A study on Water Leakage Detection in buried plastic pipes using Wireless Sensor Networks

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Abstract-- This paper focuses on an application of wireless sensor networks for leakage detection in underground water pipes to overcome the problem of water dispersion in water distribution networks. Leakage prevention and breaks identification in water distribution networks are fundamental for an adequate use of natural resources. Nowadays, all over the world, water wasting along the distribution path reaches untenable percentages (up to 80 % in some regions). Since the pipes are buried within the terrain, typically only relevant breaks are considered for restorations: excavations are very expensive and consequently the costs to identify the position of the leakage or just the position of the pipe itself are too high. To address this problem, and simplify the leakage identification process, the authors have designed a wireless network system making use of mobile wireless sensors able to detect breaks and reveal unknown tracks and monitor the pressure spectrum of the fluid flowing in the pipe. The sensors transmit the acquired data from the terrain to the surface by use of a wireless connection. On the surface ground there are stations that receive the signal, process it, and communicate with a central unit where necessary intelligent signal processing techniques are used to detect leakage sources. Compared to other leakage detection solutions already available in the market (such as: Ground penetrating radar (GPR), pure acoustic techniques and tracer gases), the proposed technique appears very efficient and much more inexpensive.

Keywords—Wireless sensor networks, Leakage detection, Leakage prevention, GPR, Acoustic techniques, Tracer gases.

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1. INTRODUCTION

WATER represents a primary necessity, for everybody's *daily* life and for an effective accomplishment of many industrial processes. In the most remote and isolated regions, as in the most urbanized ones, water provisioning to domestic premises represents a fundamental living necessity. At the same time, the lack of water may prevent the development of business activities from handicraft manufacturing to goods transformation and energy production. Water demand is expanding continuously, as a direct con- sequence of the growth of the Earth population, but water re- sources are facing a problematical and constant decrease, caused by global heating and climate changes. Unlike other more peculiar phenomena, water availability decrease is common to developing and developed countries, as well as to northern, equatorial and southern regions. While the protection and improvement of water resources is a complex process based on political long term strategies, water distribution can be enhanced from an engineering point of view, mainly by limiting the water waste that occurs along the path, between the source and the end-users. Some recent publications [1]-[3] show dramatic estimates about the percentage of liquid lost along the conduits, where leakages are mainly caused by generally aged and consequently breakable water distribution infrastructures. Depending on the oldness and degrade of the conduits, the percentage of unaccounted water can range up to 70%, while a percentage of less than 20% is not considered a leak and restorations are mandatory only when the percentage exceeds 50%. The restoration of damaged pipelines is a complex task. First of all, water pipes are typically interred in the ground and typically their path is not known with sufficient precision. As pipes are not directly accessible, the identification of leakages is not obvious and the only information obtainable is an approximate localization, between two consecutive accessible valves, bifurcations, or pressure monitors. Without the use of advanced monitoring technology, the problem is solved by carrying out expensive excavations, over the full pipe path, until the exact position of the leakage position is identified. As a matter of fact, excavate drawback becomes worse and worse, as the infrastructure gets older and older. Service interruption is an auxiliary drawback, and it should be avoided or limited only to the time dedicated to the restoration or replacement.

Consequently, despite the facts that breaks represent a huge dispersion of primary resources for companies and for the social community, the renovations are complex and require long times in order to significantly decrease water wasting. As far as costs are concerned, the first factor is represented by the technological process needed to identify the leakage. Hence, it is strongly related to time drawbacks. As an example, detecting failures by means

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of advanced technology may cost from 30 000 USD/km per day, up to 120 000 USD/km per day, if the damage occurs in a complex metropolitan environment. In general, expenses increase with the complexity of the urban scenario, because of the indirect costs generated by the excavations. Especially when works concern relatively huge areas, there can be an unbearable effect on traffic, public services and business activities. For all these reasons, in the last decades many efforts have been dedicated to the development of monitoring techniques, for the identification of unknown paths and for a fine identification of breaks and leakages. Thanks to these techniques, the restoration costs may be decreased by at least a factor of 10.

2. WATER INFRASTRUCTURE MONITORING TECHNIQUES

Several leakage localization techniques have been proposed and few papers in the literature illustrate comprehensive reviews [4], [5]. Among all these, tracer gases [6] and ground penetrating radars (GPRs) [7] are very efficient since they do not require the introduction in the pipes of probes wired to the ground surface. Unfortunately, they are not suitable to identify small leakages or to survey pipes to prevent damages. Gas tracing makes use of a special gas mixture, e.g., a mix of hydrogen (5%) and nitrogen (95%) that is inserted in the conduit, by replacing the fluid normally transported in the pipe. The gas is subsequently investigated from the exterior, by using special instruments able to detect the concentration of gas in the environment. The system requires service interruption and is very expensive, due to the high cost of the gas itself, together with the gas sensors on the ground surface. GPR, on the other hand, may allow an easy estimation of unknown tube paths, but cannot provide a comprehensive monitoring of small pipe damages.

Accurate techniques make use of pressure or vibration sensors [8], able to detect either ground acoustic waves, or conduit vibrations, or liquid pressure variations, all generated by water losses. Ground acoustic waves are measured by means of geo phones; this technique requires an operator with high professional background and good expertise, in order to identify the acoustic noise produced by losses in the framework of an external acoustic background. For this reason, the technique is critical in urban environments with high background noise. Furthermore, it becomes even more critical in case of large losses and fluids with low hydraulic pressure. Conduit vibrations can be measured in several ways, e.g., with a time-domain technique that makes an analysis of the vibration propagation delay. A correlation technique is applied to two measured acoustic/vibration signals on the pipe, before and after the leak [9]. For this purpose, two different sensors are applied on the pipe surface in separate positions. Synchronizing the sensors and calculating the time taken by the noise to reach the two probes, it is possible to identify the position of the damage. Depending on the mechanical properties of the material used to construct the tube, the technique works on distances ranging from 50 to 200 m.

Hydrophones can be efficiently used to monitor pressure gradients inside the liquid [10]. The sensor moves inside the pipe, following the natural path of the liquid; the acoustic signal is monitored from outside and leakages are identified in correspondence of its spectrum variations. Unfortunately, this technique requires a wired connection between the sensor and the spectrum analyzer outside the pipe. Hence, its applicability is limited to few hundreds of meters from the operator. More recently, it has been possible to deploy hydrophones in the pipe, processing the data on-site, without the need of a further elaboration. In this case, the main drawback is represented by the need to keep the flow of the sensor under control, to re- construct its position and make correlations between the sensor position and the monitored acoustic spectrum [11]. Apart from the last one, all the known acoustic techniques require a wired connection with the sensor on or inside the tube. Therefore, they are inappropriate to investigate pipes networks over long distances. Furthermore, they do not provide useful solutions for the detection of underground paths.

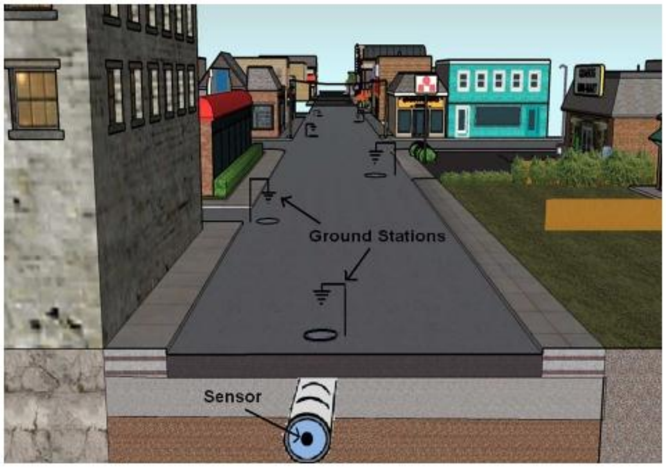

Fig. 1. Wireless sensor network configuration. The ground stations are collocated in fixed or movable positions intercepting the normal direction to the pipe (typically, where manholes are located). Ground stations distribution can be rare or frequent, depending on pipe complexity.

3. WIRELESS SENSOR NETWORK SOLUTION

To overcome the listed drawbacks, an architecture based on use of underground mobile wireless sensor networks is pro- posed, starting from a simple preliminary realization of a microwave sensor published and validated in [12]. It is observed in practice that the wave speed (speed of leak noise propagation through the pipe) varies considerably from case to case, and that this noise does not propagate long distances in *plastic* pipes. These two properties are governed by the behavior of the wave responsible for the propagation of the noise along the pipe. Although there are many waves in a buried fluid-filled pipe, there is only one that generally plays a dominant role in the propagation of leak noise. For a 170 mm diameter MDPE water distribution pipe, the energy associated with this wave is mainly carried in the fluid. It propagates at a much slower speed than in a corresponding metal pipe, typically being around 400 m/s. An experiment was carried out at a special test site, shown in Figure 2, at the University of East Anglia [11]. That publication demonstrates the feasibility of the concept from an experimental point of view, reporting introductory results measured in a single simplified, but realistic environment. In this paper, the concept is extensively examined both with theoretical and experimental approaches. Initially, a simplified 2-D full-wave method is applied to analyze microwave propagation characteristics through the ground. Subsequently, a model applicable to the design of the antenna mounted on the mobile sensor is re- ported. Matching results are validated experimentally, thanks to the use of a dedicated measurement setup. Finally, a complete set of experimental data, acquired in a real scenario, for four different and independent cases of study, is illustrated.

As shown in Fig. 2, the suggested network is made up of ground stations, collocated in fixed or even movable locations, in proximity of known pipe crossing positions. The ground stations are equipped with directive antennas, pointed towards the terrain and communicating with mobile sensors that flow through the pipe network, transported by the liquid. These sensors represent the core of the monitoring system. They are made up of a hydrophone as a sensing unit, and a radio frequency (RF) or microwave radio as a transmitting unit. The wireless component is able to connect to the ground stations, even if it is collocated within the liquid, inside a pipe interred in the terrain. Since the sensor is transported by the liquid under normal working conditions, the proposed solution preserves water provisioning, without the need to take the liquid out of the conduit. The flow of the sensor is controlled by means of hydraulic tricks and kept constant along the path.

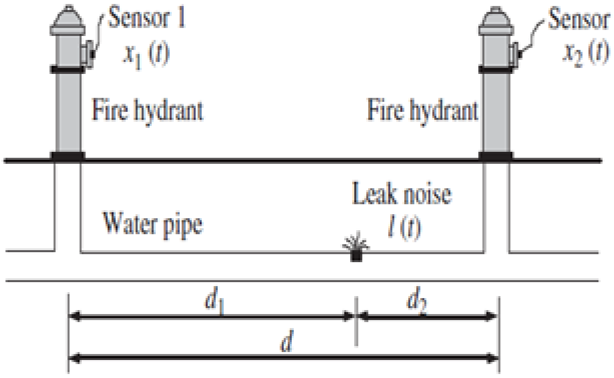

Fig. 2 Schematic of pipe with leak bracketed by two sensors

In this way, it is possible to make real time and continuous pressure acquisitions without the use of wires or cables. Furthermore, when the sensor intercepts a ground station, its position is identified and the acquired spectra are correlated to leakage positions.

A typical measurement layout to determine the location of a leak in a buried plastic pipe is shown in Fig 2. The proposed network scheme allows detecting breaks by monitoring the spectrum of the fluid pressure, and revealing un- known paths, by tracking the sensor movements. The detected information is transmitted through wireless channels; hence, a physical connection to the surface is not required. An accurate detection of the leakage position is provided. An easy and repeatable identification of the track is enabled.

4. CHOICE OF SENSORS AND SIGNAL PROCESSING

Because the amplitude of the wave responsible for the propagation of leak noise decreases both with distance and frequency, the pipe effectively acts as a low pass filter, with the cut-off frequency decreasing as the distance from the leak increases. Thus if two sensors are placed, one each side of a leak, but at different distances from the leak, then the leak noise passes through two different filters. This means that the degree of correlation between the signals will change as the relative distance between the leak and each sensor changes. The worst situation is when one sensor is placed at the leak and the other is placed at some distance from the leak [9]. A typical cross-correlation function calculated from two leak noise signals is shown in Figure 3. The position of the largest peak indicates the time difference between the leak noises arriving at the two sensors, and is the variable Δt. Clearly a peak that that is large compared with other spurious peaks is desirable. A peak value of one would indicate perfect correlation and only occurs if there is no background noise, and if the sensors are equidistant from the leak.

Provided that the background noise at each sensor is uncorrelated, then increasing the time over which the measurement takes place will increase the signal-to-noise ratio (at the rate of 3 dB per doubling of data acquisition time). The other quantity of interest in the cross-correlation function is the accuracy of the time difference estimate and the width of the peak (discrimination). It has been shown that the signal-to-noise ratio has only a marginal effect on the accuracy of the estimate [14]. However, the positioning of the sensors and the type of sensor used can have a significant effect on the width of the peak [14, 15]. Clearly, as the distance from the sensor to the leak increases, the higher frequency components of the signal will be significantly attenuated, resulting in a much smaller signal to noise ratio; this will reduce the height of the peak in the cross-correlation function. Also, because the higher frequency content of the signals is diminished, the ability to accurately locate a leak will be adversely affected because the width of the peak increases.

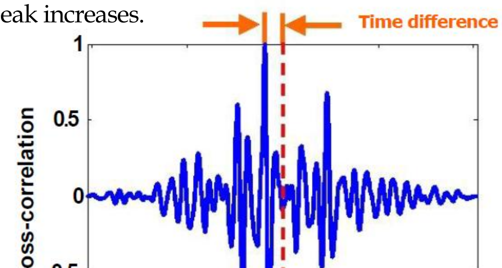

Fig. 3 A typical cross-correlation of two leak noise signals made in a measurement system similar to Figure 1 [7].

The acoustic pressure inside the pipe is related to the radial displacement of the pipe integrated around the circumference, and a sensor that measures this will indirectly measure the pressure. A sensor has been developed based on this principle a few years ago [16], and has been recently modified with the application of leak detection in mind [17]. If an accelerometer is used instead of a pressure or displacement sensor then the filter that the leak noise passes through is modified, because acceleration is proportional to the product of displacement and square of frequency. Thus an accelerometer will amplify high frequencies compared to a hydrophone. So, for better discrimination of the leak location, an accelerometer is preferable provided that it is positioned to sense the fluid wave; a hydrophone or integrated displacement sensor is preferable, however if the signal to noise ratio is small [15].

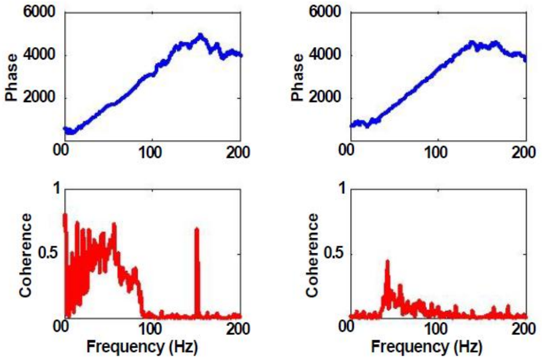

Fig. 4. Comparison between the phase of the cross-spectra and the coherence of two leak noise signals measured on a NRC test facility, Canada [7][15].

The time difference information in the cross-correlation function can be represented as a phase difference in the corresponding cross-spectrum. Examples of the phase together with the coherence between the two signals are shown in Figure 4 for hydrophone and accelerometer measured signals.

The useful information in these plots is the straight-line characteristic of the phase. In both phase plots it can be seen that there is significant background noise for the first few Hz (environmental noise) and also at high frequencies (due to the filtering properties of the pipe). There is always a limited range of frequencies which contains the information on the location of the leak. It should be noted that the coherence is less for the accelerometer measured signals, but the bandwidth is much greater, because of the reasons discussed above.

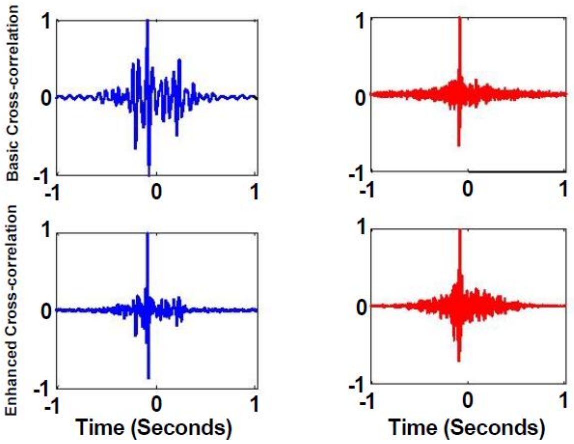

Fig. 5 Comparison of the ordinary and enhanced cross-correlation functions for leak noise measurements made using hydrophones and accelerometers at an NRC test facility, Canada [7][15].

Figure 5 shows the cross-correlation plots for the signals in Figure 4, and illustrates the improvement that can be achieved by some additional signal processing. Four graphs are depicted, two for the hydrophone measured signals and two for the accelerometer measured signals. It should be noted that these are normalized by setting the maximum to unity. For each case the basic cross-correlation function has been calculated and for comparison and enhanced cross-correlation function has also been calculated. The enhancement process involves pre-whitening the signals to remove the amplitude filtering effects of the pipe and weighting the signals at each frequency according to their coherence [14]. The difference between the results from the accelerometer measured signals and the hydrophone measured signals is clear; the higher frequency components from the accelerometer measured signals is evident. Perhaps the most striking feature is the enhancement in the cross-correlation function of the hydrophone measured signals by the additional signal processing.

5. CONCLUSION

Based on an analytical model of the cross-correlation of pressure responses established in an earlier study, the effectiveness of the correlation technique using different acoustic/vibration sensors has been evaluated for leak detection in plastic water distribution pipes.

Theoretical predictions of the correlation coefficients of pressure, velocity and acceleration responses show the following.

a. The use of pressure signals leads to the highest peak cross-correlation coefficient. Therefore, a measure of pressure responses using hydrophones would be the most suitable for locating leaks having small SNR. This is consistent with practical experience.

b. Pressure signals are the least sensitive to the relative positions of the sensors and therefore are the most suitable for extreme positions. Good levels of peak cross-correlation coefficient (e.g., greater than about 0.5) are only possible when the ratio of distances satisfy 1=10pd1=d2p10; 1=4pd1=d2p4 and 1=3pd1=d2p3 for pressure, velocity and acceleration responses, respectively. In practice, these limits will be less stringent due to the limited bandwidth of the leak source and background noise.

c. The use of acceleration signals results in the sharpest peak of the cross-correlation coefficient. It also exhibits the least spreading of the envelope. This suggests that accelerometers are most suitable in multi-leak and coherent noise situations.

The theoretical predictions have been validated to some extent by comparison with results obtained using real leak signals from a test site in Canada measured by hydrophones and accelerometers.

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