A Review of Inspection Methods for Continuously Monitoring PVC Drinking Water Mains

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Abstract—**The drinking water mains, mostly buried underground and stay there for decades, require proper maintenance to prevent failures. Among different kinds of material, polyvinyl chloride (PVC) has been widely used due to positive features such as high durability, corrosion resistance, low price, and easy installation. To the best of our knowledge, this is the first paper that reviews the inspection methods toward continuously monitoring the structural health of PVC drinking water mains. To understand which properties need inspecting, we first investigated the attributes that influence PVC pipe and joint failures. Then, we reviewed the methods that have already been applied or can inspect these influencing attributes. We categorized the prospects into five groups: sound wave, fiber optic sensing, hydraulic monitoring, multiple discrete sensors, and other inline methods. Finally, we discussed the possibility and challenges in implementing these methods into a continuous monitoring system of PVC water mains for early failure warning. The result, which includes active sound wave, fiber optic sensing, hydraulic vibration, multiple discrete sensors methods, can help future researchers select the appropriate methods to develop the continuous monitoring system for the PVC water mains.**

Index Terms—**drinking water mains, PVC pipe, pipeline inspection, continuous monitoring, early failure warning, leak, pipe crack.**

I. INTRODUCTION

GRADUALLY, polyvinyl chloride (PVC) has become the dominant material in the Dutch drinking water mains due to its many advantages such as high durability, resistance to many chemicals, low price, and great flexibility [1]. Although more reliable than other pipes [2], PVC mains also become old and defective. They need proper maintenance so that defective pipes can be replaced to prevent failures (leaks or pipe breaks), which are costly because of water loss and interruption to community activities. Replacing mains is also costly due to the groundworks, while early replacement is wasteful. Therefore, the water utilities must evaluate the mains' structural health and assess the remaining time before failure for on-time replacements.

Prediction models are used to predict failure probability and estimate the structural health of a pipeline section for on-time replacements [3]. These models, however, still have significant challenges in estimating the structural health of individual sections. One of these challenges is collecting data of influencing factors, including the physical state of mains, environmental condition, and internal operation. These data can be collected through physical inspection of the mains, but because mains are buried, inspecting all pipeline sections is difficult and costly. In recent years, thanks to the developments of the Internet of Things, new inspection techniques have enabled cost-effective continuous monitoring systems [4], [5]. These systems are implemented with permanent sensors integrated into the pipeline that are connected as a wireless sensor network. Inspection data are then fed into a prediction model to estimate a pipeline section's health and generate an early failure warning for on-time replacement.

In this paper, we review the state of the art in inspection methods for PVC mains. Furthermore, we evaluate their suitability for being integrated into continuous monitoring systems. Previous reviews have looked at various types of inspection methods for all kinds of materials [4]–[10]. Though proven efficient in metallic and cement-based pipes, some may not be suitable for PVC mains. For instance, electromagnetic inspection requires a conducting layer that is not available in PVC pipe. As for the remainder, their applicability to PVC mains is still questionable. For example, ultrasonic inspection, which is useful for measuring wall thickness of metallic and cement-based pipes, is meaningless for PVC because of its immunity to corrosion and abrasion. There is a need for a review of these methods to evaluate their applicability in PVC mains for future research.

In this review, we address the following three questions:

- Which attributes of PVC mains are important for evaluating structural health?
- Which state-of-the-art methods can be utilized to assess these attributes?
- Which methods can be implemented in a continuous monitoring system for early failure warning?

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Fig. 1. Influencing attributes of PVC mains' failures in a schematic representation: A leak is caused by direct attributes. The direct attributes are initialized by internal attributes and escalated by external attributes.

We first investigated PVC main failures, including pipe and joint failures, to determine attributes that need monitoring. For these attributes, we investigated suitable inspection methods and found five promising groups of inspection methods, including sound waves, fiber optic sensing, hydraulic monitoring, and multiple discrete sensors. Next, we reviewed the state of the art of these methods, focusing on their principle, current uses, prospects, and challenges. Finally, we filtered out methods that can be embedded into continuous monitoring systems for early failure warnings and evaluated their individual advantages, challenges, and prospects.

This paper is organized as follows. Section II identifies the attributes of PVC mains that need monitoring. Section III discusses methods for inspecting PVC water mains. In Section IV, we discuss the advantages, challenges, and the prospect of implementing these techniques in continuous monitoring systems for PVC water mains. Section V contains our conclusions.

II. ATTRIBUTES RELATED TO PVC WATER MAIN HEALTH

In this section, we inquire into PVC mains failures to find critical attributes that reflect or influence the water main's health.

We investigated PVC joint and pipe failure mechanisms described in [11]–[16]. The schematics in Fig. 1 illustrates these mechanisms. A leak is caused by direct attributes initiated by intrinsic attributes and reinforced by the external attributes. Joint leaks are caused by gasket degradation or excessive displacement of pipes [11]–[13]. The displacement starts from pipe deformation due to bending or thermal effects. Pipe leaks are caused by cracks, which mostly follow flaws created during production or installation [14]–[16]. These flaws locally reduce the wall's strength, make it prone to microcracks. These microcracks gradually grow, and the pipe will eventually break under excessive internal and external loads.

Table I summarizes the attributes introduced in Fig. 1, their importance with regard to failures, their location, and occurring chance. The leak attribute is important because it straightly indicates a failure. In addition to that, leak data are essential for the ground truth of failure prediction models [17]. However, evaluating pipeline health based on leaks can lead to inefficient failure prevention because it focuses on limiting consequences rather than on prevention. Other attributes can help estimate the water mains' health prior to the development of leaks. In Fig. 1, the direct attributes directly indicate the pipe's current state. However, to estimate their remaining lifetime, we need to evaluate their future development, which is influence by the indirect attributes, including internal and external attributes. In the rest of this section, we will investigate their impacts to failures, their importance and their required inspected period by looking in the theory and failure reports.

A. Direct attributes

At joints, gasket degradation and pipe displacement are two direct failure causes [11], [12]. The degradation leads to the gasket be failed at the end of its lifetime and induces leakage through the joint's seal. However, this attribute is not an essential attribute for inspection due to it is not the dominant cause of joint failures [12] and the difficulty to access for inspection. In contrast, pipe displacement is an important attribute because it is the major cause of joint failures. Furthermore, because its state can change spontaneously, it needs continuously monitoring. Pipe displacement is the rotational and axial movement of the pipe at the joint. The excessive rotation creates stress that can cause a pipe break or a leakage gap at the gasket, while extreme axial movement

TABLE I
INFLUENCING FACTORS FOR PVC WATER MAIN HEALTH

Attributes	Location	Impact on failure	Importance	Inspected period
Leak	Pipe Joint	Indicates failure	High	Continuous
Pipe displacement	Joint	Leads to leaks	High	Continuous
Degradation	Pipe Joints	Reduces energy absorption of pipe Makes pipe brittle Gasket deterioration and induces leaks	High Low	Periodically Periodically
Pipe deformation	Joint	Pipe displacement	High	Continuous
Crack	Pipe	Lead to leak	High	Continuous
Microcrack	Pipe	Grows into larger crack	High	Continuous
Temperature	Pipe Joint	Brittleness in low temperature Speed up degradation in high temperature Increase ductile-brittle transition temperature Pipe displacement	High	Continuous
Internal pressure: • Dynamic pressure • Transient surge	 Pipes	 Fatigue crack Amplifies cracks	High	Continuous
External stress	Pipes Joints	Amplifies cracks Loosening joints	High	Continuous

caused by pipe bending or temperature expansion pulls the pipe out of the joint.

At pipes, longitudinal cracks are the main failure indicator, and indeed it is an important attribute to be addressed. Moreover, a crack requires continuously monitor its development to predict failure. PVC pipes experience two types of fracture: ductile and brittle [18]. In a ductile fracture, the pipe deforms to absorb the energy before failing. Consequently, ductile cracks are often small as the impact energy mostly transfers into ductile deformation of the PVC. In a brittle fracture, the pipe becomes more rigid and does not deform, by contrast. The energy imposed on the pipe transfers directly into crack propagation, leading to larger and longer cracks. In PVC mains, brittle fractures are major failures, which may happen in three stages: creation of weaknesses, slow ductile crack growth, and fast brittle fracture [15]. These failures mostly result from flaws created during pipe production and during installation [14]. In the second stage, under extreme loads, these flaws develop into microcracks or craze, of which widths are typically less than $10\,\mu m$ [19]–[21]. The microcracks sufficiently reduce the wall's fracture toughness. They gradually develop to larger cracks in ductile mode until satisfying specific conditions of pipe age, crack size, temperature, and loading. From this point, the cracks will progress into the third stage, in which their size increases quickly in brittle mode and becomes leaks [22]. As a result, identifying crack size for prediction purposes is only useful in the second stage, where the growing speed is slow. However, determining the threshold size beyond which a crack suddenly increases to a leak is challenging because there are multiple influencing factors besides the crack size, including pipe properties, temperature, and loading.

B. Internal attributes

The internal attributes are related to pipe properties. At joints, it is pipe deformation. The deformation can be thermal axial elongation and contraction, or pipe rotation due to uneven ground settlement. Pipe deformation generates forces that make pipe displace [12]. The pipe's displacement and deformation are interchangeable so that we can estimate one from another. Therefore the pipe deformation is necessary to be addressed when measuring the pipe displacement is difficult.

At pipes, the internal attributes are degradation and microcracks. They play as initiators of the failure. Though the pipelines are designed with loading margins that can withstand extreme conditions [23], the initiators sufficiently reduce these margins and make them prone to failures [15], [19]. Microcracks concentrate impact stress at their sharp tips and reduce the local wall's toughness significantly [15], [24]. Degradation resulting from aging reduces pipe toughness [25]. Because pipeline failures mostly start from these initial attributes, they are essential to be addressed. However, whereas microcracks can develop quickly to leaks and need continuous inspecting, the degradation process takes place gradually from 60-100 years before failure and just require periodical inspection [26].

C. External attributes

The external attributes represent the influence that the environment exerts on the mains, such as the effects of temperature and loads, which gradually escalate the pipe's flaws into failures during long-term operation.

a) The temperature effect The temperature substantially influences the performance of PVC pipes. High temperature increases the speed of degradation, whereas low temperature reduces the toughness of the pipe wall [25]. In PVC water mains, the pipe temperature is usually below 20°C, so high temperatures rarely affect pipes [27]. On the other hand, the low temperature has a significant influence on PVC pipe performance. A higher failure rate in extreme winter was reported by Wolset al. [28]. This influence is two-fold. First, at low temperatures, the freezing and contraction of the surrounding soil induce additional axial stresses on the pipe wall, which could be damaged if the aggregated stress exceeds

Fig. 2. Different possible acoustic inspection techniques for PVC mains depicted graphically.

its material strength [16]. Second, PVC material becomes more brittle if its temperature dips below a specific temperature, which is around -10°C to -5°C for new pipes, the so-called ductile-brittle transition temperature [25]. In work by Arsénio, the lowest encountered temperature for buried PVC pipes was 5°C, even though the corresponding air temperature was -10°C [27]. This temperature (5°C) is above the ductile-brittle transition temperature (-10°C to -5°C), so in theory, this pipe was in ductile mode. However, in reality, the transition temperature can shift upward as a result of aging and high-temperature storage before installation. In theory, three years of storage at 23°C can add 5°C to the ductile-brittle transition temperature [25]. In addition, residual stresses in the pipe wall, inevitably created during production, can also increase the transition temperature [29]. Moreover, extreme winter temperatures can be lower than -10°C and bring down the pipeline temperature. All these influences combined can cause the pipe temperature to reach the transient temperature, making it prone to brittle failure.

At joints, temperature variations cause expansion and contraction of the pipe. For each 10°C increase in temperature, a 10-m-long pipe elongates by about 5.4 mm and vice versa [30]. Therefore, for a temperature decrease of 20°C, a 10-m pipe's length shortens by about 11 mm. Such a length reduction can lead to a leak if the pipe has an insufficient reserved length as a result of improper installation or has become bent.

b) Loading effects: During the operation stage, loads from various sources, including internal pressure and external stress, regularly impact the pipe wall [31]. These impacts gradually escalate the existing pipe flaws to cracks and eventually to leaks.

An essential loading attribute is the internal hydraulic pressure. A higher number of PVC pipe failures due to the high and fluctuating pressure in the report [28] proves the importance of the internal pressure. It induces hoop stress on the pipe wall and must be between a minimum and a maximum value, depending on diameter and wall thickness [32]. High pressure generates more stress on defects and causes frequent failures [33]. In addition, transient pressure surges frequently occur whenever a sudden change in operating conditions due to rapid valve closing, pump initiation, or hydrant operation [34]. The transient surges are significantly higher than the normal pressure and can escalate existing defects into failures, especially at low temperatures when the pipes become more brittle.

Another internal stress effect on pipe failures is material fatigue caused by internal pressure fluctuations during their lifetime. The fatigue forms under cyclic stress with amplitudes exceeding a threshold called the endurance limit. It leads to failure when a finite number of cycles is reached [35]. In drinking water distribution, the fluctuating amplitude of hydraulic pressure is small and, in theory, does not exceed the endurance limit [32]. Nonetheless, the presence of microcracks can substantially increase the stress concentration at these points beyond the endurance level [34], [36]. Furthermore, the aggregated stresses from different sources such as pipe bending, residual and external stress can make the mean amplitude of the oscillation approach the endurance limit, which then can be exceeded more easily and cause fatigue. There is a positive linear relationship between the longitudinal break rate and pressure fluctuations [34]. Therefore, internal stress caused by fluctuating pressure can significantly contribute to the failure of water mains.

Yet another crucial internal attribute is the result of external stresses, such as those caused by the surrounding soil, tree roots, vehicles, and impacts by third parties [16], [28], [37], [38]. Interactions with the soil are the main source of external stress; the soil's contraction or expansion caused by temperature variations induces significant stress and causes pipes to deform or break [16], [28]. Furthermore, pipe deflection due to non-uniform ground settlement or groundwater fluctuations also produces bends and creates stress on pipes and joints [13], [38]. Impacts from tree roots were clearly explained by the higher failure rates with increasing wind speeds and storms in the Netherlands in et al. [28]. Heavy vehicles can create dynamic loads on pipes and make them vibrate. Groundwork can directly damage pipes or indirectly affect them through ground movements after completing the work and making pipes prone to future failures.

Fig. 3. Noise correlation technique for acoustic leak detection. A leak generates noise, which travels toward the sensors. A correlator compares the leak noise's arrival time to locate the leak.

III. PVC PIPE INSPECTION METHODS

Inspection techniques for drinking water mains have been developed in the course of decades. Most of them are still geared toward materials like metal or cement-based. To identify suitable methods for PVC mains, we examined existing reviews of inspection methods for water mains in [4]–[10] and eliminated unsuitable ones, such as electromagnetic inspection. We used keywords from Table I to search for publications about inspection methods for PVC mains. In addition, we also analyzed potential methods that had not been investigated yet to our knowledge. We ended up with a selection of methods that fall into five categories: sound wave, fiber optic sensing, hydraulic monitoring, multiple discrete sensors, and other methods.

A. Sound wave methods

Sound wave methods analyze vibrating waves that are generated or changed by pipe defects. The frequency range of these waves falls between 20 Hz to 5 MHz. Sound wave methods can be divided into two categories: passive and active methods, as Fig. 2 shows. In passive methods, the waves are induced by uncontrollable events such as leaks and excavations. In active methods, a controllable source induces the wave on the pipe wall or liquid medium. Table II lists the techniques used in sound wave methods and compares them in terms of defect types, advantages, disadvantages, and types of sensors used in the studies we looked at.

1) Passive sound wave methods: The passive vibration method measures the noise induced by the pressure fluid's interaction with the pipe through the leak. Traditionally, a person would travel along the suspect area, stick a rod with a sonic amplifier into the ground or fittings, and listen to abnormal sounds to identify the leak. This work relies heavily on human skills and, therefore, is costly and time-consuming. Moreover, due to the fast attenuation of high-frequency waves in PVC mains, this technique's detectable frequency range is limited to below 100Hz, which is difficult to detect by human ears [92]. Meanwhile, human ears have been replaced by vibration sensors integrated on above-ground noise analyzers and inline listening devices.

a) Above-ground noise analyzers: Above-ground noise analyzers are listening devices attached to pipeline fittings, such as valves or fire hydrants. These devices listen to leak-induced noise propagating in the PVC main. Because the high-frequency waves attenuate quickly in this material, the detectable frequencies are below 100 Hz [92], [93]. This method includes two techniques: leak noise correlators and leak noise loggers [49].

Leak noise correlators, as illustrated in Fig. 3, pinpoint a leak by comparing the sound's arrival time (or time lag) from the leak to the sensors at the leak's two sides [7]. The sensors can be accelerometers or hydrophones. Accelerometers are more convenient as they can be attached to the fitting's outer wall, whereas hydrophones must be immersed in water. However, hydrophones have a higher signal-to-noise ratio and can measure both vibration and pressure for locating and sizing the leak, respectively, whereas accelerometers only measure vibration [46]. The sensors' data are fed to a correlator to calculate the time lag. Finally, the leak is calculated from the time lag, the wave velocity, and the sensors' distance.

Several experiments with a test rig located in Ottaw in Canada showed the prospects of this technique [41]–[46]. The authors of that study conducted experiments on a 200m test rig with buried PVC pipes with a 75-mm diameter. They could detect leaks within a 100-m sensor distance. However, the accuracy highly depends on the determination of the time lag and wave velocity. The first factor highly depends on the surrounded environmental noise (e.g., pump operation and reflected wave) and the low-frequency resonance of the pipe [41]–[43], [45]. To reduce the noise, a prefilter can be applied before the correlator [41], [44]. However, in practice, selecting a correct prefilter is challenging because of the pipe's resonance and the non-predetermining effective filter's bandwidth [43], [45], [46]. It leads to complicated practical operations, with many trials needing to be carried out and parameters determined to achieve accurate results. The second influencing factor for this technique's accuracy is the dependence of the sound wave speed on the pipeline structure, the pipe wall's temperature, and the soil's shear stresses [39], [92]. A 10% error in sound velocity estimation leads to a 5% error in leak location, corresponding to 5-m error for a 100-m inspection range [94]. Two techniques can be used to remedy this error, namely the use of artificial sound waves and two correlation runs [49]. The sound velocity is determined by measuring the traveling time for a known distance. For artificial sound waves, actuators are attached at the sensors' locations and sound waves are induced on the other side [94]. The velocity accuracy highly depends on the shaker's coupling to the pipe wall, the investigating bandwidth, and the ratio between the exciting signal and the leak noise [94]. When using two correlation runs, a third sensor is located at a known distance from the second sensor. The technique's accuracy depends on the similarity of the pipeline structures between the two pairs of sensors.

A comprehensive survey test with different commercial equipment of noise correlation leak detection such as Gutermann ZoneScan Alpha, Echologics LeakFinderRT, and SebaKMT Correlux is described in [47]. The simulation field test, including 33-m PVC and 27-m ductile iron pipes, revealed that Correlux yielded the best results. It could detect leaks from 4 to 30 liter per minute, and accurately pinpointed their location to within 1 m as well as the leak rate, with 100% detection and

TABLE II
SOUND WAVE INSPECTION METHODS FOR PVC WATER MAINS

Technique	Detection	Pros	Cons	Sensors
Noise correlation [39]–[47]	Leak	Easy deployment Leak localization	Requires accurate sound speed Low localization reliability	Accelerometer Hydrophone
Noise logger [48]–[54]	Leak	Easy and quick deployment Large inspecting area	Low reliability Difficulty in localization	Accelerometer
Smartball [55], [56]	Leak	Small leak and high accuracy Work well for PVC mains	Large Pipe Diameter May get stuck in pipeline	PZT
Pulse echo [57]–[60]	Crack	Accurate surface flaw localisation	Small inspection area Limit at thick wall pipe	PZT
TOFD [61]–[65]	Crack	Can detect crack on opposite side of thick pipe wall	Small inspection area Can not detect small cracks on the same side of the transducers No research on PVC pipe	PZT
Guided wave [66]–[73]	Crack	Long inspection area	Complicated & unreliable Unaccurate sizing No research on PVC pipe	Array of PZT, MFC
Acousto elastic [74], [75]	Crack Stress	Can measure residual stress	Need baseline of pristine material Only for excavation inspection	PZT
High harmonic [75]–[81]	Crack	Detection does not depend on stress	High harmonics may also come from electronics equipment	PZT
Collinear wave mixing [82]–[85]	Microcrack	Eliminate high harmonic Noise effect	Need contact from sensors and pipe wall	PZT
Noncollinear wave mixing [86]–[91]	Microcrack Degradation	No need for direct sensor contact with pipe wall	Not much research Need baseline of pristine material	PZT

0% false positives. However, in a field test with multiple leaks and sensor distances of up to 15 m, the method's reliability was reduced to less than 20%.

Noise loggers detect a leak by using flexible accelerometers attached to the pipeline fittings and recording the noise in a large area [49]–[51]. This technique is used to detect leaks in a large area to narrow the inspecting zone. A leak is identified as located somewhere between the loggers by anomalous stationary noise that is loud relative to the background noise. Leak size can be derived from the noise amplitude [50]. This technique's weakness is its dependence on the leak noise signature on the pipeline structure, which leads to inaccurate results in a complex network. In recent years, machine learning, especially deep learning, has been successfully applied in data processing to solve complex problems. It is a technique that mimics the human brain's operation, which helps computers learn to solve complicated tasks based on cause and effect instead of algorithms. This approach is also used in processing noise logger data to improve the results [52]–[54] and help locate the leak [95]. These results show that it is a promising direction for efficient leak detection.

Finally, above-ground noise analyzers can be used for detecting a threat from third-party operations on the pipeline. Nam *et al.* used accelerometers for detecting excavation with a hammer or driller near gas mains [48]. After applying a noise filter, they could distinguish the third party's operation with an accuracy of more than 90% within a distance of up to 13 km. Though this research was conducted on metallic gas pipes, the fundamentals can also be applied to PVC pipes with a smaller distance between the sensor nodes.

b) Inline listening device: An inline listening device can travel freely inside the pipeline and listen for leak-induced noise. For instance, SmartBall™ is a free-swimming ball that moves by rolling under the flow of water or oil [96]. It has a piezoelectric transducer (PZT) as an acoustic sensor fixed to the shell, and accelerometers and gyroscopes as navigating sensors. While traveling, the device records data about its movement and environmental noise. The data can then be analyzed to identify a leak's location. A point is considered leaking if it has a sufficient acoustic power increase in a characteristic frequency spectrum [55]. Moreover, for accurate localization, the device also detects the periodic pinging sound pulse induced by an above-ground actuator.

This device's benefits are i) it can travel a long distance in the pipeline within a battery cycle, which can be more than 10 km, ii) in ideal conditions, it can pinpoint the location of a small leak, which can be as small as 1 liter per minute with an accuracy of 2 m [56] and iii) it can overcome the high damping of the acoustic waves that limits the distance that the sound travels in a PVC pipeline. By comparing the change in acoustic power at each point, this technique can identify an anomaly in situ irrespective of pipe material. However, this device also has multiple limitations. i) It has low reliability when in noisy environments, in which the signature of an external operation such as a pump, vehicle, or excavation can be misidentified as a leak [55], [97]. Furthermore, the shell contacting the pipe wall also adds noise to the measured signal, leading to difficulties in small leak detection. ii) Its localization accuracy depends on the network structure and the distance between the device and the above-ground actuator's accuracy. iii) It is only able to work in larger-diameter pipes. Moreover, the device's moving ability must be carefully inspected before starting an investigation, as an incline or obstacle can trap it. iv) Similar to other intrusive devices for use in drinking water systems,

(a) Pulse echo technique (b) Time-of-flight diffraction technique

Fig. 4. Local linear active sound wave methods to detect cracks (a) on the same side of the sensors by identifying power and time of reflected wave and (b) internal and surface macroscracks on the opposite side of the sensors. A beam from the transducer reaches the receiver in 2 to 4 different waves; determining the power and time of these waves reaching the receiver reveals the size and location of the crack.

safe operating standards, such as cleaning, must be carefully implemented to protect water quality.

2) *Active sound wave methods:* Active sound wave methods utilize sound actuators to excite sound waves propagating along with the water. These waves interact with any defects and generate reflected, diffracted, or modulated waves. Receivers measure the products of these interactions to identify the pipe's condition. As opposed to passive methods, active ones can be used for structural inspection and look for degradation and cracks. Active sound wave methods comprise linear and nonlinear methods.

a) *Linear active sound wave methods:* These methods are used to detect cracks of which the size is comparable to the wavelength. The interaction of the transmitted waves at the defect results in reflection, diffraction or amplitude reduction. Their arrival time and signal strength at the receivers inform the location and size of the defects. Linear active sound wave methods can be used for small local and for larger area inspections. In a local inspection, the investigated area between the ultrasonic transmitter and receiver is small, which leads to high accuracy, while an area inspection can cover a larger area but generally with lower accuracy.

The local inspection method consists of two techniques that can be applied to PVC mains: pulse-echo and time-of-flight diffraction. In the first technique, the time and energy of reflecting waves can depict the location and size of a crack as depicted in Fig. 4a. In [59], to detect axial cracks in a metal pipe, an inline inspection device with an electromagnetic acoustic transducer excited ultrasonic surface waves in the circumferential direction. The time and power of the reflected signal made it possible to create an axial pipe image to detect dents. It could detect 100% of all artificial axial cracks down to a depth of 1 mm and a length of 30 mm inside small dents. The field test conducted with this technique found 27 locations suspected of having cracks with one false positive [98]. All true positive results were long cracks of a type of surface corrosion. Four locations went undetected because the cracks were less than 1 mm deep and had a non-axial orientation. Though this research used an electromagnetic acoustic transducer, which is only suitable for metallic pipes, other transducers can be used for PVC pipes, such as PZTs.

The second technique that uses local linear active sound waves is time-of-flight diffraction (TOFD), which can detect and measure inner and outer surface cracks in a thick wall. In PVC pipes, this technique can identify cracks on the surface of a thick wall. Compared with pulse-echo, TOFD has a lower inspection speed but is more accurate in crack depth identification [61]. Figure 4b illustrates the fundamentals of TOFD. A pair of sound transmitter-receiver are on opposite sides of the crack. The transmitter beams a bulk wave at a defined angle into the pipe wall. The signal arrives at the receiver along four paths: the direct propagation from the source (L1), the reflection from the opposite wall (L2), and the diffraction at both sides of the crack tip (L3, L4). The latency between the arriving waves makes it possible to determine the position and size of the defect. If a crack is on the surface, only two of the four paths (L1 and L2, L3 and L4) can reach the receiver; and overlap with the other two paths. If there are minor surface cracks on the same side of the transducers, the TOFD method is not very effective because the discernment between L1 of the good sample and L3 of the defected sample is small [62], [64], [99]. Therefore, it is only helpful in detecting a small crack on the opposite surface relative to the transducer. In a field test with a metal pipe, this technique could detect surface cracks with the smallest detectable depth of 0.5 mm, and a 1-mm accuracy at 80% confidence [65]. Though there has been no research that applies this technique to PVC pipes, to our knowledge, the same principle can be applied to detect cracks in PVC.

Fig. 5. Guided wave technique: an array of transducers induces waves traveling along the pipe, interacting with defects, which causes part of the signal to return to the source. The power and arrival time of these echos are used to reconstruct the pipe's acoustic image.

Local inspection methods, suitable for inline or excavating

(a) Collinear wave mixing technique (b) Noncollinear wave mixing technique

Fig. 6. Nonlinear wave mixing technique: (a) Two parallel incident waves interact at the crack and produce a modulated third wave; (b) Two waves from a different source interact inside the pipe wall and produce a modulated third wave, of which the amplitude conveys the degree of pipe degradation.

inspection, require an inspector to move along the pipe during the investigation. In non-intrusive inspection, where only a part of the pipe is accessible, the area inspection method with the guided wave technique can be used. In this technique, as illustrated in Fig. 5, an array of transducers induces waves that travel a long distance in the pipeline, interact with any present defect, and return to the source [68], [100]. The power and arrival time of the echo to each array element is used to reconstruct the pipe's image to identify the flaw's size and location. This method knows two modes: axisymmetric and non-axisymmetric mode [66]. In the former, a group of ultrasonic waves travels symmetrically to the center of the pipe to detect cracks [68]–[70]. In the latter mode, a wave is steered directly toward the defect location by using a phase array [67], time reversal [71], [72] or synthetic technique [73]. It is used to obtain more information about the defect. It helps narrow the inspection area, thus reducing the noise from other areas and getting more detail of the suspect area. However, the steering is complicated due to the dispersion and differences in wave propagation in the pipeline.

Though the guided wave is a promising method to detect a crack in a large area, it has multiple challenges when applying it to PVC pipe: i) The wave's complex propagation in the pipe makes it difficult to quantify, localize, and size the defect accurately [60]. ii) The transducer array is large and heavy and must be attached to the outside of the pipe, which makes it unsuitable for buried infrastructure. iii) The high attenuation of the high-frequency ultrasound in PVC material limits its inspection range. The efficient frequency for application on metal pipes is often around 5 MHz, which damps significantly in PVC. Bareille *et al.* showed that the 15-kHz torsional wave has decreased by 15dB at 2 m from the source. One solution is to decrease the operating frequency, which leads to an increase in the detectable size of the defect [70].

b) Nonlinear active sound wave method: Microcrack and degradation of PVC pipe are essential attributes for early failure warning. These attributes present as a nonlinear rather than heterogeneous elastic area, which are insensitive to the linear sound wave method [76], [88]. The nonlinear active sound wave method is an advanced method to inspect these attributes, especially for viscoelastic materials such as PVC. This method is based on the nonlinear sonic responses of these defects, including acoustoelastic, higher harmonic generation, and wave modulation effects [101].

The first effect, the acoustoelastic effect, is based on the nonlinear change of ultrasound velocity under static stress. It can measure fatigue rate on the material as well as residual stress on the pipe wall) [74], [102]. Nagy investigated fatigue development by inspecting the second-order coefficient of the velocity during fatigue failure of a PVC specimen [102]. The second-order coefficient changed significantly compared to the linear ones under fatigue development. This makes it possible to detect the early state of fatigue, in which microcracks are small and randomly distributed. Furthermore, it can be used to measure residual stress on the pipe wall [74]. However, this technique requires determining the stress at the inspection area as well as a baseline stress response, which is challenging in practice.

The second effect is based on higher harmonics produced when an ultrasonic wave travels through a nonlinear zone [75]–[78]. The amplitude ratio between these harmonics and the original frequency depends on the size and distance of the fatigue crack [75]. Though much research has been conducted on metal surfaces, this technique has not been tried on PVC yet. Its limitation is the influence of intrinsic effects such as the boundary condition and the non-linearity of electronics equipment that can create higher harmonics [80], [81]. This leads to difficulty in discerning the signal of the defect and intrinsic factors.

The third effect is the interaction of two different waves in the nonlinear zone to produce a third modulated wave. In recent years, wave-mixing techniques based on this effect have shown to have many advantages in microcrack and degradation detection. It lacks some of the limitations of the two previous techniques, such as the stress requirement and unwanted harmonics caused by electronics components [82]. Moreover, wave-mixing techniques can localize a defect by adjusting the delay between the incident waves. Figure 6 depicts two types of wave-mixing techniques: collinear and non-collinear techniques, in which the difference is the orientation of the incident waves.

As for the collinear wave-mixing technique (Fig. 6a), two transducers excite parallel waves that travel along the pipe wall. They interact at a defect and produce a third modulated wave. The modulated wave returns to one of the sources, and its energy represents the crack size [83]. Moreover, this technique can scan the whole specimen area to localize the flaw by applying different trigger times between the two wave pulses [82], [84]. In [85], Hong *et al.* detect circumferential cracks by attaching two PZT transducers on the outer PVC pipe wall to generate two sets of ultrasonic waves. Using the wavelet energy method to process the nonlinear signals, they could discern different crack sizes. Though this approach has some limitations, such as the short distance between the transmitter and receiver (50 mm) and the direction of crack (circumferential, while axial cracks dominate in practice), this technique can work for microcrack detection in PVC pipe.

The noncollinear wave-mixing technique uses two non-parallel waves for the modulation. It makes an easier setup for inline inspection devices than the collinear method, as consistent contact with the pipe wall to generate parallel waves is challenging. Moreover, this technique can identify PVC degradation, to which the collinear technique is insensitive [88]. As illustrated in Fig. 6b, two waves intersect at a certain angle. Their interaction creates a third wave of which the frequency and direction is the vector sum of the original waves [86], [87]. Demcenko *et al.* measured and compared the amplitude of generated waves between pristine and aging PVC specimens. They found that the noncollinear method's result, the amplitude of modulating wave, can demonstrate the degradation more clearly than the linear result, including the change of attenuation and phase velocity. Regards to crack detection, Demcenko *et al.* investigated the interaction of two waves at the kissing-bonded interface between two tightly pressed together PVC plates [89]. The result showed that the contact surface decreases the power of the generated wave. In another study, Lv *et al.* found two new waves generated at the microcrack that together represent the orientation of the crack [90]. However, in this study, the resulting power increases significantly at the fatigue crack zone, which is in contradiction to the work by Demcenko result [89]. This difference can be explained by the different crack sizes used in the two experiments [79]. In Lv's experiment, the fatigue crack was small so that the nonlinear effect is dominant and increases with the crack size. In Demcenko's experiment, the crack was larger; the nonlinear effect decreases with crack size. The first challenge of this technique is the steering of the two transducers aiming at the to-be-investigated zone. A phased array of actuators can be used to adjust the steering angle by sequentially changing the time of each actuator to address this challenge [91]. The second challenge for using this method for PVC pipe is to mimic the defects in studies; degradation acceleration is time-consuming as it takes months to years, and it is difficult to generate microcracks.

B. Fiber optic sensing method

This method uses a fiber optic cable bonded to the pipe wall and continuously monitors the temperature, strain, and vibration [116]. Depending on the application, this method can monitor hundreds of meters to one hundred kilometers in a single cable without electromagnetic interference. A sudden spatial and temporal change in the information coming from the inspected pipe might imply a risky situation. For instance, an anomaly in the temperature or strain can indicate a leak or excessive pipe bending [103]. Table III lists the application, advantages and disadvantages of two main sensing techniques of this method: distributed fiber optic sensing (DFOS) and fiber Bragg grating sensing (FBGS). The former is suitable for a cost-effective monitoring system for a long pipeline, which requires moderate accuracy and resolution over a long distance. On the other hand, the latter is suitable for a short pipeline with high measurement resolution and accuracy.

1) The distributed fiber optic sensing: This technique is based on the scattering effect of light when traveling through a nonhomogeneous area in a fiber optic cable, as depicted in Fig. 7a. Under normal conditions, the light scatters back to the source in a known amount. When traveling through a nonhomogeneous area of strain or temperature, the intensity and frequency of scattering light will vary. Moreover, if using a pulse light, the interval between the source pulse and the scattering will depict the anomaly location.

The distributed fiber optic sensing is typically used to monitor temperature and axial strain of a long pipe, of which the length can be more than ten kilometers, with 1 m in spatial resolution [104], [105]. In laboratory experiments [104], [105] with such range and spatial resolution, this method can detect temperature and strain with a precision of 1 C and 20 . In a practical experiment of a 500-m gas pipeline, this technique measured the temperature at a resolution of 1 C and strain with a resolution of 15 for each 1.5 m length [103]. The result proved this technique's potential for continuous monitoring systems to detect leaks and excessive pipe bending.

In another application, by using an optical cable wrapped along the pipe in a helical form, this technique can measure the hoop strain distribution to identify PVC pipe ovalization, stiffness, and internal pressure [106]. Moreover, it can be used to identify fatigue crack development in a metal pipe through measuring of the hoop strain distribution adjacent to the crack [107].

Measuring the hoop strain requires wrapping the cable around the pipe, however, which is challenging to deploy in the field. To simplify the sensor setup, Wong *et al.* developed the submersible optical fiber-based pressure sensor, which included an optical fiber bonded to a sealed piece of small-diameter PVC pipe. The sensor floats inside the pipeline and measures the internal pressure using the distributed fiber optic sensing [108]. The inner pressure information can help detect leaks through the transient response of hydraulic pressure. Though the experiment was conducted on a 2-m PVC pipe, it showed this technique's potential in pressure-based leak detection.

Distributed vibration is the other application of distributed fiber optic sensing that has gained much attention in recent years. Identifying vibration can increase the reliability of leak detection by temperature and pressure. Moreover, it can also be useful to detect threats from third-party activities.

TABLE III
FIBER OPTIC METHODS FOR INSPECTING PVC WATER MAINS

Technique	Detection	Pros	Cons
DFOS [103]–[109]	Leak Temperature Internal pressure Pipe deformation External stress Crack	Online monitoring for long distance Continuous spatial and temporal measurement Multi-signal measurement in one cable Moderate temperature and axial strain resolution Long service lifetime Immunity to electromagnetic interference Small size	Limited resolution, frequency, multi-point in measuring vibration Long sampling time Complicated setup for hoop strain measurement Difficult to get though valves Reconnecting cut cable change the historical data
FBGS [100], [110]–[115]	Leak Internal pressure Microcrack	Low noise, high sensitivity, quick response Can measure ultrasonic wave Not interfere by physical impact on the cable Immunity to electromagnetic interference Easy maintenance	Local point monitoring High cost

(a) Distributed fiber optic sensing

(b) Fiber Bragg grating sensing

Fig. 7. Fiber optic sensing method (a) A pulse of light travels inside an optical fiber, which scatters a certain amount back to the source. When passing through a nonhomogeneous area of strain, the intensity and frequency of the scattered light varies. (b) A special optical fiber with gratings reflects a narrow band of broadband light to the source. An axial strain of the grating will shift the center of the reflected wavelength. pipe.

Many techniques have been developed for distributed fiber optic vibration sensing [109]. However, it is still challenging to achieve the combination of high spatial resolution, long inspection range, high signal accuracy, and high vibration frequency.

Finally, another distributed fiber optic sensing drawback is that the long cable must be bonded to the pipe wall for measuring the strain and vibration, which makes it difficult to be reconnected when replacing pipes.

2) The fiber Bragg grating sensing: This sensing technique is applied for inspecting a small pipe section, which requires high accuracy and resolution. As illustrated in Fig. 7b, in a special optic fiber, a segment of printed parallel gratings reflects a narrow band of broadband light to the source. Any axial strain of the grating will shift the center of the reflected wavelength. This phenomenon is used to measure the strain and vibration on the pipe [110], [117].

The first application of this method is leak detection based on the negative pressure wave [111] by attaching fiber Bragg grating (FBG) sensors to the outer pipe wall to measure hoop strain. The formation of a leak induces negative pressure in the pipeline and is detected by upstream and downstream sensors. The time and amplitude of these waves to the sensors indicate the leak's location and size, respectively. The sensor's detectable range can be hundreds of meters to tens of kilometers, depending on the pipeline structure, the leakage size, and the sensor sensitivity [112]. Furthermore, multiple FBG strain sensors can be connected as an array in one optical fiber using wavelength or time division multiplexing to extend the range [113]. Though the number of monitoring points on a cable of this technique is far less than the DFOS, the FBG strain sensor has a faster response and higher sensitivity. Moreover, due to the local measuring, it has less noise caused by the unwanted impact of strain or temperature on the connection cable between the sensors.

The second application of this method is microcrack detection, in which the FBG sensor is an ultrasonic sensor. Compared with a PZT sensor, it has higher sensitivity, is less vulnerable to damage, and immune to electromagnetic interference [117]. It can be combined with a PZT or macro fiber composite (MFC) transducer in the sound-guided wave technique to detect pipe cracks [100], [114], [115]. Using the FBG sensor as an ultrasonic sensor can increase 50% the detectable range of the sound guide wave technique [114]. Though these experiments were conducted on metal pipes, a similar principle can be applied to PVC pipe and could be a direction for future research.

C. Hydraulic monitoring methods

These methods measure pressure or/and flow to identify leaks in pipeline networks. Because hydraulic pressure and flow are transported by the water, not the pipe, this method is suitable for any material, including PVC. As listed in Table IV, these methods have two variations: steady state and transient state. The former identifies the leak based on the difference of pressure and flow in long periods, whereas the latter is based on the transient pressure wave.

1) The steady state hydraulic method: This method detects a leak by comparing the change of steady pressure and flow

TABLE IV
HYDRAULIC MONITORING METHODS

Technique	Detection	Pros	Cons	Sensors
Steady-state [118]–[126]	Leak	Continuous monitoring Cost effective	Unable to detect small leaks Long time observation Unreliable in vast network Can not accurately locate leaks	Pressure Flow
Transient-state [7], [127]–[134]	Leak Crack	Continuous monitoring Fast detection	Complicated in a vast network High false alarm rate, hard to detect multiple leaks in macro network Not much research on the hydraulic vibration	Pressure Force sensor Strain gauge Accelerometer

from available sensors in the network. It is called the software-based method, which uses computer software to analyzed data from these sensors by two approaches: model-driven and data-driven approaches [6], [7].

In the model-driven, simulation software first reconstructs the distribution network and generates its hydraulic patterns in no-leak operations [118]. The model requires various information, including pipeline properties (structure, pipe size, and pipe roughness) and nodal demands (pressure and pump operation) [118], [123]. Secondly, the software calculate optimal sensor placement to identify the required numbers of sensors, their coverage, and sensitivity [119], [120]. Thirdly, several leaks are introduced to create hydraulic leakage models, including several sensitive matrices. Each matrix depicts the pressure responses of all nodes of a specific leak [121], [122]. Finally, the residual between the measured and no-leak operation is computed and compared to the predefined thresholds. If the residual exceeds these thresholds, then it will be applied to the matrices in the third step to search for the leak.

This method's first drawback is its dependence on mathematical models, which are difficult to adapt in a complicated and broad network. Moreover, some uncertain inputs, such as pipe roughness, influence its accuracy [123]. Secondly, fluctuation and sudden change in operation generate noise that reduces the reliability and the detectable leak size. Therefore, it is often conducted at midnight when the consumption is low and requires a long observing time. Moreover, the leak localization can only narrow down the failure area to hundreds of meters, including few pipe branches, which limits the speed of the repairing service [124]. Finally, to have good accuracy, the models require optimized sensor placement, which is mostly hard to deploy in practice.

To overcome the limitations in the complicated network, the second approach or data-driven model has prevailed in recent years with the emergence of machine learning. It uses a large amount of historical data to train the system to detect and localize failures based on cause-effect instead of a mathematical algorithm. Thus, it is suitable for a large and complex network that is infeasible with mathematical models [125]. Geelan identified the burst in the network based on the recurring pressure data [126]. He used ML to find the anomaly of pressure compared to the history from multiple network sensors. The result showed that the accuracy is about 92% and 94% for a 2013 and 2017 data set, respectively.

2) The transient state hydraulic method: This method is based on a transient response of pressure waves in the pipeline to detect a fault. The transient response can be sudden negative pressure waves or reflection of transient waves [127]–[130]. For the negative pressure method, right after the leak forms, a negative wave is induced and detected by two sensors at its two sides [129], [130]. The amplitude and the difference in arrival times depict the fault's size and location. The advantage of this method is that it can quickly detect the leak. However, it often has false-positive results due to noise from operations, such as a pump starting or valve opening. As for the transient reflected wave, a pressure wave is deliberately induced by pump operation and valve closing. These waves travel along the pipe, interact with the leak, and back to the sensors. The power and time of the reflected waves depict the leak size and location [127], [128]. The false-positive results are eliminated by repeat multiple times the transient event. However, the detectable leak size must be significant, and the precision depends on the pipe properties such as friction factor, shape, and dimension [131]. Furthermore, this method can detect only a single branch with a single leak, and the detection of multiple leaks on multiple branches is yet challenging [132].

Another approach of this method is permanently integrating a high density of low-cost pressure sensors to the pipeline. It helps to narrow the suspect area. In [133], Sadeghioon et al. attached force sensors as a ring clip to the outer pipe wall. Two clips were placed at a few meter distance, and the difference in their transient response when the leak was introduced depicts the presence of a fault. The advantage of this method is that it can precisely and quickly detect the leak. Furthermore, the degradation of the sensors can be compensated by using relative rather than absolute pressure. However, there was no false alarm that has been reported in this research to give a more accurate picture of its reliability.

Finally, an important hypothesis of the hydraulic methods, but has not received much attention, is the response of a crack to hoop pressure. It can help identify the pipe defect before growing to the leak by using vibration sensors [7]. In another experiment, Al-Sagheer et al. used accelerometers to measure the frequency response of small crack induced by the oil fluid in small PVC pipes [134]. At a crack depth of 3.5mm on a 10 mm wall, the frequency response is linearly correlated with the crack length. Moreover, the crack position and fluid velocity affect the line slope and offset.

TABLE V
MULTIPLE DISCRETE SENSOR METHODS FOR INSPECTING PVC WATER MAINS

Technique	Detection	Pros	Cons	Sensors
Pressure & temperature [135]	Leak	High reliability Simple, quick detection	Unknown detectable range	Force sensors Temperature sensors
Strain gauge & temperature [27]	Joint displacement Internal pressure Temperature	Simple	Unclear Experimental result Battery lifetime	Strain gauge Temperature sensor
RF resonance frequency & temperature [136], [137]	Leak Pipe deformation	No battery requirement	Humidity influences the result	RFID antenna Temperature sensor

TABLE VI
OTHER INSPECTION METHODS FOR PVC WATER MAINS

Methods	Detection	Pros	Cons	Sensors
CCTV [138]–[142]	Leak Large crack	Popular method Simple, visualization Combine with advance computer vision	Human skill dependence Not much research on PVC water mains	Camera
MIT robot [143]	Leak	Small leak Sensitive Long range operation	Not verified in practice	Pressure sensor
Electro-scan [144]	Leak	High reliability	Short inspecting range Require tether	Ground earth impendence
Geopig [145]	Pipe shape	High accuracy	Large pipe only	Accelerometers Mechanical calipers Odometers

D. Multiple discrete sensors method:

This method uses a combination of sensors to improve the accuracy and reliability of defect detection. In recent years, with the development of the Internet of Things, low price and low power discrete sensors can be embedded into the pipeline and connect as a sensor network to collect data. The monitoring signals can be temperature, strain, vibration, soil condition. These signals are useful for detecting leaks, estimating external stress and pipe shape. Table V lists the research using this method for the PVC pipe inspection.

Sadeghioon *et al.* made a wireless sensor network with each node consisting of a ring of pressure strain gauge attached to the pipe wall to detect a leak right [135]. They could quickly identify the leak by comparing the transient pressures between nodes and the temperature of the pipe and adjacent soil. The field test was conducted over six months on a medium density polyethylene pipe, with a 2 m distance between sensors. The result showed that it could detect the leak with high accuracy (92.11%) and no false positives.

As for the pipe displacement at a join, Arsenio *et al.* attached several strain gauges and temperature sensors in a PVC pipe buried underground [27]. They measured the temperature to predict the contraction and expansion of the pipe. Four strain gauges were installed at locations 3, 6, 9, and 12 o'clock of a pipe cross-section to identify in bending rate and then predict the joint displacement rate. Moreover, during their experiment, many water hammers were also detected by investigating the strain data. Their experiment found that one challenge of this method was battery life limitation, especially in cold weather.

Kim *et al.* designed a wireless network using RFID attached to the pipe wall for an inline robot to communicate and navigate while traveling in a pipeline [136]. Furthermore, this network can measure the pipe strain using the shift of RFID resonant frequency [137]. This idea is useful for designing an inline network that can help an automatic inspection robot operate inside with minimum support from humans regularly. However, the strain result can be influenced by humidity, and research is needed on this influence.

E. Other methods:

The other methods are built on the robot or inline inspection, which are listed in Table VI. Most of them are for leak detection, which can help identify the leak size and position more accurately and reliably.

The first one, a tethered device with "close circuit television" (CCTV), can detect macro defects inside the pipeline by capturing images [139]. It could inspect a pipeline with a distance up to 2 km and quickly point out the defect location based on the tether length. This method can detect many defects, such as a leak, crack, blockage, dent, and pipe deformation. Furthermore, a suspicious area can be carefully inspected to reduce fault results. Its limitation, firstly, is the limited tether length, which shortens the inspection range. Secondly, it is difficult or impossible to determine outer defects. Finally, this method highly depends on the inspector's skill in processing the images, and limits the moving speed and increases the cost [138], [139]. In recent years, novel research has applied deep learning and computer vision to improve the accuracy and speed of visual inspection [140]–[142]. Surprisingly, despite much research applying computer vision in the sewer pipeline, there is no research, up to this report's time, applying computer vision to inspect the PVC mains.

An MIT team developed a robot for inline leak detection with a sensitive pressure sensor to detect the pressure difference at a leak location [143]. This technique can detect a small leak with different types of pipe with almost zero false positives. However, the result was obtained from the laboratory experiment and will need to be verified in the field.

The electro-scan method measures the ground impedance of the soil adjacent to the pipe to identify the leak [144]. It is suitable for nonmetallic pipes, especially plastic pipes. Leakage water makes adjacent soil wet and, therefore, reduces the ground impedance. An inline gauge travels along the pipe to measure earth impedance from the inner pipe to the outer ground. If there is a sudden change of impedance, then there is a high probability of the leak occurring at that position. This technique can detect small leaks with almost zero false positives.

Finally, the GeoPig, is an inspection robot for gas pipes [145]. It is equipped with an inertial navigation system, mechanical calipers, and odometers to reconstruct the pipeline's 3D shape. From the system's 3D image, the bending ratio, deformation, and strain of the pipe can be calculated. Though the GeoPig application field is the gas industry, it can also be applied for drinking water mains. However, its operation is limited to large pipes and seems to costly for drinking water mains.

IV. DISCUSSION

In the previous section, we looked into the inspection methods for PVC mains. Here, we will discuss the possibility of implementing them into a continuous monitoring system, where sensors are permanently integrated and continuously collect information. Since the goal is for an early warning system, we focused on detecting leakage threats before leaks occur. They include all the attributes in Table I except the actual leak. Therefore, we scanned through the Table II, III, IV, V, VI cancelling the methods which are only for leak detection and inline inspection. The removed ones include noise correlation, noise loggers, Smartball, steady-state hydraulic monitoring, RF resonance frequency, and inline methods. The final result includes: i) distributed fiber optic sensing methods ii) active sound wave methods iii) the hydraulic method, including vibration and strain effects and iv) multiple-discrete-sensors method.

Table VII summarizes these methods with their detectable attributes, type of sensors, spatial resolution, accuracy, energy consumption, lifetime, cost, and challenges. For the methods (ii-iv), we supposed every 6m of pipe (a standard length of a PVC water pipe) has a central unit. It electrically connects to sensor nodes installed along the pipe to collect data and wirelessly transfer them to centers via a LoRa module. The central unit can be powered from a grid by cable or from batteries. Estimating cost for an electrical system is complicated. Therefore, we supposed the central device powered by a 36 Wh (10 Ah) Lithium-ion battery pack. It sleeps most of the time to save power and only turns on in ten minutes per day. The estimated additional power for this task is 50 mW peak or 0.4 mW average. This central unit would cost about 50-100 USD for a 6 m pipe or 10-15 USD per meter. The central unit's average power consumption and cost are aggregated with the sensor nodes for the total numbers.

A. Distributed fiber optic sensing

This method can continuously measure multiple signals, including pipe temperature, axial and hoop strain, and vibration. Besides detecting leaks within one meter accuracy, the temperature and axial strain can be used to estimate the pipe deformation and displacement, external stress, and internal pressure. Depending on spatial resolution, precision, and reading speed, a line fiber optical cable can continuously monitor from ten to hundred kilometer long pipelines. For instance, it can monitor temperature and strain of every 2m of a 40 km long pipeline, with precision of 1C and 20 [104]. Regarding the vibration signal, this method can locate 1kHz acoustic sources with 2m resolution in a 9 km range [146]. This result is helpful for detecting a leak or a vicinity dangerous operation. As for the hoop strain signal for crack detection, it can detect a crack within a 40mm distance based on the change of hoop strain [107]. However, the cable needs to be wrapped helically around the pipe. This setup leads to a large decrease of the detection range and increases in the cost more than a factor ten, depending on the pipe diameter. Because this method can monitor a long range distance, we assume that it ends at the data center with a power supply for the analyzer. However, for comparison between methods, we use average energy per meter monitoring length, which equals to the analyzer consumption divide the range. The average power consumption is about 5mW per meter based on the power of the device for a 40km range, based upon the specification of a device in [103].

The cost of this method per meter varies depending on range, resolution, and information. For temperature monitoring only, a 40 km system as in [103] costs 3-7 USD, including equipment and sensing cable cost. However, measuring strain requires a special fiber optical cable [147]. Therefore, a system that measures both strain and temperature increases the cost to 20-40 USD. Though the investment cost is high, the maintenance cost is very low because the cable lifetime is at least 60 years and comparable to the pipe lifetime [148]. Therefore, it only requires annual maintenance at the analyzer, where the accessibility is convenient.

The first challenge of this method is the complement between the inspection range, spatial resolution, sensitivity, precision, and response speed [149]. Recently, distributed acoustic sensing gets more attention. Nonetheless, its resolution and precision together with acoustic damping are not sufficient to detect a crack in a long-range system. Secondly, the high price of the analyzer limits it in long-range applications. In an urban area, water mains consist of many branches, which are more suitable for short-range applications.

B. Active sound wave method

This method is used to detect cracks and requires sound actuators and sensors bonded outside the pipe. The actuators can be piezoelectric transducer (PZT) or macro fiber composite (MFC) [85], [100]. Therein, PZT is efficient in inducing sound wave but vulnerable to mechanical impact because of hard surface, whereas MFC is less efficient but flexible because its film form can easily be applied to the pipe surface.

TABLE VII
INSPECTION METHODS FOR A CONTINUOUS MONITORING SYSTEM OF PVC MAINS.

Method[1]	Attributes	Sensors[2]	Spatial resolution	Accuracy[4]	Energy[5] (mWh)	Lifetime (years)	Cost[6] (USD)	Challenges
DFOS	Temperature	lDFOS	2m [3]	1-2 C	5	> 60	> 3-40	Complement of range, resolution, sensitivity, speed, and complexity Complicated re-connection.
	Strain:			20-50				
	• Pipe deformation			Unknown				
	• Pipe displacement			Unknown				
	• External stress			Unknown				
	• Internal pressure		20m [3]	0.1bar				
	Vibration:							
	• Threat by activities		100m [3]	10m				
	Hoop strain for crack	hwDFOS	> 40mm	> 100mm	> 50		> 400	
ASW	Crack	PZT, MFC, PVDF, FBGS	20cm-2m	> 100 m	2	15-40	> 100	Complicated sound wave propagation. High damping characteristics. Transducer's short life time. High energy consumption.
HV	Crack	Acc SG	< 1m	20mm	< 0.4	> 50	15-20	Relation between size and location of crack to the sensors. Influence of temperature and stress.
MDS	Temperature Pipe bending Inner pressure	TS, SG, PG, FS, Acc	1-3m	1 C Unknown mbar	< 0.4	> 50	15-20	Optimal information.

[1] DFOS: Distributed Fiber Optical Sensing, ASW: Active Sound Wave, HV: Hydraulic Vibration, MDS: Multiple Discrete Sensing
[2] lDFOS: Linear Distributed Fiber Optical Sensor, hwDFOS: helical wrapped Distributed Fiber Optical Sensor,
PZT: piezoelectric transducer, MFC: macro fiber composite, PVDF: polyvinylidene fluoride (PVDF), FBGS: fiber Bragg grating sensor,
Acc: accelerometer, TS: temperature sensor, SG: strain gauge, PS: pressure sensor, FS: force sensor
[3] Spatial resolution of DFOS is estimated for a 40 km long single cable.
[4] Accuracy of DFOS is estimated for a 40 km long single cable.
[5] Average energy demand per meter length of pipe and per day. For AWS, HV, MDS methods: each 6m pipe has a central unit that electrically connect to sensors nodes, collect data and send wirelessly to data centers. Wireless communication time is 10 min/day. AWS turns on 10 minutes/day. HV and MDS turn on one minite/hour.
[6] Average cost per meter pipe length.

Regarding the sensors, they can be PZT, MFC, polyvinylidene fluoride (PVDF) and fiber Bragg grating (FBG). Though PZT and MFC can be used as both transducer and sensor, their sensitivity is less than PVDF and FBG [114], [150].The PVDF sensors have an electrical connection and is influenced by the electromagnetic interference, whereas the FBG sensor has an optical connection and is immune to electromagnetic interference [113].

Crack detection requires high-frequency waves, from 1 kHz to 1 MHz depending on crack size. Due to the high attenuation of these waves in PVC material, the range of this method in laboratory experiments was below two meters [70]. Especially for the microcrack detection, which requires above 100 kHz range sound waves, the range is below ten centimeters [85], [89].

The power consumption depends on the applications, which vary with the number of sensors, frequency, inspecting range. For a 10 kHz single PZT transducer to inspect 2 m pipe similar in [70], we estimated the average power is about 100 mW per meter, including the excitation, processing, and communication. If the frequency change to 5 Mhz as in [89], the active power will increase to 2-3 Watt per meter with the transducer because the detection range is short. However, the pipe does not need inspecting continuously for crack detection. It can be turned on say one minute per day and remain off for the rest. Therefore, the total average power consumption per day can be about 0.5 mW to 2.5 mW per meter, allowing it to run from 4 months to 1.5 years.

Regarding the lifetime of the sensors, they can be similar to the life time of the pipeline with proper protection. For the transducer, the faillure from material fatigue, lowering the lifetime must be considered, as the amount of vibration cycles is limited [151], [152]. However, because the inspection time is 1 minute per day, the transducer lifetime can be 15-40 years. It is still shorter than the average PVC lifetime.

We estimated the cost for a simple setup, including 2 PZT of [151] for each 2m distance. A 6m pipe is divided into three sections and electrically connected to a signal generator and analyzer at the central unit. The average cost excluding the mechanical cost is higher than 100 USD per meter. Moreover, the battery replacement every one or two years will increase its operational cost.

Besides the lifetime and short-range, this method challenge is the complicated wave propagating path in the pipeline. It leads to difficulty in signal interpretation.

C. Hydraulic methods

This methods can detect a crack or defect based on the pipe vibration and hoop strain under hydraulic pressure [107], [134]. For the vibration, the frequency is below 200Hz. A low-cost accelerometer sensor node can be attached to the outer wall, with the range of detection is about a meter in laboratory circumstances [134]. For the hoop strain, an array of strain gauges or force sensors can be used to measure the change of strain under hydraulic pressure change. The range of detection could be up to 40mm as in [107]. We can not determine the accuracy of these methods due to the lack of experimental data conducted in the field.

Regarding the accuracy, for the vibration mode cracks longer than 20 mm can be detected. Nonetheless, the experiments were conducted in laboratory conditions, where the pipes were placed on supports. In practice, the pipes are underground, and soil conditions will significantly influence the result. For the hoop strain response, there was no experiment using strain gauges to detect cracks found in literature.

An advanced accelerometer node can draw less than 20 mW. For the strain gauges, they can be read simultaneously. Therefore, a strain node can consume as much as an accelerometer node. With appropriate off time, it can consume very little energy. For instance, a minute on-time per hour can reduce the total average power to less than 0.4 mW per meter, lasting for two years with the central unit's battery.

The lifetime of the sensor with proper protection can be comparable to the lifetime of the pipe. For the strain gauges, serious protection should be considered because they need to be bonded to the pipe wall. In recent years, PVC pipe can be produced in a multi-layered process, allowing a conductive layer printed directly inside the pipe wall. Therefore, strain gauges could be printed as an inner layer, and their life can be as similar to the pipe.

Regarding the cost, a setup including one accelorometer node per meter estimated cost is 15-20 USD. We cannot estimate the strain due to the unknown number of strain gauges needed per circumferential location, which may change with pipe size. This method's main challenge is determining the correlation between the vibration and strain to the size and location of the crack. Moreover, during operation, the change network structure, temperature, and external stress can significantly influence the result.

D. Multiple discrete sensors

The method using many discrete sensors is used to detect a leak and identify external effects on the pipeline, such as temperature change, internal pressure, and external stress distribution. The sensors to measure these attributes are a temperature sensor, strain gauge or force sensor, and accelerometer [27], [133]. Furthermore, accelerometers can be used to detect potentially dangerous activities in the vicinity. Though having a smaller range than the fiber optic, it is flexible for a new node to be added or removed with minimum influence. The spatial resolution of this method is not limited. However, we use the same resolution and precision as what we utilized in section IV-A for cost and energy comparison. In that, the spatial resolution is two meters for temperature, strain in the length direction, and vibration.

Multiple sensor nodes can draw less than 30 mW, equivalent to 15mW per meter, and the total acquisition time can be one minute per hour. The total average power is less than 0.4 mW per meter, lasting for two years with the central unit's battery.

Regarding the lifetime, these modules with proper protection can be comparable to the lifetime of the pipe, which is more than 50 years. For the strain gauges, serious protection should be considered because they need to be bonded to the pipe wall.

Regarding the cost, a setup for a 2-meter pipe consists of two strain nodes for axial and hoop strain distribution, a temperature sensor, and an accelerometer costs 15-20 USD per meter. The challenge of this method is determining the optimal information for predicting the failure in future.

E. Summarizing

Summarizing, four inspection methods are applicable to be implemented in a continuous monitoring system of PVC water mains for failure warning. The first one is the distributed fiber optic sensing, which can measure the most information density about the pipe. It has a long detection range with sufficient resolution and does not depend on battery energy. Therefore, it also requires little maintenance. The investment cost for multiple information is still high. Its main challenge is the complement between range, resolution, sensitivity, and speed. The second method, the active sound method, can be used for small crack detection, including microcrack detection by ultrasonic inspection. This method is expensive and consumes much power. The main challenge of this method is the complicated signal processing to interpret the measurement results to find a crack and the short inspection range due to the high attenuation of high-frequency sound in PVC pipe. Another challenge is the high voltage required for exciting the vibration, which restricts the deployment for safety. However, due to the advantage of microcrack detection, this method deserves attentions to research. The third method is the hydraulic method based on vibration and strain to identify cracks in PVC pipe. The challenge of this method is the high dependency on surroundings. The last method, the multiple discrete sensors, is to collect information from an external impact. This method is more flexible than fiber optic. Their main challenges identifying the optimization of these sensors to acquire sufficient information. The cost of the last two methods is less than fiber optical systems for multiple information acquisition. However, in practice, they require a good protection to environmental attack to be working for decades. Furthermore, the batteries also need to be charged or changed yearly. These two factors makes the cost increase substantially.

V. CONCLUSION

In this paper, we reviewed the inspection methods for PVC mains. This paper is limited to the research or reports that have been published. There are few field testing reports for these methods' reliability, which can be collected through the surveys and internal reports of water utilities. This reliability can be differ between utilities because of different network structures.

We found three groups of attributes that can be inspected to evaluate the PVC main's health:

- Leaks
- Intrinsic attributes including pipe degradation and crack, gasket degradation, pipe displacement, and deformation at the joint.
- External attributes including temperature and loading (internal pressure and external stress)

Most available inspection methods are for detecting leaks. Their present challenges include one to many of these: range and size of the leak, deploying simplicity, reliability, network structure, and cost. Among these methods, non-intrusive methods have received much attention due to deploying flexibility and collecting data continuously. Large data sets can help future research to apply machine learning to improve the results.

Other attributes can be useful for evaluating the remaining health of PVC mains. However, their data need to be regularly collected in a continuous monitoring system due to their temporal variation. There are a small number of available or prospective methods to be applied in this system to inspect these attributes. The challenges of deploying these methods to the continuous monitoring system can lead to trends for future research:

- Regarding the external attributes, they can efficiently be measured with fiber optical sensing and multiple discrete sensors methods. Future research can develop a model to predict the PVC mains' health based on these impacts and the optimization sensor's location to aid prediction.
- Regarding the intrinsic attributes, which directly indicate the defective mains, it is still challenging to detect these attributes, such as crack, pipe degradation, and joint displacement. Future research can improve these current methods or find a new approach, combined with advanced signal processing and machine learning, to efficiently identify these attributes.

Lastly, the investigated inspection methods are based on previous reviews of inspection methods for general pipeline inspection. It may miss other methods that can be efficient approaches. Future research can look for a new efficient approach to detect these attributes, especially the microcrack and degradation.

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