Nondestructive Monitoring of a Pipe Network using a MEMS-Based Wireless Network

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ABSTRACT

A MEMS-based wireless sensor network (WSN) is developed for nondestructive monitoring of pipeline systems. It incorporates MEMS accelerometers for measuring vibration on the surface of a pipe to determine the change in water pressure caused by rupture and the damage location. This system enables various sensor boards and camera modules to be daisy-chained underground and to transmit data with a shared radio board for data uplink. Challenges include reliable long-range communication, precise time synchronization, effective bandwidth usage, and power management. The low-cost MEMS technology, saved wiring cost, and simple installation without destructive modification enable large-scale deployment at an affordable cost.

Keywords: Water pipe monitoring, MEMS sensors, ruptures, wireless sensor network

1. INTRODUCTION

Pressurized pipeline systems such as a water distribution network can be monitored nondestructively for the purpose of damage localization by measuring vibration on the pipe surface at various joints. The change in pipe vibration can be primarily attributed to the sudden change in the water pressure caused by a rupture in the network. One can locate the damage by analyzing time-synchronized data samples from two end joints and computing the local maxima of the water pressure gradient.

To enable large-scale deployment at an affordable cost, we develop a micro-electro-mechanical systems (MEMS)-based wireless sensor network (WSN). It is composed of sensing nodes, each of which consists of one or more sensor boards that can be daisy-chained underground to a shared wireless board for data uplink. A sensor board is equipped with MEMS accelerometers for measuring vibration on the exterior surface of the pipe without expensive, destructive modifications required of invasive monitoring techniques. MEMS accelerometers can be made much less expensive than piezoelectric ones, while the use of wireless links can save significant wiring cost for data communication and power. At the same time, wireless communication poses several challenges, including reliable communication over a relatively long distance, precise time synchronization over a relatively slow link, effective arbitration and allocation of bandwidth, and power management. We include multiple radio transceivers for failure redundancy and short-range transmission and control. Our system architecture is expandable and enables additional types of sensing devices to be incorporated, including camera modules, moisture sensors, and gas sensors for monitoring gravity pipes.

The condition of water pipes infrastructure is a growing concern in California and throughout the United States. As reported by the California water Plan update in 2009, the American Society of Civil Engineers gave water infrastructure a D-minus in its 2005 "Report Card for America's Infrastructure." The EPA (Environmental Protection Agency) estimated a total need of 324.9 billion dollars over the next 20 years to be used for water infrastructure assessment in their 2007 Drinking Water Infrastructure Needs Survey and Assessment.[1] The 39 billion dollars estimated for California's need represents about 12 percent of the national need. The DWR (Department of Water Resources)[2] made several recommendations to direct effort to upgrade, improve and enhance the security and emergency response capability of the water infrastructure

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in order to maintain a reliable supply and delivery of drinking water in the case of damage caused by natural disasters or deteriorating pipelines. Identifying the location of failure quickly and easily can be crucial in most situations, yet the current technology in use is not capable of doing so in timely manners.

This paper introduces PipeTECT, a wireless sensor networked system for real-time monitoring and condition assessment of utility water distribution systems particularly during and after natural disasters. The system consists of multiple long-distance wireless communication unit and high precision sensor nodes. The data sampled by MEMS sensor nodes are transmitted in real time for evaluation and assessment to a nearby data aggregation unit. The current generation of PipeTECT is equipped with three MEMS accelerometers, whose accuracy has been verified against traditional high-precision piezoelectric accelerometers in the lab. The substantial cost-effectiveness, robustness, durability, small size and light weight of PipeTECT components make configured observational networks possible for many types of civil infrastructure systems such as bridges and buildings as well as pipeline networks.

In this study we focus on PipeTECT's application to pressurized water distribution systems, and we develop methods for rapidly detecting and locating the source of anomalies in the water system. Such anomalies can be caused by one of many events such as the pipe rupture and pump failure. To develop the means of identifying the location and extent of pipe damage, numerical simulation using transient hydrodynamic analysis was carried out by the industry-grade computer code HAMMER,[3] as shown in Ref. 4, which revealed that the temporal pressure change is larger at a location closer to the source of transient and decays with distance in both pipe directions. Thus, we can identify the damage location(s) in the pipe by observing MWHG (Maximum Water Head Gradient) between the two adjacent joints.

In this paper, we propose a novel damage detection method based on MPAG (maximum pipe acceleration gradient) instead of MWHG (maximum water head gradient). The preliminary experimental results show a sharp change in the water pressure is always accompanied by a sharp change in the acceleration on the pipe surface at the corresponding location along the pipe. This makes it possible to replace the entire process of water pressure monitoring with acceleration monitoring on pipe surface where the latter is significantly less costly compared with the former due to the fact that the acceleration measurement requires noninvasive sensing using generally much less expensive MEMS acceleration sensors rather than expensive pressure gauges in an invasive mode for pressure monitoring. Thus, monitoring is made not for MWHG but for MPAG.

As a first step, using a small-scale pipe network, this paper shows the result of a field experiment that serves as the proof of concept of this advanced technology, which represents a prototype of the next-generation of SCADA (Supervisory Control And Data Acquisition) for water distribution systems. In the remainder of the paper, we outline the design of PipeTECT and the results and evaluation of our initial deployment as well as the lab results.

2. BACKGROUND AND RELATED WORK

2.1 Related Work

The use of WSN to continuously monitor water system performance to detect any failure or security breach has been explored and studied by many researchers. The research approaches varied in their sensing techniques, mathematical formulation, data acquisition methods, and data processing algorithms.

Stoianov et al[5] presents a prototype hierarchical wireless monitoring system deployed at Boston Water and Sewer Commission (BWSC) in December 2004. The system consisted of three tiers: a middleware and backend tier containing web, application, and data servers, as well as network management tools. The second tier consists of the cluster heads and gateways that manage the cluster controls and communication. The system uses the Stargate platform with high computational power, and uses NTP (Network Time Protocol) and GPS (Global Positioning System) for time synchronization. In addition, this second tier is responsible for establishing and maintaining long-range communication links with the back-end servers. The third tier consists of a cluster of battery-operated sensors and sensor nodes with low data storage and performing signal compression and local data processing. The experiment in Boston used the iMote sensor node platform developed by Intel Research. The short-range node communications was established using Bluetooth (2.4 GHz). They monitored pressure and pH in 12-inch and 8-inch pipes.

In a more recent research work by Stoianov et al,[6] a lab-based experiment analyzed acoustic data in order to detect and locate small leaks in 1-inch pipes. The sensor board used in the Boston deployment was redesigned to interface the iMote to various analog sensors used to collect acoustic data. The localization and leak detection was performed using existing algorithms via cross correlation of the collected data in a nearby backend server. As part of ongoing research by the National Research Council, Canada (NRC) to provide a solution for water loss through early leak detection in all kinds of water pipes.

Hunaidi introduced LeakfinderRT.[7] It is a system composed of sensors, wireless signal transmission system, and a PC. The system uses vibration sensors and hydrophones installed at fire hydrants or air release valves along the water pipe to detect leakage noise. The signal from the sensors is wirelessly transmitted to a PC to be analyzed. A graph of the frequency spectra, coherence, and correlation functions of the leakage signals is displayed on the base PC. The system introduced the advantage of using low-frequency vibration sensors over the inconvenient, hard-to-install hydrophones to detect leaks especially in plastic (PVC) pipes.

Using another sensing technique, Jin and Eydgahi[8] mounted a network of Lead Ziroconate Titanate (PZT) actuators/sensors on the curved surface of the pipeline for generating and measuring guided waves along the pipes. While Huaidi and Giamou[9] explored the possibility of using ground-penetrating radar (GPR) to identify leaks in buried water pipes. The study did not give promising results on the usage of GPR to detect leak in pipes buried under soft soil, where the radar signal was highly affected by the nature of the soil.

In another approach focusing on the transport layer, Medidi et al[10] deployed a multi-hop wireless sensor network and proposed a transport protocol consisting of monitors and senders. Monitors in the network work as watchdogs to detect congestion and recover lost packets. Lin et al[11] studied the radio propagation and the determination of the path loss encountered between nodes in a wireless underground sensor network (WUSN) installed on fire hydrants and its above-ground relay nodes in a setting very similar to the ones carried by Hunaidi.[7]

Finally, Misiunas et al[12] validated and tested the use of pressure transient for detecting water pipe breaking in lab setting and real networks. The study adapted the continuous monitoring technique and used a modified two-sided cumulative sum algorithm to detect abrupt break-induced changes in the pressure data. Although the technique successfully detected the location of the break, this technique is applicable to single pipelines under two conditions, the side pipe has to be smaller in diameter than the pipeline and the reflection characteristics of the end boundaries can be derived, which limit its application in the real field.

3. PROPOSED METHOD OF DAMAGE DETECTION

The proposed advanced damage detection and identification method takes advantage of the non-invasive monitoring of pipe vibrations due to pipe rupture for pressurized pipe networks. The MEMS sensor network monitors the pipe surface acceleration typically at each network joint in a non-invasive fashion and computes in real-time a measure of acceleration change. More specifically, we install MEMS sensors at all the joints in the pipe network. As a result, at least two end joints of every link of the network are monitored.

When a rupture or significant leakage occurs in the monitored network, the transient change in the water pressure propagates through the network and induces corresponding change in the acceleration of pipe vibration. Based on the analysis of this measured acceleration data, the pipe damage can be found in the pipe between the two end joints, where the acceleration gradient values form local maxima. This is parallel to the observation, as demonstrated in Ref. 4 by analytical simulation, that the damaged pipe is found between two end joints where the water head gradient form local maxima. The procedure, utilizing the non-invasive pipe surface acceleration measurement, facilitates extremely simple and cost-effective identification of damaged pipe.

Fig. 1 shows a comparison between this novel damage identification methodology and the local maximum water head gradient (MWHG) method. We note that the development of the exact correlation between the water pressure and the corresponding acceleration on the pipe surface needs further analytical study aided by the calibration on the basis of scaled model tests and the field tests on a segment of some actual water systems such as Irvine Ranch Water District and Orange County Sanitation District.

For the field test, we plan first to take advantage of scheduled events by the system owner/operator including valve opening or closing and switching on and off the pumps. In this connection, we also caution that the acceleration change reflects not only the effect of pipe damage but also other effects including soil-fluid-structure interaction, particularly under earthquake conditions.

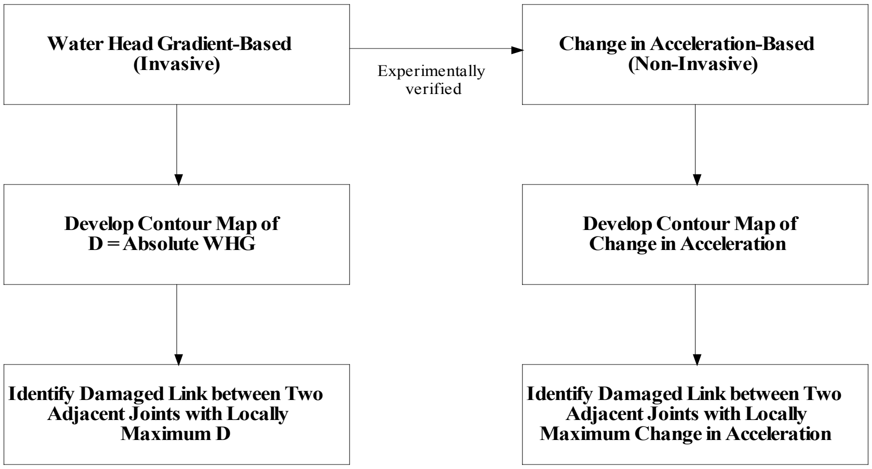
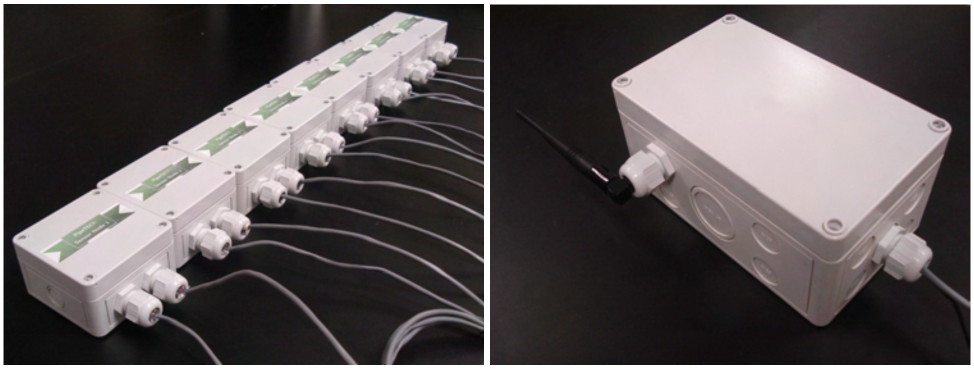


Figure 1. Damage Identification Methodology

All wireless sensing applications require the collected data or detected event to be transmitted to a central office for analysis and assessment. Wireless platforms can be roughly classified into three types: real-time monitoring, data logging, and event-detection. The first requires the measured data to be sent immediately after the event, while the other two cases are to collect data for later analysis. The proposed sensor technology provides a platform with near-real-time monitoring capabilities for wireless data acquisition, transmission, processing, analysis and decision making. The challenges to designing a real-time monitoring system are fast communication links, fair and efficient media access control (MAC) protocols, and low-latency routing protocols. In PipeTECT system, data aggregator units named Roocas are currently equipped with multiple radio transceivers for failure redundancy and short-range transmission and control, whereas sensor nodes named Gopher are built with high-precision MEMS accelerometers with low noise figure. For data communication between Roocas and Gopher, we apply to both wireless and wired interfaces. For this application of pipeline monitoring, we employ CAN (Controller Area Network) protocol for underground communication. Our system is a much more cost-effective, scalable approach compared to others.

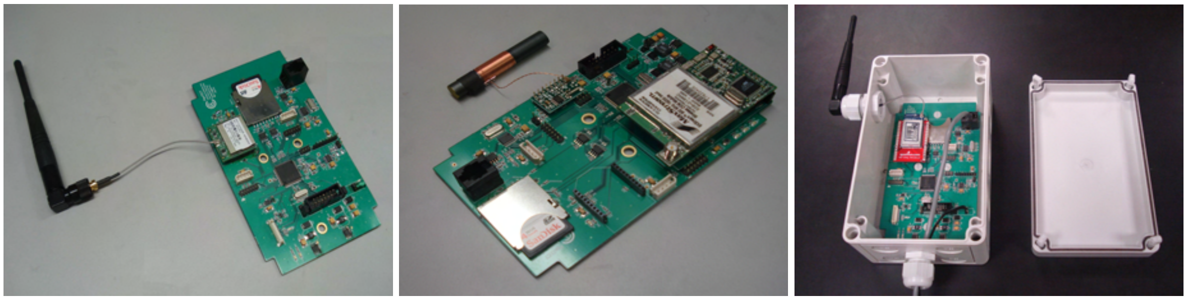
4. ARCHITECTURE OF WIRELESS SENSING SYSTEM

The PipeTECT sensing system is tiered networked system consisting of sensing nodes named *Gopher* and data aggregation and wireless bridging units named *Roocas*. Fig. 2 shows this MEMS-based PipeTECT sensing system. Since the pipes are usually located in the basement of pump station or under the manhole cover, the sensor system needs reliable, robust and stable communication to aggregate data from multiple sensing nodes. We need to consider unique enclosure with protection against windblown dust, rain, splashing water, and hose directed water. In this section, we first discuss the wired



(a) “Gopher”: Sensing Nodes (b) “Roocas”: Wireless Communication Unit

Figure 2. Photo of the PipeTECT sensing system



(a) PCB XBee (b) PCB Xstream (c) Open Wi-Fi

Figure 3. The PCB Assembly of Wireless Communication Units

and wireless communication interfaces for connecting nodes between tiers, and then we describe the hardware systems and software organization.

4.1 Communication Interfaces

We use both wired and wireless interfaces for connecting nodes of various tiers. For underground communication (i.e., between Gophers and Roocas), we use the Controller Area Network (CAN); for above-ground communication (i.e., between Roocas and the Internet), we support several different wireless interfaces. This section discusses these choices.

4.1.1 Wired interface: CAN

We choose CAN as the link between the sensing nodes and the wireless communication units. CAN is a low-complexity, high-throughput wired bus that can support the requirements of real-time monitoring and damage localization of pipes. The robustness of CAN has been proven in the automotive field. Up to 100 Gophers can be daisy-chained on the CAN bus to a Roocas for data aggregation. All PipeTECT sensing nodes also get powered by two additional power wires that run alongside the two CAN data wires. We use the modular RJ-10 jack commonly used in corded telephones to enable very easy chaining multiple Gophers in the field.

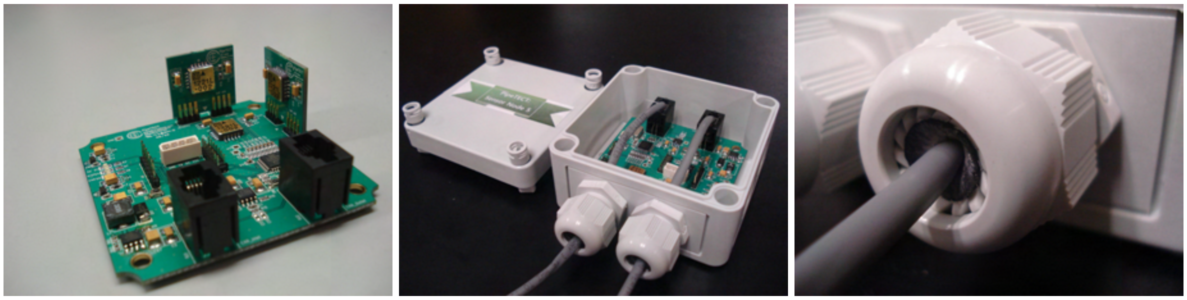
4.1.2 Wireless interfaces

The wireless unit, named Roocas, adopts three types of wireless technologies: XStream, XBee Pro, and Wi-Fi modules. Figs. 3(a) and 3(b) show the XBee and XStream modules, which are very similar to each other in that they are both weather resistant and support long distance communication (several to tens of kilometers) with the ISM 900 MHz operating frequencies, support for peer-to-peer mesh, and point-to-point and point-to-multipoint network topology. Their data rates are lower than Wi-Fi and more suitable for event reporting, rather than for data streaming. For data streaming, the wireless module with high data rate is applied to PipeTECT wireless communication unit as shown in Fig. 3(c). Wi-Fi offers several advantages for data streaming, including much better power efficiency, higher data rates, and world-wide license-free operation.

The three key issues with wireless communication are the communication range, data rate, and power. The XStream module provides very long range wireless data communication of up to 20 miles in direct line-of-sight and used in conjunction with a high-gain antenna. The throughput of the XStream is 19.2 kbps, while the XBee Pro supports 156 kbps of RF data rate with a range of up to 6 miles. The disadvantage of these wireless modules is the lower data rate compared to the shorter range ones that are suitable for event driven data collection. Thus, these two types of wireless techniques make our PipeTECT system very flexible: that is, PipeTECT sensing system can support both event-driven and data-streaming types of applications. Table 1 summarizes a comparison of the three types of wireless modules equipped with new wireless sensor system. We use the Wifly 802.11b/g module, which can support up to 11 Mbps. The one drawback of Wi-Fi is the shorter communication distance compared to the other two. To extend the communication range, we need better antenna positioning and focusing in order to operate effectively outdoors.

Table 1. Comparison of three types of wireless modules

Type	XStream	XBee Pro	WiFly
Throughput	19.2 Kbps	156 Kbps	11 Mbps
Frequency	900 MHz	900 MHz	2.4 GHz
Range	20 miles	6 miles	300 meters



(a) PCB Sensing Board (b) Open Sensing unit (c) Knockout

Figure 4. Photo of the PipeTECT sensing system

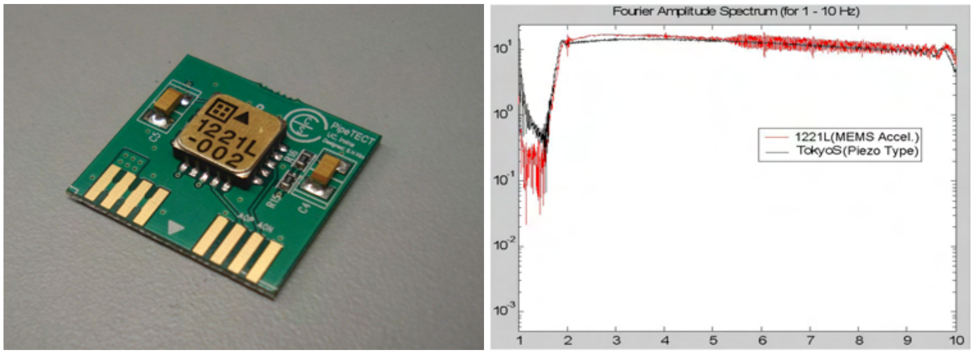
4.2 Time Synchronization

With regard to time synchronization, we use the NIST atomic clock broadcast (WWVB), GPS, and RTC (Real Time Clock). WWVB and GPS are for global time synchronization, and RTC is for local time synchronization. GPS enables more precise time synchronization, but it can fail when not in direct line of sight to multiple satellites. In contrast, the WWVB signal was strong and synchronization took place on the first pass even in a sheltered or enclosed environment because of its low signal carrier frequency (60 kHz).

We connected the wireless communication unit on the mote with two 256-Kbyte FRAM (Ferromagnetic RAM) chip, buffering vibration data into a short-term storage. Comparing to the flash memory, FRAM has many advantages in terms of low latency, low energy consumption, and high number of write cycles. In addition, a 16-GB Secure Digital High Capacity (SDHC) flash memory card acts as a local data logger. This SDHC card is has higher memory performance, speed rating, and storage capacity than a regular Micro-SD card does.

4.3 PipeTECT Sensing Node (Gopher)

The PipeTECT sensing node, named Gopher, is characterized by the use of a low-noise, high-precision MEMS-based accelerometer and user-adjustable digital filters. The sensing units can be equipped with three MEMS accelerometers in X, Y, and Z directions. One accelerometer is on the Gopher board, while the other two are of a pluggable type with sockets. Thus, we can adjust the number of axes from one to three to meet the requirements of different applications.



(a) MEMS-Accelerometer (b) Fourier Amplitude Spectrum

Figure 5. PipeTECT Sensing Unit Lab Validation Test: Comparison of SD1221 and Tokyo Sokusin Accelerometer

A main distinguishing feature of PipeTECT sensing units is the application of a 4-channel programmable signal converter (QF4A512) and the SD1221L-002 MEMS-type accelerometer. The MEMS accelerometer is of low noise characteristic, at 5 μg/Hz typical for the 2 g full-scale version. Its physical interface is analog, not digital, so we need to consider ADC (analog to digital converter) functions. Besides, signal conditioning is required to avoid aliasing error and analog and digital conversion noise. In this sense, Quickfilter QF4A512 is a very attractive component, because it supports a 16-bit ADC, four individually programmable 512-tap digital FIR filters, and programmable sampling rates. Fig. 4 shows the sensor node. From Fig. 4 (a), we can see an on-board uniaxial accelerometer and two other pluggable ones. By utilizing the pluggable external ports, we can easily extend the number of accelerometer axes to up to three. The enclosure of PipeTECT system has several knockouts for the power or data cable connection. This knockout port is also designed to protect the system against wind blown dust, rain, splashing water, and hose directed water as shown in Fig. 4 (c).

To evaluate the performance of MEMS accelerometer (SD1221L-002) equipped in the PipeTECT sensing node, we conduct an experiment in the lab by employing a shake table. Especially, this experiment has been carried out at the low frequency range of 1-10 Hz to show the possibility of applying to acceleration-based water pipe monitoring. The MEMS sensor applied to PipeTECT system and a traditional high-precision piezoelectric accelerometer, Tokyo Sokusin, were both installed on the shake table to measure the vibration. Fig. 5 shows the FFT (Fast Fourier Transfer) results from the MEMS accelerometer and the Tokyo Sokusin one to be nearly identical.

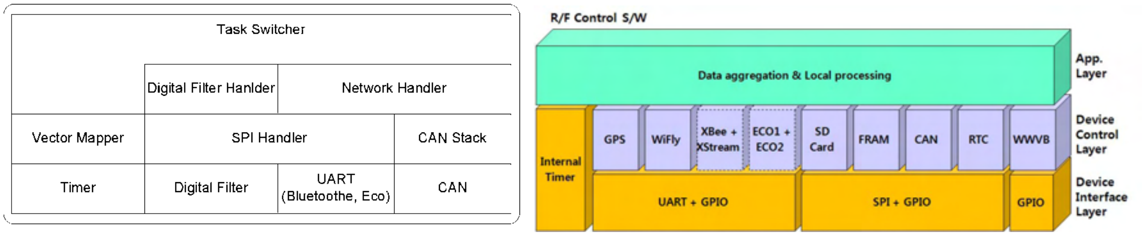
4.4 Software Implementation

PipeTECT system software consists of three tiers corresponding to the hardware configurations. The first tier collects data from accelerometers with association of a digital filter to mask noises and resides at the sensing node. The second is the data aggregation software operated in the Roocas unit. Host software including graphical user interface is in the top tier.

The main role of the sensor processing software is to collect and transmit data from accelerometers that are supposed to output three axes of acceleration data sampled at 1200 times per second, or with a period of 820 μs. Unwanted noises are filtered with a digital filter that can be configured with predetermined settings generated by specialized software. The configured digital filter eliminates the aliasing effects accompanying the sampling processes by limiting the frequency bandwidth. Every periodically sampled and filtered acceleration data record can be encapsulated in the predefined format that is designed to utilize CAN network protocol effectively as requested to be transmitted. Acknowledgments to requests are not considered so as to maximize the bandwidth and to lighten the computation load for sensing nodes. Since CAN network protocol takes care of collisions of carriers with its own arbitration scheme, a sensor node does not need to consider the transmission timing when multiple nodes access the bus at the same time.

The software architecture for the sensing node is shown in Fig. 6(a). The sensor processing software includes a task scheduler that handles multiple repetitive tasks in turn. Time assigned to a period of a task must be carefully considered so as to prevent a task from hogging CPU time. The scheduler eliminates needs of an operating system or excessive usage of timer interrupt. Those require a fairly large amount of resources, which cannot be found on the microcontrollers used in our Gopher sensing node. With the scheduled repetitive tasks, fast sampling and responsiveness upon spontaneous requests coming from network are guaranteed.

The software structure of data aggregation is shown in Fig. 6(b). Data aggregation software built in Roocas is in charge of transporting the acceleration data to HOST for the present. All acceleration data from up to eight sensor nodes are firstly stored into local storage (16GB SDHC card or 256K FRAM) with time stamps attached. A time stamp is 2-byte long and is not enough to represent the full timing data. A time stamp is an offset from a reference time issued periodically and has



(a) Sensing node. (b) Data aggregation.

Figure 6. The software architecture of the PipeTECT sensing system.

1-ms precision. A reference time has fields to represent a full time format, and is stored approximately every 1 minute. This scheme enables it to reduce usage of storage and bandwidth between Roocas and hosts. This time information is essential to analysis of the existence and nonexistence of rupture. WWVB and GPS (Global Positioning System) signals are utilized to get global time information because all data should be synchronized. However, the time interpolation is executed using RTC (Real Time Clock) and internal timer because this global time lacks sufficient resolution for 1 millisecond.

The acceleration data are buffered for one second before transmitted. Although commercial wireless products such as WiFly, WSN802G (Wi-Fi), XBee, XStream and Eco are different, the data is simply fed into the common serial interface to be converted into outgoing wireless packets. However, to improve the efficiency of data transmission and reduce the power consumption, each Roocas is allowed to transmit the data only during its assigned time slot, and it should be in sleep mode except during this time slot. We design Roocas to wake up for 100 milliseconds and sleep for 900 milliseconds. In the Wi-Fi case, data transmission per sensing node takes 12 milliseconds, and the remaining time is reserved for additional data request. Also, data compression can be selectively applied due to the difference in wireless data rate. Local processing algorithm for rupture detection can be imported into this software later.

In Fig. 7, the operation of the system is described in the following sequence:

1. To initiate the transmission of sensor data, the host computer sends the start request `RF_REQ_START_ACC` to Roocas unit(s).
2. Roocas sets the reference time for time packet and broadcasts the start request `CAN_REQ_START_ACC` to its Gophers (sensing nodes).
3. Each Gopher periodically transmits the acceleration data with the response command `CAN_CYCLE_DATA_ACC` after sampling the accelerometer.
4. Roocas receives the data from the Gophers and attaches the time stamp. Data is written into local storage sequentially.
5. After time packet, the reference time packet `RF_CYCLE_TIME_ACC` follows. Then, all collected data during one second is split based on Gophers and `RF_CYCLE_DATA_ACC` packet is transmitted to the host including the reference time packet `RF_CYCLE_TIME_ACC`.
6. Repeat the transmission for other sensing nodes.
7. Roocas waits for additional requests from the host. After the elapse of its time slot, Roocas sets its wireless module into sleep mode. During data transmission from Step 5 to 7, Roocas executes Step 4 in background mode.

The communication between Roocas units and hosts are realized with various wireless communication devices. To illustrate the case of using a WiFly module that enables Roocas to build a Wi-Fi channel to a specified network, each UDP packet contains a series of normal data segments preceded or followed by fragmented segments. The host software

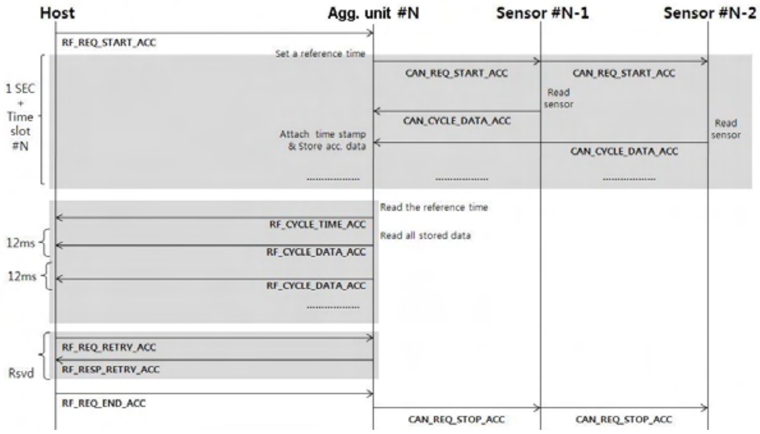


Figure 7. Sequence flow of overall system.

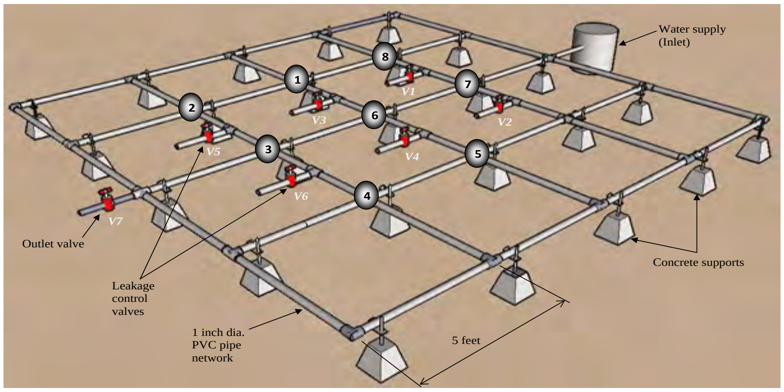
assembles the chunks extracted from UDP packets in order to connect them to build a series of complete segments out of them. The host software includes a packet sniffer to identify possible fragmented IP packets (broken UDP packets) due to the communication channel problems. The fragmented IP packets might have a chance to be recovered by the command builder. The host software not only interprets the received segments and records them into files but also indicates the total number of packets received, number of commands received per second, and elapsed time information in order to help performance analysis. The recorded data is comprised of reference times and acceleration data with time stamps. Support for SNMP protocol is also included to enable interoperability with other types of Wi-Fi modules such as RFM WSN802G module that utilizes SNMP protocol to transport data and status of the module itself.

5. PRELIMINARY EXPERIMENTS

5.1 Experimental Setup

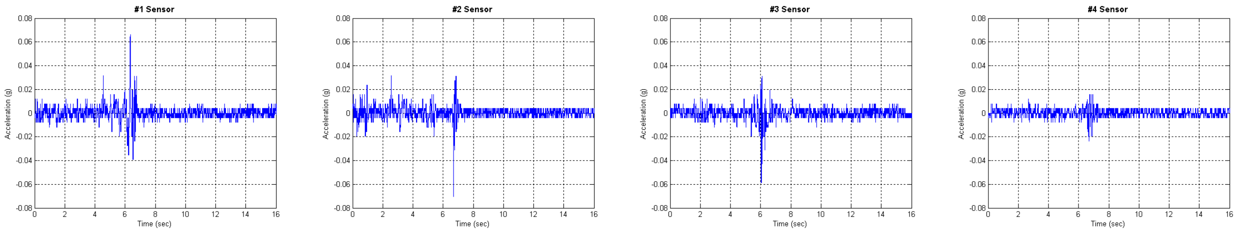
A small-scale, symmetric water network modeled with 40 PVC pipes of 1-inch diameter is designed with seven valves labeled V_1 thru V_7 as shown in Fig. 8 in order to examine the impact of multiple ruptures in a single system. Fig. 8(a) shows the photo of this pipe network, while Fig. 8(b) shows the overall size of this pipe network to be about 20×20 ft, where valve V_7 is used to control water pressure inside the pipe network and valve V_1 through V_6 to emulate multiple ruptures, respectively. Besides, eight Gophers (sensing units) labeled 1-8 in gray circle were daisy chained to one Roocas (Wi-Fi unit) to make a sensor network. Four pressure gauges are installed at locations *inlet*, V_3, V_6, and *outlet* to monitor the steady state flow under the initial condition. More specifically, the inlet was connected to the utility water supply line, and all valves were initially closed, allowing the pressure to accumulate gradually, and then valve V_7 was opened half way. This procedure can provide not only a semi-steady state water pressure inside the pipe network but also ambient noise due to water flowing inside the pipe.

(a) Photo of a 5×5 Water Pipe Network

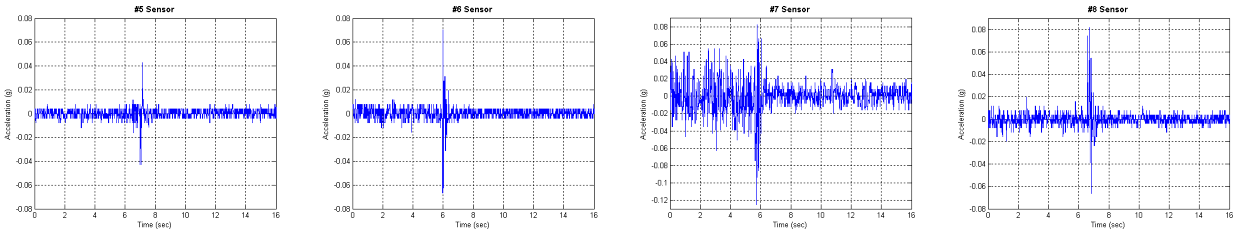


(b) Drawing of Water Pipe Network and the locations of PipeTECT sensors

Figure 8. Experimental Setup Showing a Small-Scale Water Pipe Network

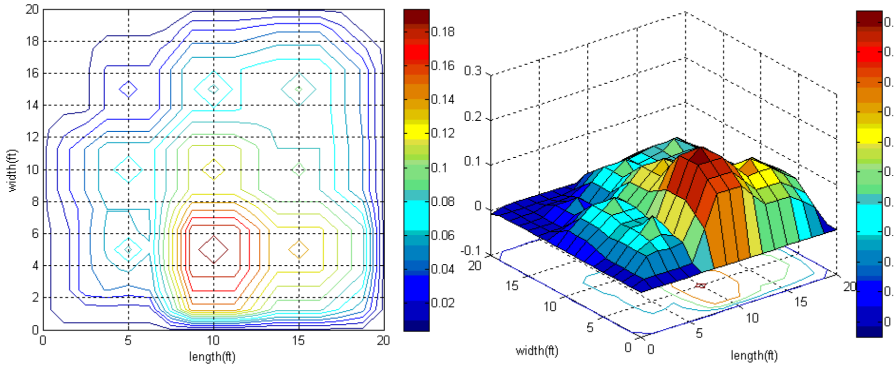


(a) Sensor Unit 1 (b) Sensor Unit 2 (c) Sensor Unit 3 (d) Sensor Unit 4



(e) Sensor Unit 5 (f) Sensor Unit 6 (g) Sensor Unit 7 (h) Sensor Unit 8

Figure 9. Acceleration Data Measured by PipeTECT sensing system



(a) 2D Contour Map (b) 3D Contour Map

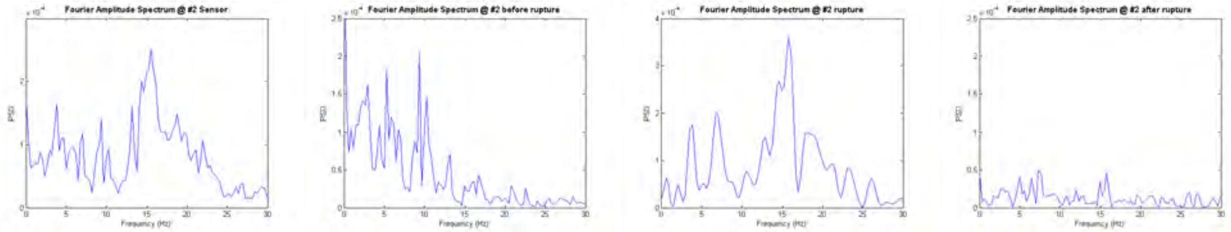
Figure 10. Simulation results for a miniature water pipe network.

In steady state, the pressure in the pipe network was shown to be 18 psi at all pressure gauges. Then, two valves were opened simultaneously and began to discharging water, and the water network eventually dropped down to zero psi. Sudden opening of two valves simulates multiple ruptures due to pipe breaking during a natural disaster. The combinations of multiple ruptures are (V_1, V_3), (V_1, V_6), and (V_3, V_4), chosen based on the symmetry of water pipe network. The eight Gophers on the water network collected vibration data in real-time and sent the data to the Roocas for data aggregation and Wi-Fi uploading to a host computer via an access point in real-time.

5.2 Results and Analysis

Each Gopher was equipped with up to three MEMS sensors for X, Y, and Z directions as mentioned in Section 4. In this experiment, Gopher measures the change in acceleration in the Z direction, which is the orientation of its internal MEMS accelerometer. All eight Gophers successfully transmitted acceleration data at 150 samples per second in real time to a laptop computer at the site. Recording of the data began when the water pipe network reached steady state after injecting water to the pipe network, and recording stopped after a few seconds from half opening of the valves V_1 and V_3 abruptly at the same time to simulate multiple ruptures in the pipe network.

Fig. 9 shows a set of Z-direction time-history acceleration data measured by eight Gophers during the simulated multiple rupture case at valve locations V_1 and V_3. These plots show that the effect of simulated rupture measured in terms of the amplitude (intensity) of acceleration depends on the distance between the rupture location and the sensor locations. For example, Figs. 9(a) and (f) or (g) and (h) show two representative acceleration data measured on the segment of rupture; (b),



(a) Entire time history (b) Pre-rupture (c) Rupture (d) Post-rupture

Figure 11. Frequency Domain Analysis of PipeTECT Sensor#2

(c) and (e) show those measured one segment away from the rupture point; (d) is those one diagonals away, respectively. The sharp change of acceleration in each chart corresponds to the event of opening valve V_1 and V_3.

Upon closer examination of Fig. 9, we find that the amplitude at joints 1 and 6 (or 7 and 8) on the rupture segment are 0.105 g and 0.136 g (or 0.21 g & 0.15 g), respectively. At one segment away (joints 2, 3 & 5), they are 0.1 g, 0.09 g and 0.084 g, and at one diagonals away (joints 4), it is 0.04 g. Therefore, it is clear that the acceleration change near the rupture locations is higher (or locally largest) than those of other sensing locations. The amplitude of the acceleration change decreases as one moves away from the rupture point in distance. This peak value of acceleration is considered as the main parameter in identifying the rupture location in the pipe network. By taking all the peak values obtained from the acceleration time histories, contour map can be plotted for the pipe network, as shown in Fig. 10 for the V_1 and V_3 rupture case. The simulated damage in this case is located in the innermost and smallest polygon on the 2D and 3D contour maps. It is comparable to the contour map plotted from numerical simulation results of a damaged pipe network with two rupture locations in terms of water head gradient.[4]

Frequency domain analysis is carried out for the detection of rupture. Fig. 11 shows the Power Spectral Density (PSD) in frequency domain for Gopher#2 for the purpose of examining the nature of the rupture signal. In more detail, Fig. 9(b) describes the time histories of Sensor #2 for the rupture locations at V_1 and V_3. Fig. 9(b) can be classified into three parts: pre-rupture (0-6 sec), rupture (6-8 sec), and post-rupture (8-16 sec). Fig. 11 (b), (c), and (d) are plotted using these three different time windows of the signals. From Fig. 11(c), we can recognize the frequency range of 16-17 Hz is related to the rupture frequency. The peak frequency ranged between 0 and 15 Hz before the rupture happened, as shown in Fig. 11(b), whereas after the rupture, the peaks in the 0-15 Hz range rapidly decreased while the peak in the 16-17 Hz range stayed almost same, as shown in Fig. 11(d). Thus, it is reasonable to say the range of 16-17 Hz is the rupture frequency. This frequency domain analysis will be useful for distinguishing the rupture signal from those caused by earthquakes or ambient noise on the water pipe. In time domain, it is not always possible to distinguish between an earthquake event or ambient noise by just looking at a sudden change of the signal, but in frequency domain, the frequency content of the signal the pipe rupture event can be precisely detected.

6. CONCLUSIONS AND FUTURE WORK

The concept of a novel water-pipe damage detection method based on maximum pipe acceleration gradient data was validated by the small-scale water pipe network experiment. The PipeTECT sensing system collected the acceleration data from different joints of a water pipe network. Each PipeTECT sensing node measures the acceleration change on the pipe surface non-intrusively to determine rupture events and to locate the multiple rupture points. The results show that we can detect and identify the damage locations of water pipe by the contour maps, time-correlated acceleration data analysis, and frequency domain analysis. To enhance the accuracy of detecting damage location in a larger-scale network, we need to improve the local processing algorithm for rupture detection, data compression technology, enhanced communication protocol between Roocas and Gopher nodes. Further study is needed to correctly analyze the situations in sharp bends and T-joints and to understand the pipe vibration under the ambient and transient hydraulic conditions. We plan to install a PipeTECT sensing system on a subset of a regional water supply network such as the City of Westminster and the Irvine Ranch Water District, where their existing SCADA measurements can be used for possible comparison.

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