Sustainable Leakage Monitoring Systems for Water Distribution Pipeline Networks

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Abstract

An estimated 26.5 million m^3 (≈ 20%) of treated water is lost through leakages from water distribution pipelines every day in the U.S., and this loss is expected to grow in the coming years as a result of deteriorating infrastructure. Over the past few years, there has been a strong research focus on developing and deploying permanent pipeline leakage monitoring systems that will detect and locate significant leakages in near real-time. While novel non-invasive, cyber-physical algorithms are emerging to enable continuous system-wide leakage monitoring, their life cycle cost are yet to be thoroughly investigated. In an attempt to address this knowledge gap, this paper presents a framework for estimating the life cycle costs of network-wide leakage monitoring systems, and demonstrates it using a benchmark water distribution system layout. This paper identifies the hardware and software needs of a surface vibration-based leak detection technique and elucidates its operational scheme that will impact the life cycle cost for reliable leakage monitoring of water distribution systems. The approach and the demonstration presented in this paper will inform how sustainable (i.e., cost wise) and feasible the studied leakage detection system is and as a whole, this paper will be informative to water utility owners.

1. BACKGROUND

Yazdekhasti et al. (2016) recently proposed and validated a vibration-based water pipeline leak detection technique, called Leak Detection Index (LDI) technique [1]. LDI technique requires continuous monitoring of the change in the cross spectral density (CSD) of surface vibration measured at discrete locations along the pipeline. The following LDI index is used to quantify the variation in the CSD of acceleration due to the onset of a leak [1]:

$$LDI(x, y, SC_b, SC_d) = \frac{\int \left| f_{x-y}{}^{d}(t) - f_{x-y}{}^{b}(t) \right|}{\int \left| f_{x-y}{}^{b}(t) \right|} \tag{1}$$

where, x and y are two locations along the pipeline length where the acceleration data is collected, SC_b is the baseline scenario, SC_d is the damaged scenario, $f_{x\text{-}y}{}^{b}(t)$ is the

CSD of data from x-y locations in the baseline system state, and $f_{x\text{-}y}^{d}(t)$ is the CSD of data from x-y locations in the damaged system.

As can be observed from Eq. 1, LDI quantifies the normalized difference between the CSD of acceleration data collected from any two locations in a baseline system state (i.e., before the onset of a leak) and a leaky state (i.e., after the onset of a leak). Preliminary findings based on a two-phase experimental validation campaign revealed the capabilities of LDI technique to detect leakages in a real-size, multi-looped pipeline system made of PVC that is comprised of various complexities such as joints, bends and pipes of multiple sizes [1, 2]. While further validation is required to thoroughly understand the extent of technical capabilities and limitations of the LDI technique, it is important to evaluate the sustainability merits of this technique to be even deemed practically acceptable for network-wide leakage monitoring. Consequently, the aim of this paper is to estimate the life cycle cost (LCC) of a network-wide leakage monitoring set-up using LDI technique.

2. SENSING AND COMMUNICATION: HARDWARE OPTIONS

This section presents an overview of various sensor choices and communication schemes available to support leakage monitoring using LDI technique.

Sensors: Bruel and Kjaer 4507 B 006 type of accelerometers with nominal sensitivity of 500 mV/g were used in the prior demonstration of the LDI technique [1]. Although this type of accelerometer is reliable, it would be prohibitively expensive for monitoring longer pipe sections in real-world systems using these accelerometers because of its high unit cost. Frequency response, sensitivity and noise floor level are three critical parameters that determine the suitability of an alternative sensor for the LDI technique.

The vibrational frequency range of interest for leakage detection in water pipelines varied in the literature. Some studies focused on a broad range of 0-1000 Hz for monitoring small diameter plastic pipelines [1, 3, and 4], while others focused on a limited range of 0-200 Hz for monitoring large diameter pipelines [3, 5]. Upon evaluating the efficiency of the LDI technique with 0-200 Hz, this range has been chosen to be used in this study for determining suitable sensor alternatives to the B&K accelerometer. It was found out that the LDI technique not only detected the onset of leakage, but also differentiated leaks of varying severities by monitoring 0-200 Hz frequency range. Consequently, any vibration sensor with a minimum frequency range of 200 Hz will be suitable for use with the LDI technique. Furthermore, accelerometers with high sensitivity are usually preferred [6], for sensitivity indicates the variation in the electric signal output subjected to variation in the mechanical energy from the monitored vibration. On the other hand, sensors with low noise floor level are preferred, for higher noise floor level would mask low amplitude signals and prevents the detection of smaller leakages.

Upon reviewing the specifications of various sensor options (such as PCB393A03, PCB352B, SD1521, SD1510, and etc.) applicable for acceleration measurement, ADXL362 type of sensor was found to be a suitable alternative with relatively high sensitivity and low cost compared to the previously used B&K

accelerometer, as shown in Table 1. In order to compensate the higher noise floor level of ADXL362 compared to the B&K type, it is proposed that a high-pass filter be used on the collected data and also that shorter sensor spacing be prescribed.

Sensor Spacing: While using accelerometers, sensor-to-sensor spacing of 100 m in case of plastic pipelines and up to 200 m for metallic pipes are recommended in the literature for detecting leak-induced pipeline vibrational changes [7, 8]. The optimal sensor spacing is the function of various factors, such as pipe size and material, leak size and its location, and leak-induced change propagation. As a result of uncertainties associated with the optimal sensor spacing, various distances have been considered in the current study to assess the sensitivity of LCC. Specifically, a wide range of 30 m - 100 m for sensor spacing, with 10 m increments is studied.

Table 1. The unit cost and specifications of sensors

Type	Sensitivity	Frequency response (nominal, 3db) (Hz)	Noise floor μg/√Hz	Unit Price	Input Range	Operating Voltage (V)	Operating Current (mA)
B&K450 7B006[9]	500 mV/g	6000	2	$600	±14 g	13	2-20
ADXL 362[10]	1* (mg/LSB)	200	175	$3.97	±2, 4, 8 g	3.5	0.013

*ADXL362 produces analogue output unlike B&K which produces digital output and thus different units of sensitivity are used; For the sake of comparison, the sensitivity of B&K is computed to be 1.6 mg/LSB with a working voltage range of 0-3.3 V (operation voltage of typical micro-processor) and is therefore comparable to the sensitivity of ADXL362 (1 mg/LSB).

Communication strategies: Vibration data from multiple locations need to be gathered and analyzed in a centralized manner to determine the onset of leakage in the distribution system. Various communication schemes currently exist for supporting sensor networks. The uniqueness of the proposed leakage monitoring system is that data needs to be collected underground and transmitted to a receiver located either on the ground or closer to the ground surface. Another challenge with network-wide monitoring systems is the difficulty in using wired communication due to high costs and other practical limitations [11]. Consequently, wireless sensor networks are preferred for pipeline monitoring purposes [12]. Among wireless communication technologies, electromagnetic-based approaches are increasingly becoming the attractive choice, and among those Zigbee (developed based on IEEE 802.15.04 protocol) is a useful technique due to its longer transmission range (up to 300 m through the air at 433 MHz) compared to other techniques [13-16]. Wireless communication technologies suffer in buried soil environments due to high levels of wave attenuation caused by soil and water absorption and path loss [17]. It is therefore proposed that Zigbee wireless communication be used for aboveground communication, while the collected data from senor node placed on the pipeline surface is transmitted to the ground surface through a wire.

Conceptual prototypes: Two types of monitoring nodes are characterized in the proposed leakage detection scheme; they are *sensor node* and *gateway node*.

Sensor Node: Sensor nodes comprise an accelerometer (i.e. ADXL362), micro-controller and a power source placed on the pipeline surface which is attached to a transceiver located at the ground level. The transceiver receives the vibration data from the pipeline surface and it transmits that data to the gateway node. The transceiver comprises a radio chip, antenna, power source, and a microcontroller. A schematic representation of the conceptual sensor node prototype is shown in Figure 1. The total cost of such sensor node scheme is estimated to be about $16 per node based on the following prices for individual components: $3.97 for ADXL362 sensor [10], $9 for two microcontrollers [18], $1.2 for a radio chip [19], $1.2 for antenna [20], and $1 for the transmitted cable [21]. It may be necessary to purchase these individual components in bulk to pay these estimated prices.

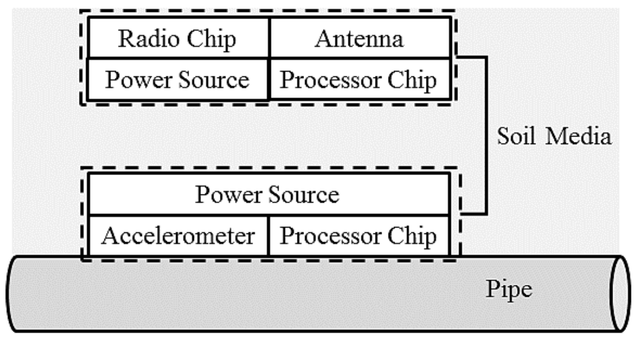

Figure 1. Schematic of the conceptual sensor node prototype

The micro-controller chip (MSP430FR6989) which is proposed to be used in the prototype sensor node is an ultra-low power microprocessor selected based on its reported successful performance in combination with the prescribed radio chip and antenna (CC1150 and Pulse Helical) in various sensor network applications [22].

Gateway Node: The gateway node acquires data from a cluster of closely located sensor nodes for local processing and further transmission to a data center for comprehensive decision making. A gateway node consists of a radio chip and antenna for data reception from multiple sensor nodes, a powerful micro-controller for data processing, as well as a power source. The BeagleBone micro-processor is prescribed based on its reported capabilities of high performance processing and low power requirements [23], which is suitable for rapidly calculating Cross Spectral Density and subsequently LDI indices in the proposed leakage detection scheme. The BegaleBone micro-processor can be either connected to an Ethernet connection or a cellular modem (e.g. SparkFun Cellular Shield - MG2639) along with a Quad-band Cellular Duck antenna SMA for data transmission. The total cost of such a gateway node would be about $120 per node based on the following estimated prices for the individual components: radio chip at a unit cost of $1.2 [19], antenna at a unit cost of $1.2 [20], BeagleBone micro-processor at a unit cost of $55 [24], cellular modem at a unit cost of $59 [25], and Quad-band Cellular Duck antenna at a unit cost of $7 [26].The prescribed hardware for the prototype sensor node and gateway node have been chosen with the goal of striking a reasonable balance between cost and efficiency, based on the review of their promising performance in previously demonstrated wireless sensor networks along with the current system requirements. A total of sixty data sets of pipeline vibration samples are proposed to be collected each night over a period of five hours starting from 00:30 AM, with one data set collected every five minutes, which is a strategy consistent with previous leak assessment studies [4]. Various uncertainties prevail with the monitoring scheme and these include the sensor spacing, data sampling rates, frequency range of interest, data transmission rate, and power sources and their reliability. For the sake of simplicity, only battery power is considered in the analysis presented in this paper.

3. NODE DEPLOYMENT ALGORITHM

Sensor nodes are grouped into clusters that transmit data to gateway nodes and the locations of the gateway nodes are optimized to ensure maximum network-wide communication at minimum cost. Sensor node clusters are determined by using the K-means algorithm [27-30] which comprises the following steps:

1. Exclude the relatively isolated nodes from calculation.
2. Extract the horizontal and vertical coordinates of each node to a matrix set {Xi| Xi ∈ R^2, i = 1, 2,…,m} and randomly set K points {Cj | Cj ∈ R2, j = 1, 2,…,K} as the gateway nodes. In addition to the pipe connections which will house a sensor, numerous sensors will be placed along the pipe length with spacing equal to the predefined sensor spacing.
3. Compute the Euclidean Distance ($D_{i,j}$) between sensor nodes and every gateway node. The sensor node will belong to the gateway cluster with least $D_{i,j}$:

$$D_{i,j} = \sqrt{(X_i - C_j)^T (X_i - C_j)} \quad (2)$$

where, X_j is the coordinates of sensor node *i*, C_j is the coordinates of gateway node *j*, and *T* notation means transpose operation.

4. Recalculate the gateway node (cluster center) location by:

$$C_j = \frac{1}{N_j} \sum_{X \in G^{(j)}} X \quad (3)$$

where, N_j is the sensor nodes number in cluster j, and $G^{(j)}$ is the collection of sensor nodes in cluster *j*.

5. Evaluate the Convergence Criterion *(J)*, to determine if the gateway location is converged upon:

$$J = \sum_{j=1}^{K} \sum_{i=1}^{N_j} D_{i,j} \quad (4)$$

6. Calculate the maximum $D_{i,j}$ and terminate the algorithm if it is less than the predefined communication radius, i.e., 300 m [14]; otherwise, set *K=K+1* and return to step 2.

4. DEMONSTRATION

A benchmark water distribution network, shown in Figure 2 and used in several previous studies [31], is used in this study to demonstrate the proposed life cycle analysis of the LDI-based leakage monitoring system. As a specific application scenario of the LDI technique, pipelines 2, 3, 5 and 6 are chosen as the critical pipelines that need to be monitored because they connect the reservoirs to the distribution network. These pipelines would also be larger in diameter compared to the rest of the network and are therefore even more critical. The length of each of these pipelines is approximately 1.6 km and the total monitoring length adds up to about 6.4 km. As shown in Figure 2b, sensor nodes are placed at all the junctions (black dots) as well as between them (white dots) if the distance is more than the specified minimum sensor spacing in a given scenario. The K-means algorithm is employed to determine the clusters of sensor nodes, as depicted in Figure 2b, and also to determine the positions of gateway nodes in each cluster.

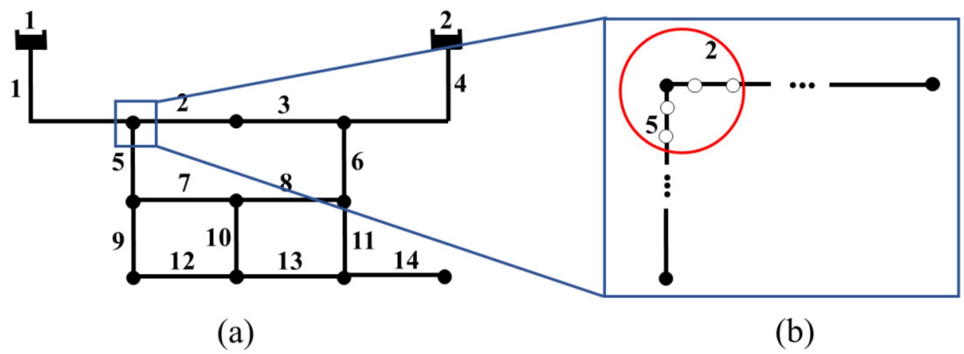

Figure 2. (a) The case study water distribution network, (b) proposed sensor deployment scheme and sample clustering of sensor nodes

The sensitivity of LCC to variation in sensor spacing and data sampling rate is evaluated for monitoring just the four critical pipelines of the benchmark water distribution network. Senor spacing ranging from 30m to 100m at 10m increments is used in various scenarios of analysis. The clustering required for monitoring these pipes is determined using a MATLAB code written for the K-means algorithm. It was found that the sensor nodes need to be grouped into 13 clusters based on the communication range of the radio chips proposed to be used. The number of sensor nodes per cluster is a function of sensor spacing and it would increase when the sensor spacing decreases. More the number of sensor nodes in a specific cluster, larger the amount of data that is collected, transmitted and analyzed. The amount of data collected and processed at each sensor node is a function of data sampling cycle time (i.e., 10 secs) and the data sampling frequency. As a rule of thumb, the data sampling frequency should be at least 2.56 times greater than the highest frequency monitored (i.e. 200 Hz) [32]. Therefore, data sampling frequencies ranging from 500 Hz and above are used for evaluating the sensitivity of LCC. Specifically, data sampling frequencies 500, 600, 700, 800, 900, and 1000 Hz (or samples/sec) are used in various scenarios of analysis.

4.1 Life Cycle Cost (LCC):

The total life cycle cost of the leakage monitoring system is a function of: (a) initial cost, and (b) operation and maintenance cost.

Initial cost mainly consists of *equipmen*t and the *installation expenses*. Equipment cost can be estimated based on the number of sensor and gateway nodes required for monitoring the four critical pipelines in the benchmark network and subsequently multiplying with the unit cost of each sensor. The number of sensor nodes is estimated based on the pipeline configuration and the specified minimum sensor spacing. The number of gateway nodes, on the other hand, is the function of transmission range and the total amount of data which needs to be transmitted and analyzed in a specific cluster, and is derived using the K-means algorithm. Installation cost, on the other hand, is estimated based on the assumption of employing air-vacuum excavation for exposing the pipeline surface for sensor node deployment. The excavation expenses for creating a vertical borehole with diameter of 25 mm based on the latest unit cost data[1] would be \$4.7/node. While the installation costs of wireless sensor nodes is reported to be insignificant [33, 34], a nominal cost of \$0.3/node is used for labor expenses in this study. The installation costs of gateway nodes, on the other hand, are considered to be about 50% of their hardware cost [35].

The *operation and maintenance* expenses are primarily dependent on the amount of power consumed by the monitoring system. While replacement of batteries is considered to be a maintenance expense, the operating cost is simply assumed to be the cost of power consumption. Power can be supplied to the monitoring nodes through batteries, wired AC connections, or renewable alternatives such as locally placed solar panels or locally harvested energy. As mentioned previously, for sensor nodes, only battery power is considered in this study for the sake of simplicity. The estimated operational cost is the product of unit cost of battery and the total number of batteries that will need to be replaced over a 20-year life cycle of the monitoring system. The labor expenses of battery replacement at each node, using an estimated unit labor cost of \$16/hr [36] and an estimated 10 minute set-up time, is calculated to be \$2.67/node/replacement (i.e., 10 min/node * \$16 / 60min). Two AA batteries at a unit cost of \$0.4/each [37] are used for estimating the cost of power supply using the battery option which has been reported to be successful with MSP430 microprocessor chips [38]. Based on the energy specifications of typical AA batteries, for a sampling rate of 1000 Hz and the prescribed hardware in the sensor node, they would need to be replaced every 10 years with ADXL362 accelerometer. A conservative frequency of 5 years [39] is considered for battery replacement with ADXL362 sensor. On the other hand, gateway nodes with superior processing needs have higher power requirements and it is assumed that they are served by AC power supplies aboveground. Therefore, their operational cost is estimated based on the power profiling of their hardware, active operational time of its hardware, and the unit cost of power supply. In summary, the estimated life cycle cost of the monitoring system is the sum of the equipment cost, installation cost, operational and maintenance cost, and a contingency of 15%.

The LCC of the LDI-based leakage monitoring system for the benchmark network case study is estimated for a 20-year life cycle period. For the specific

[1] Reference: http://www.homewyse.com/services/cost_to_dig_post_hole.html

scenario with a data sampling frequency of 500 Hz, sensor spacing of 100 m, the LCC is estimated to be $9,600 when using the ADXL362 sensor.

Figure 3 illustrates the variation of LCC of the proposed monitoring system over different sensor spacing distances and data sampling frequencies. It can be seen from Figure 3 that LCC is highly sensitive to sensor spacing distance, as the LCC for sensor spacing of 100 m is almost half of that for sensor spacing of 30 m. On the other hand, LCC increased only marginally with higher sampling frequency. Higher data sampling frequencies result in larger amounts of data that are collected, transmitted, and analyzed. Due to the capabilities of the chosen microprocessors for use in the gateway nodes, the number of gateway nodes would remain constant over different data sampling frequencies and therefore, the initial cost of the system will not be significantly different. The higher data sampling frequencies however requires more time for transmission and would also consume more energy and subsequently results in greater operational costs, but not significant enough to considerably change the LCC. On the other hand, as shown in Figure 4, the total cost of such network-wide monitoring system is highly dependent on the initial cost.

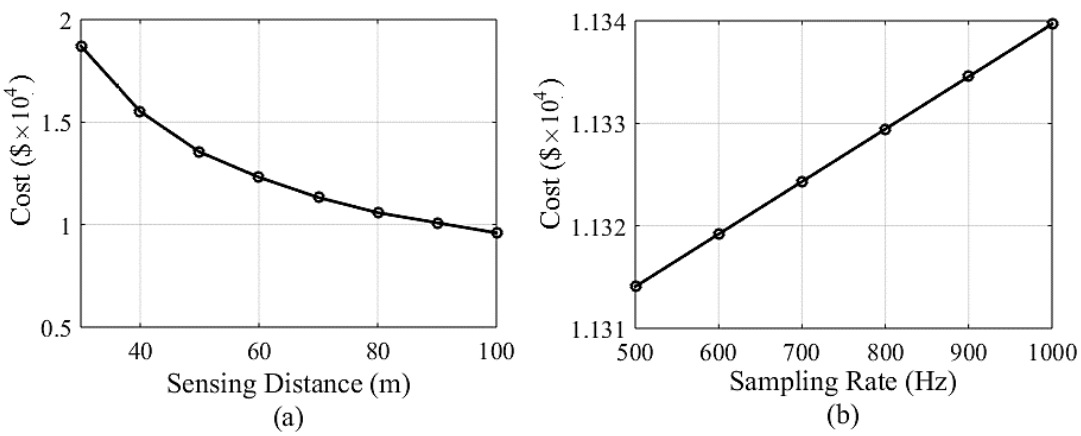

Figure 3. Variation in network-wide LCC over 20 years with: (a) sensor spacing distance (at a data sampling frequency of 700 Hz); and (b) data sampling frequency (at a sensor spacing distance of 70 m)

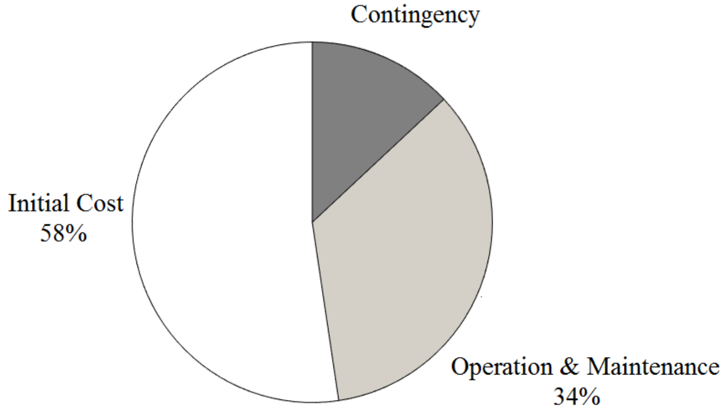

Figure 4. The distribution of LCC among various phases with data sampling frequency of 500 Hz and sensor spacing distance of 30 m

5. CONCLUSION

This paper estimated the life cycle costs associated with network-wide leakage monitoring using a novel vibration-based technique. Accelerometers need to be affixed at multiple locations along the pipeline surface and vibration data from all these locations need to be coherently analyzed for detecting the onset of leakage and determining its relative severity. The 20-year life cycle costs of such a monitoring system employed to detect leakage on 6.4 km long pipeline in a benchmark water network is estimated to be in the range of $9,600 to $18,800 with the lower estimate corresponding to the scenario of sensor-to-sensor spacing of 100 m and the higher estimated corresponding to sensor-to-sensor spacing of 30m. It was observed that the initial costs of the hardware and the set-up accounted for the major chunk of the life cycle costs in the proposed monitoring set-up. The LCC is found to be highly sensitive to variation in sensor-to-sensor spacing and less sensitive to the variation in the data sampling rate. The percentage increase in LCC when the sampling rate is increased from 500 Hz to 1000 Hz is found to be negligible and ranging between 0.6% - 0.7%. The insensitivity of LCC to variation in sampling rate is due to the use of microprocessors that are compatible with multiple sampling rates which results in similar initial costs irrespective of the sampling rate. It should however be noted that higher sampling rate will take longer time for transmission of the collected data. Future research should investigate the sensitivity of life cycle cost and life cycle energy consumption to variation in sensor type, different communication schemes and should also develop actual prototypes and perform a field demonstration.

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