type of system in typical above-ground oil and gas applications is in the region of 3−5% [101] [102] metal loss of the pipe wall cross-section. The accuracy and range of the ultrasonic guided wave technique is closely linked to the excitation frequency and to some extent to the wave mode. The operating frequency is critical as the attenuation in PE and concrete is high and increases with frequency according to a power law relationship. Where these systems have been used to inspect buried pipes, the range was usually limited to a few metres due to the significant attenuation of guided waves [111]. Use of lower frequencies can extend the inspection range, but at the cost of sensitivity and accuracy. There is potential for further optimisation by choice of wave mode, which could be chosen specifically to reduce the losses into the surrounding soil media [91]. Considering the available literature, it is possible to hypothesise that similar accuracy (as is possible in the oil and gas sector) could be achieved in the water and sewerage application, but with a much reduced inspection range.

5 Conclusions

In this paper acoustic and ultrasonic methods for condition monitoring of underground water and wastewater/sewerage pipe networks have been reviewed. Although traditionally these methods have been applied to pipes manually or installed on human-controlled robots, they are well suited for being used in combination with autonomous inspection robots for detection of the onset of in-pipe defects. Appendix A provides a critical summary of these methods in terms of their industrial applications to the inspection of clean water/sewerage pipes, advantages, limitations and potential for deployment on autonomous robots. Appendix B presents a summary describing their suitability for application to pipes made from different materials.

It has been shown that some acoustic and ultrasonic methods for blockage and leakage detection, localisation and characterisation are now widely available in a range of commercial products and open great prospects for being used in combination with autonomous robots. It has been discussed how traditional inspection methods based on accelerometers, microphones, hydrophones and ultrasonics are well suited for being used in combination with autonomous robots. Hydrophone and accelerometer sensing from the inside of a pressurised clean water pipe is highly attractive to detect leaks. Microphone sensing is well suited for being used in a partially filled sewer pipe to detect blockages, wall damage and infiltration. Ultrasonic sensor arrays are well suited to measure the pipe wall thickness loss and to detect cracks, corrosion and poor joints from within a pressurised clean water pipe. A distributed ultrasonic guided wave transducer system installed on several autonomous robots could generate and record signals over a plurality of positions operating from inside of a clean water or sewer pipe. These robots could cooperate to measure the pipe condition and over time build up an extensive picture of the state of the pipe network.

Distributed fibre optic sensors are well suited to detect the leakage noise in a clean water pipe. These systems are capable of detecting multi-leaks with a low SNR and in the presence of high measurement uncertainty. Fibre optic cables can be used in combinations with autonomous robots to help to navigate them and communicate between them. However, these systems are relatively expensive to install.

Data-driven methods using advanced signal processing and machine learning techniques are well suited for post-processing and real-time detection of change in the pipe conditions. These methods can make sense of big data collected by autonomous robots and help robots to prioritise inspection of those sections of buried pipe network which is particularly vulnerable to change.

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Appendix A. A summary of sensing technologies for buried pipes and potential for their applications on autonomous robots.

Sensing technique	Industrial application on water/sewerage pipes	Advantages	Current limitations	Potential for deployment on autonomous robots	Accuracy of the localization of defects
Accelerometer	Acoustic leak detection logger [133]	Non-invasive sensing. Low cost.	Short-range detection on plastic pipes.	MEMS are very small in size, high sensitivity, low data rate, low cost and easy to integrate within the body of a robot.	Less than 1m detection error for leakage detection [12]
Microphone	Sewer inspection [128]	Non-invasive sensing over a long pipe section.	Hard to water-prove, can be easily damaged or blocked by debris.	MEMS are very small in size, high sensitivity, low data rate and low cost. They need to be left open to the atmosphere in the sewer.	Less than 0.2m mean detection error for blockage detection [38]
Hydrophone	Smartball and Sahara [134]	Mobile measurement. High SNR.	Need to be inserted through an opening in the pipe. Sensitivity depends on size.	Hydrophones are relatively compact in size but require direct contact with the fluid. Piezo-ceramics has a relatively high sensitivity and low cost.	Less than 0.5m error for leakage detection [12]

Fibre optic detection	Fotech [135] nuron [132]	Non-invasive sensing High sensitivity	High installation costs. Need protection and containment systems	Cannot be deployed on robots, but can be used to support robot navigation and communication.	0.07m error for leakage localization [43]
Data-driven methods	N/A	Using experimental data only	Requirement of massive measurement data for system training High computational cost for real-time processing	Algorithms for multi-leaks can be used to analyse bid data collected by robots and uploaded on robot brain or hubs to pre-process information.	-
Ultrasonic bulk wave sensors	SONOTEC [102]and Ultrasonic PIG [82]	Mobile measurement. High sensitivity.	High installation costs. Require good coupling with the pipe wall. Multiple sensors on PIGs are heavy and require manual loading. Unlikely to work in a dry sewer.	Piezo-ceramic sensors are relatively compact to integrate on small robots to work in clean water pipes. An autonomous robot can work over a longer period of time to take measurements with small number of sensor elements	

				to cover a large area of pipe.	
Ultrasonic phased arrays	Phased Array Flaw Detectors [136]	High sensitivity. Fast inspection speeds. Available in a wide range of materials.	Short range and require good coupling with the pipe wall. Unlikely to work in a dry sewer.	As above.	
Ultrasonic guided waves	Wavemaker [99] and Teletest FOCUS+ [100]	Long-range detection. Provide close to 100% screening of the pipe wall	A sensor array needs clamping on the outer pipe surface only. High attenuation on non-metallic materials. Sensors must contact with pipe surface.	Autonomous robots can carry a limited number of ultrasonic sensors to repeat measurements from inside the pipe at discrete locations to emulate the work of a clamped sensor array. Robots can close on potential defect to ensure a good SNR.	

Appendix B. A summary of the classification of acoustic and ultrasonic methods for different pipe materials.

Material / Sensor	**Cast iron**	**Plastic (PVC, HDPE, MDPE)**	**Concrete**	**Vitrified clay**	**Brick**
Acoustics [G,B,L]					
Accelerometer [G,B,L]	[19] [20] [21] [137]	[9] [12] [16] [17] [18] [137]	[138]	-	-
Hydrophone [G,B,L]	[24] [139]	[6] [12]	[50]	[140]	-
Data-driven method [G,B,L]	[137]	[47] [18] [48] [49] [51]	[50]	-	-
Fibre optic sensor [G,B,L]	[39] [132]	[141] [132]	[142] [132]	[132]	[132]
Ultrasonics [I]				-	
Bulk Wave [I]	[143]	-	[144] [145]	-	-
Phased arrays	[136]	[87]	-	-	-
Guided wave [I]	[113] [114]	[115] [146] [116]	[117] [118] [119]	-	[126]

* G = geometry, B = blockage, L = leakage, I = integrity, O = operational