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ScienceDirect

Procedia Computer Science 96 (2016) 285 – 294

Procedia Computer Science

20th International Conference on Knowledge Based and Intelligent Information and Engineering Systems

EARNPIPE : A Testbed for Smart Water Pipeline Monitoring using Wireless Sensor Network

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Abstract

Large quantities of water are wasted daily due to leakages in pipelines. In order to decrease this waste and preserve water, advanced systems could be used. In this context, a Wireless Sensor Network (WSN) is increasingly required to optimize the reliability of the inspection and improve the accuracy of the water pipeline monitoring. A WSN solution is proposed in this paper with a view to detecting and locating leaks for long distance pipelines. It combines powerful leak detection and localization algorithms and an efficient wireless sensor node System on Chip (SoC) architecture. In fact, a novel hybrid Water Pipeline Monitoring (WPM) method has been proposed using Leak detection Predictive Kalman Filter (LPKF) and Modified Time Difference of Arrival (TDOA) method based on pressure measurements. The data collected from sensors are filtered, analyzed and compressed with the same Kalman Filter (KF) based algorithm instead of using various algorithms that deeply damage the battery of the node. The local low power pre-processing is efficient to save the power of the sensor nodes. Moreover, a laboratory testbed has been constructed using plumbing components and validated by an ARM-based prototyping platform with pressure sensors.

Peer-review under responsibility of KES International

Keywords: Water Pipeline Monitoring; Wireless Sensor Network; Kalman Filter; System on Chip;

1. Introduction

Water is a vital source of life in the earth. Up to 60% of water is wasted every year due to leaky pipes generating economical, environmental and possible human losses[1]. This is contributes as a major factor in water crisis all over the world. In fact, according to a new study published by Science Advances newspaper in February 2016, approximately, four billion people all over the world are facing water scarcity[2].
Hence, these alarming statistics make water preservation as a fundamental issue to maintain human life by controlling pipes transporting fresh water.

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Peer-review under responsibility of KES International
doi:10.1016/j.procs.2016.08.141

Countless leak detection and localization techniques for Water Pipeline Monitoring (WPM) are reported in the literature[3,4]. The classical methods are periodic and non technical. Experienced personnel are patrolling along the pipes looking for visual leaks or using equipments (like acoustic/ultrasound) to search anomalies. This kind of methods is painful and affected by the staff experience. Moreover, it could not be continuous and useful for inaccessible pipes. In the following, we do not consider these methods.
WPM systems are practically based on two main steps: the sensors/equipments used to collect useful information and the way to process and to analyze this information.
In fact, the sensors could be just placed on key points of the pipeline (inlet, outlet) or installed along the pipe using wired or wireless technology[5]. Wired networks have various drawbacks including the cost of installation and maintenance. Besides, a damage in a wire could alter the whole network. Recent researches have highlight the importance, performance and reliability of Wireless sensor network (WSN) in detecting and locating leaks during the last few years. It is characterized by its continuous inspection and real time monitoring[6].
On the other half of the deal, various methods have been employed to analyze data collected from the sensors. They could be divided into signal processing methods, knowledge based methods and model based approaches.
The signal processing methods are based on the signal analysis and interpretation in the time or the frequency domain[7]. Methods based on knowledge like support vector machine (SVM), pattern recognition and expert system are also extensively tested[8].
Model based approaches use in general conservation of momentum, conservation of mass or conservation of energy to build a model and predict the leaks presence. In these techniques, Kalman Filter(KF) is widely applied in its linear and extended form thanks to its low complexity and small memory requirements[9]. The variety of techniques and the continuous efforts in this fields is due noisy and variant pipe environment. Searching for optimal and accurate solutions still an open research axis.
In this context, we introduce a first prototype of EARNPIPE: Energy Aware Reconfigurable sensor Node for water PIPEline monitoring. A reliable solution for inspecting pipe infrastructure. We propose a complete WSN solution coupled with Leak detection Predictive Kalman Filter (LPKF) and other methods to detect and locate leaks.The use of WSN in junction with KF permits to benefit from their advantages, enhance the accuracy of the leak detection by avoiding false alarm and optimize the power consumption of the node and the network. This proposal combines high-performance platform and powerful mathematical non-destructive inspection methods using pressure measurements.
The paper is organized as follows. Section 2 itemizes the related WSN projects used for WPM application (WSN-WPM). A detailed description of EARNPIPE prototype in terms of network architecture, sensor node architecture, equipments and leak detection algorithm will be given in the section 3. In section 4, We explain the experimental setup and the results. We finish our work with conclusions and perspectives in section 5.

2. Exploration of WPM projects using WSNs

WPM has benefited from the WSN progress. The migration to WSN is due to is potential. A typical network consists of a large number of sensor nodes, which are densely deployed to collect and transmit data via wireless connections to inspect physical quantities and environmental conditions.
Various WSN projects exist in the literature[10,11] focusing in different aspects including efficient node communication along the pipe, the placement and replacement of nodes, etc. We review below some projects:

PipeNet[12] is a well-known project for WPM developed by imperial college, Intel, and MIT in 2007. Acoustic/vibration and pressure sensors operates to detect and locate leaks. The adopted node is based on Intel commercial mote composed of an ARM7 core, a 64KB RAM, a 512 KB Flash, and a Bluetooth communication. Algorithms like WT, cross correlation and pattern recognition algorithm, have been also implemented to process the sensors data. Although this work gives a complete solution for WPM, two significant drawbacks could be mentioned. Firstly, several high processing algorithms are employed which affect the power consumption of the nodes by accomplishing complex tasks. Secondly, the authors collect data with a very high sampling rate and high frequency. Even this make the solution real time, it also act on the increase of energy consumption of the node.

Kim *et al.* propose Nonintrusive Autonomous Water Monitoring System (NAWMS) allowing auto-calibration of water system and computing the quantity of used water by using flow meter and vibration sensors attached to the pipeline. A mixed linear geometric model is proposed for data calibration. The system is dedicated for houses to calculate the water consumption in each part of the household. The sensor node is based on MicaZ mote and the MTS310 sensor board. This proposal has the drawback of high cost as it need a large number of sensors depending on the house geometry.

Another work named PipeProbe[13] describes a prototype of a mobile sensor network system with hydro molecule form. It consists of EcoMote and a MS5541C pressure sensor from Intersema. The node maps along the pipe and gathers pressure measurements which are saved in a flash memory. These reading are then analyzed in the laboratory. Although it is based on sensor network, this solution need a lot of human intervention.

SPAMMS (A Sensor-based Pipeline Autonomous Monitoring and Maintenance System)[14] is an autonomous sensor system that permits leak detection and localization by combining static and mobile sensors. It apply varying kinds of inspection methods using pressure sensors, CCD sensors, chemical sensors and sonar sensors. A robot technology is also used for pipeline maintenance and corrective monitoring. The prototype is composed of MiCA1 mobile sensor mote, an EM4001 ISO RFID system and a robot agent. This project minimize the human intervention. However, needs high processing capabilities like image processing, signal processing algorithms, etc. In addition, we could notice that this installation require many instruments which make it unsuitable due to its high cost.

The Wireless Water Sentinel project in Singapore (WaterWiSe@SG)[15] aims to give a complete WSN solution for water distribution systems. The sensor mote consists of a Gumstix Verdex Pro, wifi communication, 2GB Storage disk, GPS(Global positioning system) unit, pressure sensor, flow sensor and hydrophone for leak detection and burst events. Its permits also hydraulic and water quality parameters monitoring.

The authors in[16] propose a magnetic induction-based WSNs for underground pipeline monitoring (MISE-PIPE). This solution allows leak detection and localization using magnetic induction technique by the mean of acoustic, pressure and soil property sensors. It focuses more on communication. Moreover, it seems that the leak detection methodology is energy consuming as their is always a communication between the base station and the nodes.

SmartPipe[5] proposes a non-invasive WSN solution for underground pipeline monitoring using force sensitive resistors. The sensor node consists of a PIC16LF1827 microcontroller, an eRA400TRS 433 MHz transceiver, two temperature sensors and one Force Sensitive Resistor pressure sensor. As the authors, this work has a low power consumption.

A recent work elaborated by Kartakis *et al.* present a testbed, WateBox which allows controlling and monitoring water distribution systems[17]. The prototype is based on six sensor nodes. Four nodes consist of Intel Galileo board, Ethernet module and two nodes are equipped by Intel Edison board and communicate through Wifi. A smart water sensor board is also employed formed of flow meter, MPX5700GP pressure sensor and motorized valve. A software application is developed to allow new users to test their algorithms. This prototype aims to give developers and scientists an environment to better understand water systems and test their application. Nevertheless, no simulation or experimental results are given to evaluate this work.

WSN research effort is diversified in WPM application as explained above. Some works are focusing on communication, some others on software solutions, etc. A different equipments and sensors have been used and tested. Despite this variety, the research in this field still have several limitations in terms of node architecture which still suffer from small memories, low processing units, high power consumption, etc. Besides, almost of analyses are elaborated in the laboratory while sensor nodes are responsible on data collection and transmission. The transmission is an energy consuming task. To minimize the transmission rate, data in-node pre-processing is necessary. Hence, taking account about all the limitation described in this section. We design EARNPIPE which takes into consideration the hydraulic challenges i.e. the harsh environment of pipes and the WSN challenges in terms of energy and performance. It focuses on sensor node architecture to find a trade off between enhanced performance and minimized energy consumption. In fact, the use of classical commercial sensor nodes decrease the performance of computing. Thus, we will design in this project our own mote. The leak detection will be accomplished in the node to minimize the transmission rate by sending only useful data. Other aspects like network architecture, simple and accurate algorithms are taken into account. In the following section, more details will be given about the EARNPIPE project.

3. EARNPIPE Principal and System Design

EARNPIPE project is designed for above-ground long distance water pipelines. The aim of this project is to provide a low power WSN solution for accurate leak detection and localization. An in-node single data processing algorithm is used to filter, compress and leak detect. We will detail in this section the WSN topology, the sensor node architecture and the leak detection and localization algorithms.

3.1. EARNPIPE Networking and Operating Concepts

Various network topologies and architectures could be adopted for WSNs[18]. The choice of such architectures contributes on the main constraint of WSN: the power consumption. Furthermore, the particular pipeline environment imposes many constraints on the WSN structure. Consequently, EARNPIPE is based on clustering architecture as explained in figure 1. As the matter of fact, a clustering routing is an efficient way to minimize the power consumption of the all network. The sensor nodes collect data every hour in a period of 5 min and with sampling rate 1000 S/s. A LPKF algorithm is run then locally to filter noisy data and detect anomalies. The compressed data and leak information are firstly forwarded from nodes to cluster heads in which the leak position is calculated in case of leak occurrence, and then to the cloud/FTP server . When the information are sent to the base station, many statistics are done and

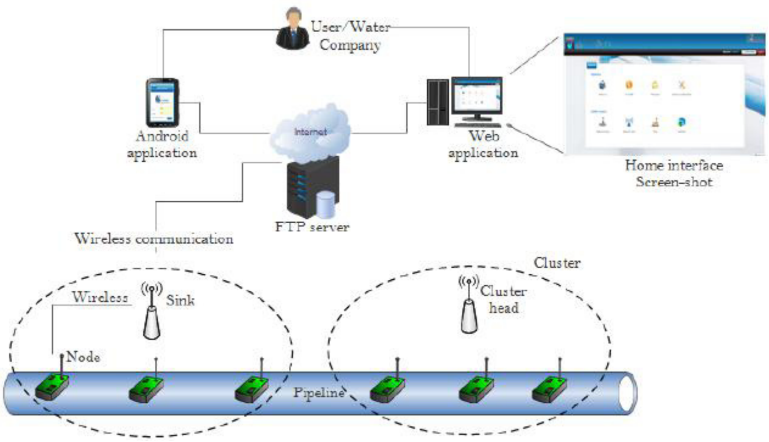


Fig. 1. General architecture of EARNPIPE Network

saved in a database for online visualization. An interactive web user interface is developed to access to the ftp server via Internet and to the database. In fact, in this application users could access to graphs, historical of data, pipeline state and network state. It provides also pipeline locations, maps and controlled area. A screen-shot of the home interface of the web application is posted up in Figure 1.

3.2. EARNPIPE Sensor Node Architecture

The architecture and technology of the sensor node is crucial to determine its performance and power consumption. A typical node is usually composed of processing unit, sensing unit, communication unit and power unit varying from simple commercial small sensor node to a high performance node architecture. Referring back to section 2, almost of WSN-WPM works are based on microcontrollers; in those projects, no much attention is given to the sensor node architecture design. However, the use of advanced technologies like a System on Chip (SoC) architecture provides a huge potential for WSN-WPM. As a matter of fact, the SoC is nowadays battling all previous technologies. Such architecture is currently under design to reach the required performance in terms of processing and energy; the choice of this technology is based on our exploration of different sensor node architectures existing in the literature[19]. A SoC involves almost of functional unit in the same single chip. It is characterized by its small space and low power. WSN has benefited from this technology. For example in[20], authors present a SoC for WSN applications using SystemC/TLM. The SoC contains a microprocessor, a memory, a bus, a timer, a transceiver and a battery. The model is designed to allow power estimation. WiseNET was the first sensor node based on SoC. It required external components such as power source, RF antenna, passive devices and sensors[21]. Using the Algorithm Architecture Adequacy (AAA) and co-design tools, we propose a sensor node SoC which consists of ARM processor, KF accelerator, a sensor interface, ADC, memory, a radio transceiver and a power management unit using energy harvesters. The figure 2 gives an overview about the system design.

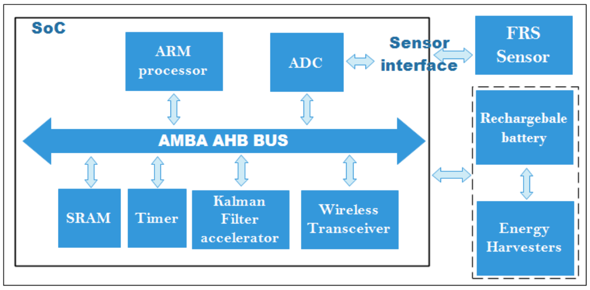


Fig. 2. Sensor node architecture

3.3. Leak detection and localization algorithms in EARNPIPE

After detailing the first aspects of the EARNPIPE: Topology and node architecture, we present in this section the leak detection and localization algorithms.

3.3.1. LPKF Leak detection algorithm

The feasibility of KF algorithm is explored in WPM application. For instance, Ye *et al*[22] propose a modified linear KF for leak detection based on hydraulic measurements. They suppose that in a given time step, the measurement state could be considered similar with this of previous week. The authors in[23] use a statistical process control and a non linear KF to detect bursts in water pipelines. Torres[24] has explored various observers and an Extended KF to detect and locate leak in water distribution system. Benkherouf in 1988 is the first that has used the Extended KF in the context of pipeline monitoring[25]. However, these works do not explore the KF in the context of WSN-WPM application.

In this work, we extend a Predictive Kalman Filter (PKF) algorithm[26] to perform not only data compression but also leakage identification (LPKF). PKF is a predictor combined with KF for reducing the communication cost of the WSN. To the best of our knowledge, our work is the first that explore the PKF in this context. In the following, we explain the LPKF algorithm. In fact, KF is a recursive data processing algorithm for a linear dynamic systems that use a set of mathematical equations and produce an optimal system estimation[27]. It has the ability of data filtering, data aggregation, data compression, event detection, and object location. As EARNPIPE is dedicated for long distance above ground pipelines, we assume that the pressure model is linear. Consequently, we have used KF in its linear form. We present briefly the steps of KF. The estimated state x, which is the pressure in our case, at time k is evolved from the updated state at k-1 as follows:

$$x_k = Ax_{k-1} + Bu_k + W_k \tag{1}$$

Where A is the transition matrix; B is input transition matrix; u_k is the input vector W_k is zero-mean Gaussian noise with covariance Q_k; u_k is the input vector.

The measurements z represented by:

$$z_k = Hx_k + v_k \tag{2}$$

Where H is the measurements matrix;v_k measurement noises with covariance R_k. The first step of KF is the prediction of the current state and covariance matrix represented by:

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k \tag{3}$$

$$P_k^- = AP_{k-1}A^T + Q_k \tag{4}$$

The second step is the measurement update or correction. In this step, we incorporate new measurements into the predicted estimate (a priori estimate) to obtain an improved estimate using Kalman gain (K_k).

$$K_k = P_k^- H^T (H P_k^- H^T + R_k)^{-1} \tag{5}$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \tag{6}$$

$$P_k = (I - K_k H)P_k^- \tag{7}$$

KF estimates pressure variations caused by leaks. The difference between the measurements and the estimated values delivered by the filter gives an idea about the occurrence of leaks:

$$R_k = z_k - H\hat{x}_k^- \tag{8}$$

In fact, when this difference exceed a given threshold (9), a flag is updated from 0 to 1. The flag and the compressed data are immediately sent as fast as possible to the cluster head in which the leak position is calculated.

$$L = \begin{cases} 1, & \text{if } R_k \geq \tau \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

Although the leak detection is an important step in WPM application, it remain insufficient without the leak location to easy and rapid response to the defect.

3.3.2. *EARN-Loca: Leak location algorithm*

Several methods have been deployed for leak location as detailed in section 1.

We present in this section, EARN-Loca, an hybrid new method for leak location based on the physical principal of the leak wave propagation and a time difference of arrival (TDOA) method at the sink. To explain, the sudden escaped water causes a pressure wave along the pipeline. This wave propagates at the speed of sound through the pipeline in

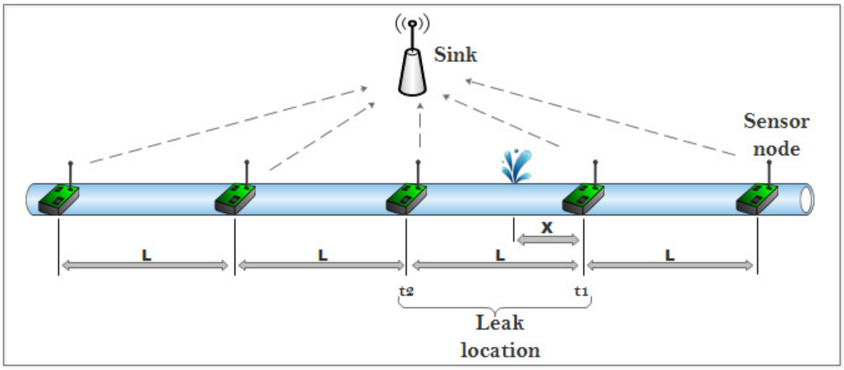


Fig. 3. Leak localization method

the water. Based on this principle, we choose the two sensors wherein the leak occurs. In point of fact, the two first signals of two neighbor sensors that arrive to the sink, are considered (figure 4). Then, TDOA algorithm is run. It is based on the following equation (10):

$$x = \frac{L - C.\Delta t}{2} \tag{10}$$

Where x is the leak distance from the nearest sensor node; L is the distance between the chosen sensors; C is the wave propagation speed and given by experimental measurements; Δt is the time difference of pressure signal arriving from the nodes that could be calculated by cross-correlate the signals. The calculated position and the flag are then sent to update the database. When the flag value in the database is changed from 0 to 1, a notification is sent to the user via the Web application and via Smart-phone. To evaluate the proposed methods, an experimental testbed has been established that we describe in the next section.

4. Experimental results and discussion

An experimental setup has been established using plumbing materials like pumps, pipes, valves, etc. A prototyping sensor node platform has been also detailed.

4.1. EARNPIPE Testbed setup

A laboratory testbed system is designed in the CRNS research center in order to test EARNPIPE system. An almost rectangular section composed of 25 m polyethylene pipes is set up as shown in figure 4 .b. These pipes have 32 mm as an external pipe. They support up to 12 bar of pressure. The choice of this sort of pipes is thanks to its low cost, their resistance and insensitivity to chemical and electrical corrosion. Furthermore, it is used in our real distribution systems (i.e. in our country). More general, the use of plastic pipes is increasingly widespread all over the world. The setup consists also of two valves in inlet and outlet points in order to vary the users demands by varying the pressure. A 1000 m^3 reservoir is used as a water source. To control the inlet and outlet water, we employ two flow meters. As the pipes are made at the same level, the water is moving along the pipes by an electrical pump with 1 hp motor providing up to 6 bar when the output valve is closed and up to 2.5 bar in open circuit. The supports are designed to have variable heights that we will explore in the future to see the effect of this variation on the pressure and to test our algorithm in varied conditions. Finally, The leaks are induced using two garden taps.

(a) EARNPIPE Testbed (b) Sensor node prototype

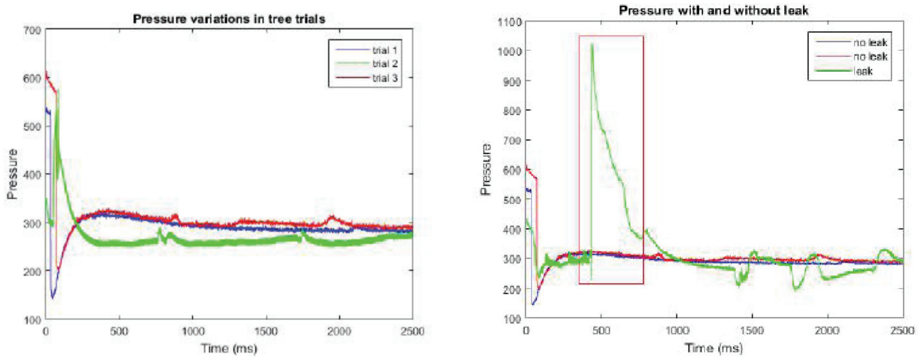
Fig. 4. Laboratory test setup

To test the demonstrator and the proposed solution, We have chosen Arduino Due board with some shields as prototyping platform due to its flexibility, easy-to-use and low cost, etc.It is the first Arduino board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. Moreover, it is a promising open source platform for easy and rapid prototyping. To our knowledge, this is the first project that use this platform in the context of WSN. The processing unit is based on ARM cortex M3 microcontroller.It is composed of ARMv7-M architecture, 84 MHz clock, 16 Kbytes ROM, until 100 Kbytes SRAM and 512 Kbytes flash memory. The ARM cortex M3 is characterized by its low power, ease of use and high performance [28]. As the occurrence of leak alter the pressure of system, the sensing unit consist of Force Sensitive Resistor (FSR) sensors which are used for pressure measuring. They are a polymer thick film devices characterized by their easy-to-use and low cost [29]. The key parameter choice of these sensors is its ability to be used outside the pipe. The sensor nodes communicate via Bluetooth technology. It is suitable for a wireless short range data transmission. This technology is economical and designed for low power consumption. It has 721 kbps as data transmission rate and 2.4 GHz as frequency. It could cover up to 100m [30]. Figure 4.b is a real picture of the sensor node prototype.

4.2. Experimental results of leak detection and localization

To evaluate the suggested leak detection and localization algorithms, we use two sensor nodes that have the architecture described above and we attach them into the demonstrator. The sensor 1 is placed at a position of 38 cm and 48.5 cm far from the leak and sensor 2 is set at 78 cm and 100.5 cm on the other side of leak. A number of scenarios has been carried out to test the effectiveness of the leak detection and localization. Figure 6.a gives the signals delivered in tree trials. These signals are almost of time correlated. The sensor takes a period to be stabilized.

The data is recorded in a period of 2500s with high frequency rate. The garden tap is used to artificially induce a leak. Then, the LPKF algorithm is run to filter the noisy data and detect the leak. To evaluate our leak detection method,



(a) Pressure collected from sensors in three trials (b) Difference between pressure variations with and without leak

Fig. 5. Pressure variations

numerous criteria could be considered including reliability, sensitivity, detection speed, availability and simplicity[31]. The reliability is the ability of system to consistently detect an occurred leak without generating false notifications. We consider that the system is low if the false alarm rate is very frequent and acceptable if less frequent. The sensitivity could be defined as the minimum of detectable flow rate. The method is evaluated as good if the minimum is 1The detection speed is considered as the response time of the method. The system taking up to minutes for leak detection could be evaluated as fast. It is medium if the time detection varies from minutes to hours. On the far side of these values, the system is considered as slow. The availability is the characteristic of system to work all the time or just during the steady state operation. Besides, when the system is easy to use, to retrofit and to install, it is called simple.

In table 1, we compare our algorithm with others in the literature based on the criteria described above. In almost of the sited criteria, the LPKF show promising results. The evaluation of the other methods is get from the literature[31,32,3].

Table 1. LPKF Evaluation and comparison with other methods

Method/ Criteria	Basic volume balance	Real-time transient modelling	Rate of change	Statistical analysis	System ID with Digital signal analysis	LPKF
Reliability	Low	Low	Medium	Low	Acceptable	Acceptable
Sensitivity	Medium	Good	Medium	Low	Good	Good
Detection Speed	Slow	Fast	Medium	Medium	Medium	Fast
Availability	part time	full time	part time	full time	full time	full time
Simplicity	Simple	Very Complex	Complex	Complex	Complex	Meduim

As figure 6, there is a difference between pressure disturbance and the pressure variation in case of leaks. After detecting leaks,the data are sent to the laptop which is used as a sink via Bluetooth. There, the signals are correlated to extract the delay between them. The coordinate of sensors are set manually and will be given in the future using Global Positioning System (GPS). Table 2 illustrates the different errors of the position estimation.

Testing the effectiveness of the experimental testbed, the accuracy of the used sensors and the leak detection and localization techniques was a primordial step before going to the SoC design. However, we remark that the simulation results are better that experimental results as FSR sensor was not accurate enough. Consequently, in the future, we will test other kinds of sensors.

Table 2. Leak error position results

Tests	Real position	Δt (s)	Error (cm)
Test1	38	0.106	1.86
Test2	38	0.208	1.73
Test3	48.5	0.308	2.19

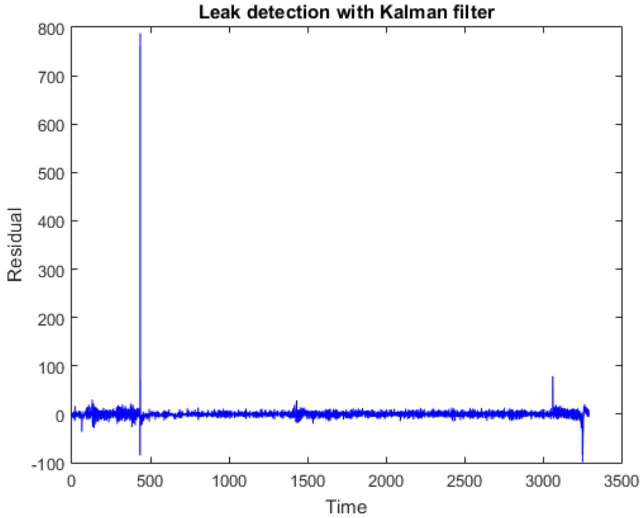


Fig. 6. Leak detection using LPKF

5. Conclusion

This paper describes the design and initial test of our EARNPIPE prototype for reliable water pipeline monitoring. In terms of the algorithms, we have proposed a novel approach using an hybrid method for continuous leak detection and localization for long distance pipes. An in-node LPKF algorithm is designed and tested for leak detection, data filtering and data compression. The idea is to implement a single algorithm that could perform all the required preprocessing tasks to decrease the unuseful communication and data transmission, which are the main energy consuming tasks. The LPKF is a promising algorithm that could be extended for leak location and size estimation.

In terms of the architecture, a robust SoC solution is under construction around an ARM processor and using dedicated hardware accelerators. The first prototype is designed with commercial platform Arduino due for many reasons. Firstly, we aim to verify the testbed functioning and operating condition. Secondly, the choice of sensor is crucial. It affects the accuracy of the detection and location methods. Hence, the test of different sensors is a primordial step.

We are currently developing a second prototype using an FPGA as prototyping platform and ameliorating the algorithm. The improved algorithm benefits from the hydraulic model of the pipe and the distributed aspect of WSNs. We are also adding other sensors and replace the ftp server by a Cloud solution.

Acknowledgements

This work was supported by King Abdulaziz City for Science and Technology (KACST) and the digital Research Center of Sfax (CRNS)under a research grant (project no. 35/1012).

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