Household Water Pipeline Leakage Detection and Localization through Differential Sensor Reading and Transient Analysis via ZigBee Wireless Technology

U.Andulte[1], J.Diwa[2], J.Manuel[3], G.Mappatao[4], G.Ocampo[5] and A. Garcia[6]
Electronics Engineering Department, Faculty of Engineering
University of Santo Tomas, Manila, Philippines.
uoandulte@gmail.com[1]
nitejosh@gmail.com[2]
joelpatrick.manuel@gmail.com[3]
grantmappatao@gmail.com[4]
riel.luis.ocampo@gmail.com[5]
argarcia@ust.edu.ph[6]

***Abstract*—Water is a limited and valuable resource henceforth it is essential to manage this resource because it is vital to human survival and it is almost an input for all production and processes in sectors such as Industry, Agriculture, Energy, etc. However, water consumption is lost due to failures in the water distribution line systems as these failures are mainly attributed to the pipe leakages and failure of the supply system itself. In this study, a Smart Water Usage Management System that can detect and locate water leakage is proposed. The said system implements an algorithm that primarily gathers data of behavioral relationship of flow rate in response to the position of the leak with the aid of flow meter sensor in a wireless sensor network.**

***Index Terms*—Differential Reading; Leakage Detection; Transient Analysis; Water Usage.**

I. INTRODUCTION

The issue of water shortage is considered one of the major challenges in the world. As such, many countries are now concerned with proper water management. Along with proper management of water, it is also important to limit water losses. This includes leakage, contamination, illegal connections, unknown use, etc. [1]

According to the OECD Environmental Outlook to 2050, global water demand will increase by 55% due to growing demand from manufacturing (+400%), thermal power plants (+140%) and domestic use (+130%). A recent study conducted by the World Bank indicates that 60% of the domestic water consumption is lost due to failures in the water distribution line system and that these failures are mainly attributed to the pipe leakages and failure of the supply system itself. In the Philippines, 81% of Maynilad's non-revenue water is attributed to leaks in its distribution network which yields to an economic impact to the consumers and to the suppliers as well. On the other hand, water leaks may also cause direct danger to people because of water pollution by contaminations in the pipelines. With this, water distribution lines need to be enhanced in order to address its socio-economical, environmental and health issues on our daily lives. [8] Most water distribution lines are installed under the surface, inaccessible to many, which results to the difficulty on locating leakages. In addition, these methods can only detect leakages at main water distribution lines and not entirely on residential household pipelines. As a result, most leakages in residential areas remain undetected in a longer period compared to those at the main water lines. A study conducted by EPA shows that there are 10,000 gallons of water wasted every year from household leakages and that the owners can save up to 10 percent of their total water bill.[2] Therefore, a system that can detect possible leakages in household pipeline system is proposed to further address these problems. The proposed system will use differential reading method to detect and locate possible leakage in the pipe system and utilize transient analysis in locating the leak. Flow sensors in a Wireless Sensor Network (WSN) connectivity will be installed to remotely monitor abnormalities using ZigBee's wireless communication. The volumetric flow rate gathered will be transmitted to a base server and will be analyzed. Leakage will be detected once the reading of a sensor drops. The accuracy of the system will be tested by comparing the detected position to the actual position of the leak.

.

II. LITERATURE REVIEW

There are several methods that are used in order to detect and locate leakages in water distribution pipes. This includes Acoustic Measurement, Vision Based System, Fiber Optic Monitoring and/or Pressure/Flow monitoring. [2]

Acoustic measurement uses hydrophones or accelerometer to measure acoustic emissions along the pipeline. This technique is based on the principle that a liquid, seeping due to leakages, creates an acoustic signal that travels along the pipe walls. Different cross correlation methods can be used to estimate the position of the leak. However, this method requires complex processing algorithms and is generally expensive. [7]

Vision Based System uses image processing or laser scanning to find cracks and faults along pipelines. For it to operate, it requires an interior access to pipes. This method may also be costly, requires high processing power and a skilled operator to analyze the result. [6]

Fiber Optic Monitoring is another method on leakage detection wherein it utilizes fiber optic technology. It can be deployed over long distances to detect leaks or measure strains in the pipes. The disadvantages in using fiber optics is the difficulty in implementation and the cost of installation. [8]

The common disadvantage of these methods is cost efficiency. Most of these methods are quite expensive and may not be practical to implement on household setting. Moreover, it requires human involvement, making it time consuming and labor intensive. System costs and complexity of installation are usually high for this type of leakage detection methods and therefore, their application is limited. [19]

Another promising method that solves all the above mentioned issue is through the use of Differential Flowrate Reading. In this method, flow meters are used to measure the flow of the water between two points, if a leak happens in a place anywhere between these two sensors, the flow rate of the second sensor drops. Thus, the microcontroller detects the drop in the volumetric flow rate and identifies this as leak. Deployed as Wireless sensor node, which eliminate human involvement, on leakage detection. Flow sensors are inexpensive and are easy to install. [1] However although it offers low cost with high accuracy of leak detection, it cannot locate the position of the leak. For an effective leakage management and control of water loss, identifying the exact position of the leakages is vital to hasten pipeline leakages and maintenance. [19]

This paper proposes leak localization algorithm integrating differential reading to detect and localize leakages along household water pipes through utilization of transient analysis on changes on flow rate reading.

III. OBJECTIVES

The main objective of this study is to devise a Smart Water Management System that can detect and possibly locate water leakage. The specific objectives of this study are as follows:

a. To integrate wireless sensor node to a single pipeline that reads the volumetric flow rate.
b. To analyze the relationship of the change of flow rate reading relative to position of leak along the pipe.
c. To implement a software based-solution by utilizing the establish relationship of the change in flow rate reading and the location of the leak.
d. To test the accuracy of proposed solution on locating the exact position of the leak.

IV. RESEARCH METHODOLOGY

A. *Water Pipe with Integrated Sensor Node*

For the experimental setup, the group only considered a single pipeline using a PVC (Polyvinyl Chloride) water pipe with a diameter of ½ inch and a length of 4 meters. Hall sensor flow meter were connected at both terminations. Flow sensors were used to measure the flow rate of the water between two points, whenever a leak happens anywhere between two sensors, the flow rate of the second sensor drops. Therefore, the difference in the readings between the two sensors will prompt the microcontroller, indicating that there is a leak. Communication between the two modules is done by ZIGBEE wireless communication. The flow rate readings which are transmitted periodically by the sensors through ZIGBEE are being received by the Arduino microcontroller which is then connected and analyzed in the PC. In the server, the flow rate values are compared if there is a change in the flow rate value. This set-up is called wireless sensor network (WSN). Each flow sensor is considered as a single node. Figure 2 shows the setup of the single pipe integrated with WSN. [13]

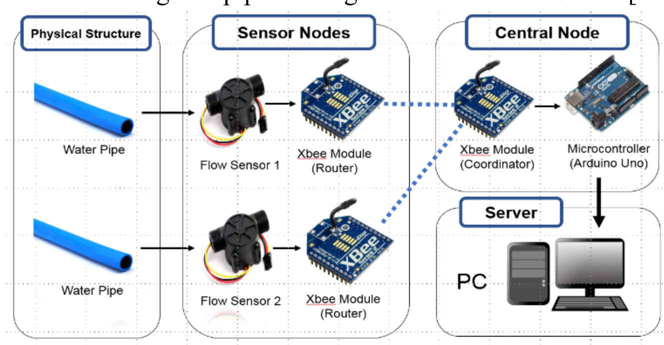

Figure 1. Overall System Architecture

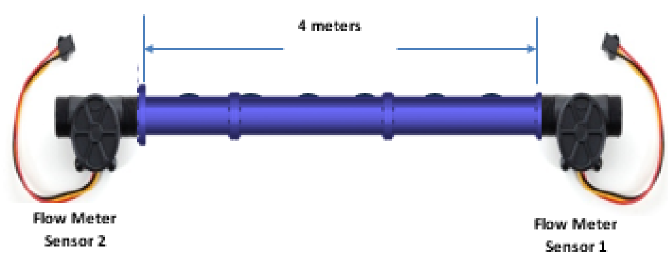

Figure 2. Pipeline Physical Setup

B. *Wireless Sensor Network for Data Acquisition*

Wireless Sensor Network (WSN) typically consists of small spatially distributed devices to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration etc. With WSN connectivity, central unit for further processing and analysis collects data from remote sensors of different types. [13]

Each WSN node is typically equipped with one or more sensors, a wireless transceiver including antenna or other wireless communications device, a microcontroller and memory to process received data and prepare data for transmission and execution of required networking tasks, a networking and application software which specifies networking protocols and application functionality, An energy source, usually a battery.[13]

A Star network topology for Wireless Sensor network will be implemented on the proposed system. Star networks are connected to a centralized communication hub (sink) and the nodes cannot communicate directly with each other. The entire communication must be routed through the centralized hub. [15]

C. Flow Meter Calibration

The flow meter used for this study is a Hall Effect water flow sensor. The sensor consists of three wires: black, red and yellow. Black and red wires are used to supply power to the sensor while the yellow wire yields data pulses whenever water is flowing through the sensor. The frequency of the pulses (pulse/second) is intended for the determination of water flow rate. Figure 3 shows the Hall Effect water flow sensor used in this study.

Figure 3. Hall Effect Flow Sensor

$$\mathbf{F = k \times Q} \qquad (1)$$

Where:
F = frequency of the pulses (Hz)
k = calibration factor
Q = Flow rate (L/m)

Equation 1 is used to calculate the flow rate (Q) of the water. The pulse frequency is obtained from the sensor while the calibration factor (k) is referred from the specification sheet of the flow sensor. The flow sensor model used in the study is SEN-HZ21WA, which has a calibration factor of 8.1. Thus, corresponds to an output of 8.1 pulses per second whenever a flow rate of 1 L/m passes through the sensor.

In order to measure the frequency each time the sensor outputs a pulse, the period for each pulse is determined. Consequently, the frequency is determined by obtaining the reciprocal of the period.

D. ZigBee Transmission

The ZigBee module, XBee S2C, was used to transfer data readings from the flow sensors to the PC server. A ZigBee module located at the transmitting end for transfer of information and another at the receiving end. One ZigBee module is configured as a coordinator while the other ZigBee module, connected with the sensor, is configured as router through a software called X-CTU. Software configuration has been done with the aid of an XBee Explorer which serves as an interface between the module and PC.

ZigBee modules are identical, having the same hardware specification and personal area network ID, in order to ensure compatibility and connectivity among the devices. This allows the periodic meter readings to be successfully received whenever the user prompted the ZigBee to send a reading at any given time.

E. Data Processing and Program Flow

The coordinator ZigBee module is connected to

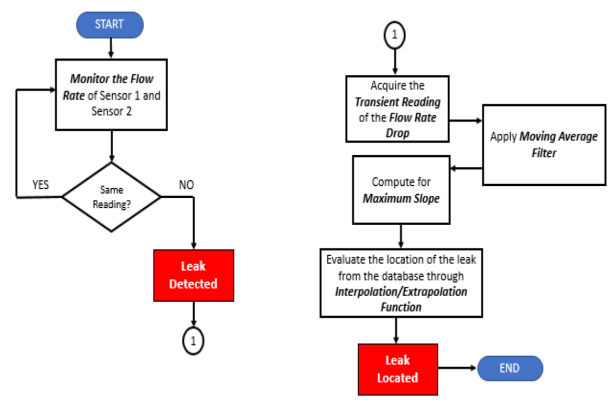

Figure 4. Program Flow

microcontroller, Arduino Uno, utilized for data sampling, calibration, and data processing that would be subjected for analysis through a personal computer.

The program is initialized by acquiring the volume flow rate (L/m) from both sensors. The values obtained are then compared by the system if the values are identical. When the two values are substantially different (i.e. a significant drop in the flowrate at the succeeding flow meter), the system will detect this as a leakage in the pipeline. This is differential reading.

This would eventually trigger the system to obtain the transient response readings of the flow rate drop. Upon obtaining the flow rate drop, a Moving Average filter was applied in order stabilizes the flow rate samples. From these, the location of the leak will be evaluated from the database by the utilization of Interpolation/Extrapolation Function which will then be compared to the actual location of the leak.

V. THEORY

Differential Reading is an ideal type of system in detecting water leak. It measures the volumetric flow rate between two sensors. If one of the flow rate reading of the sensor drops, it indicates the leak. The main advantage of the said method is that It considers whatever type of pipeline whether it is complex (with change of elevation, area, pressure) or straight it would not alter the leakage detection that leads to erroneous results proven by the equation of continuity (flow in equal to flow out). [18] Volumetric *flow rate* is defined as:

$$\mathbf{Q = v \times \mathit{a}} \quad \mathbf{(2)}$$

Where $\boldsymbol{Q}$ is the flow rate, $\boldsymbol{v}$ is the velocity of the fluid, and $\boldsymbol{a}$ is the area of the cross section of the space the fluid is moving through. Volumetric flow rate can also be found with continuity. The equation of continuity works under the assumption that the flow in will equal the flow out. This can be useful to solve for many properties of the fluid and its motion. This can be expressed in many ways, for example: $A1*v1=A2*v2$. The equation of continuity applies to any incompressible fluid. Since the fluid cannot be compressed, the amount of fluid which flows into a surface must be equal to the amount flowing out of the surface. [18]

Transient Analysis will be utilized in locating the leakage. It is basically a method that analyzes a system in an unsteady state. Since the variables defining the state of a system varies with respect to time. The term transient refers to any unsteady flow condition. It can refer to a situation where conditions are continually varying with time or to transition flow between two steady state conditions. The larger the incremental change and the faster that change takes place. [20]

According to the study held by Florida State University regarding Modeling Leakage in Water Distribution Systems, Transient analysis has become the latest method in trying to determine leakage areas within a system. In addition, previous research has suggested that transient analysis has great potential to identify leakage location rather than steady state analysis. Therefore, the study suggested that future research may utilize transient software to identify the relationship between leakage quantity and location. [21]

VI. TESTING AND ANALYSIS

It was initially investigated how the position of the leak affects the transient flow rate drop when leakage occurs, six holes were established along the pipeline which locations are 7 cm, 77.2 cm, 147.5 cm, 217.6 cm, 287.8 cm, and 359.0 cm relative from the Flow Sensor 1 as shown in Table I.

Table I. SIX HOLES LOCATIONS RELATIVE TO SENSOR

Holes	Position
Leak 1	7 cm
Leak 2	77.2 cm
Leak 3	147.5 cm
Leak 4	217.6 cm
Leak 5	287.8 cm
Leak 6	359.0 cm

Each transient response of the aforementioned leakages was obtained and projected on a graph through MATLAB. This can be seen through figures 5 to 10. The input flow rates for the experiment is 12-13 L/m, and when leaks occur, flow rate declines to 6 L/m.

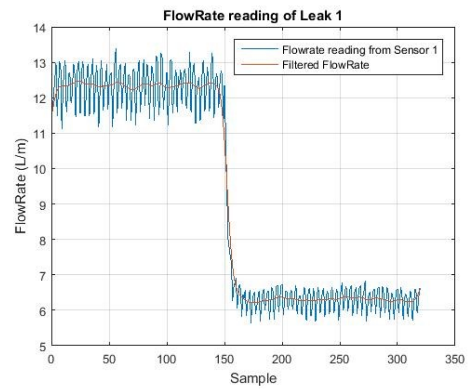

Figure 5. Flow rate reading of Leak 1

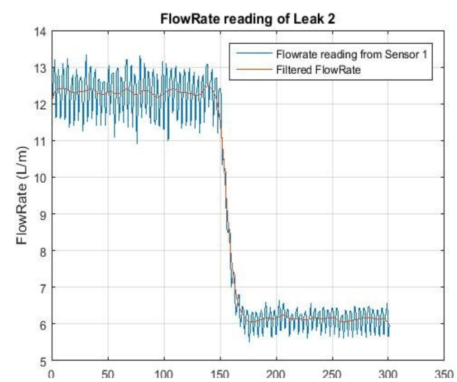

Figure 6. Flow rate reading of Leak 2

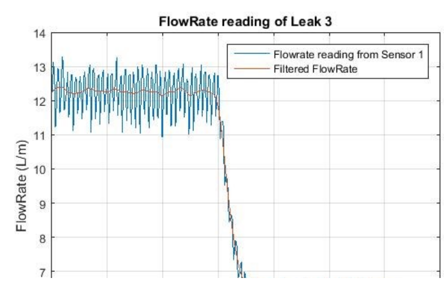

Figure 7. Flow rate of Leak 3

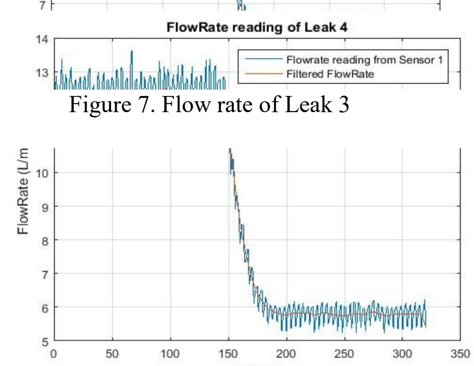

Figure 8. Flow rate of Leak 4

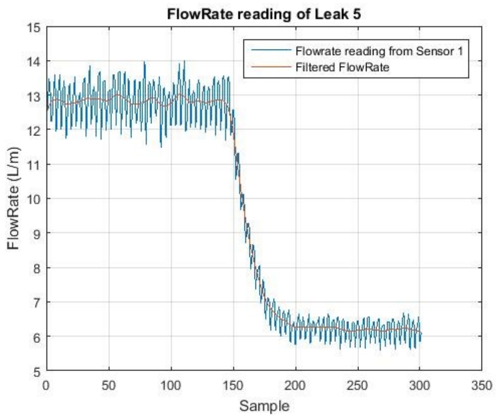

Figure 9. Flow rate of Leak 5

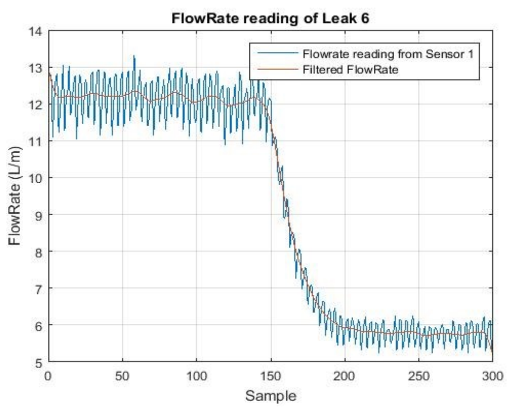

Figure 10. Flow rate of Leak 6

Since the graph projects data stream with noise as a form of oscillations. Using MATLAB, a Moving Average Filter was utilized to eliminate most of the noise in the stream as this is suitable for further analysis.

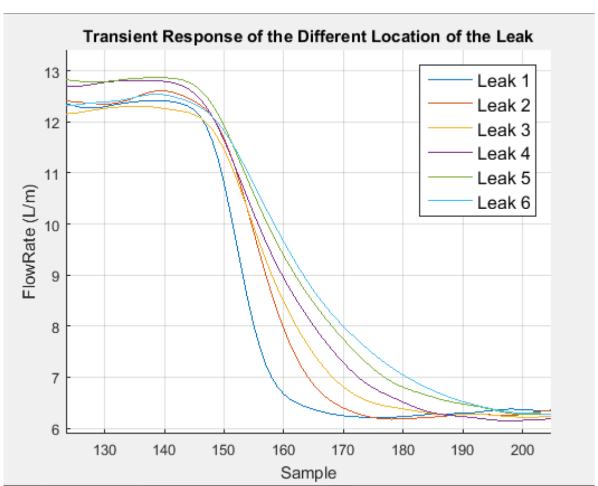

Figure 11: Filtered Transient Response of the Leakages in the System

In Figure 11, all of the leaks are simultaneously projected in the same plot to allow better analysis and comparison. Based on the result, *Leak 1* yields the nearest location of leak relative to Sensor 1, which displays the steepest slope among the leaks.

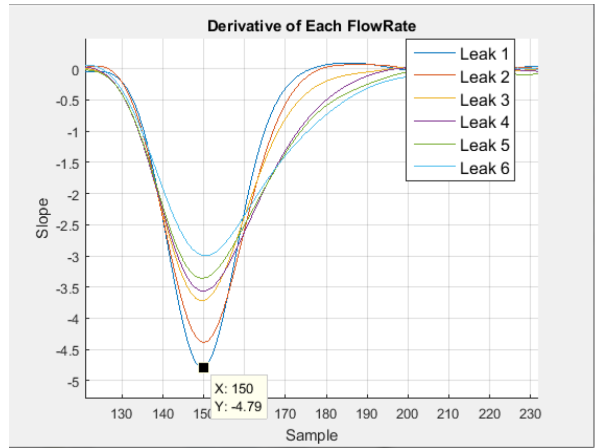

Figure 12. Derivative of each Transient Response

From Figure 12, differentiation was applied to the system as this provides normalization and better view of the slopes. Thus, the derivative of flow rates was determined to obtain the slope of each transient response which is displayed through plots. Based on Table II, *Leak 1* achieved the highest slope having -4.7901 which is the nearest leak relative to Sensor 1, while *Leak 6* having the lowest slope of -1.8598.

As the leak draws further away from the Sensor 1, the maximum slope attained decreases. The negative sign only indicates that system involves relative decline in values due to leakages.

TABLE II. THE MAXIMUM SLOPES OF EACH LEAK

Leak	Position	Maximum Slope
Leak 1	7 cm	-4.7901
Leak 2	77.2 cm	-3.4174
Leak 3	147.5 cm	-2.66195
Leak 4	217.6 cm	-2.3915
Leak 5	287.8 cm	-2.21515
Leak 6	359.0 cm	-1.8598

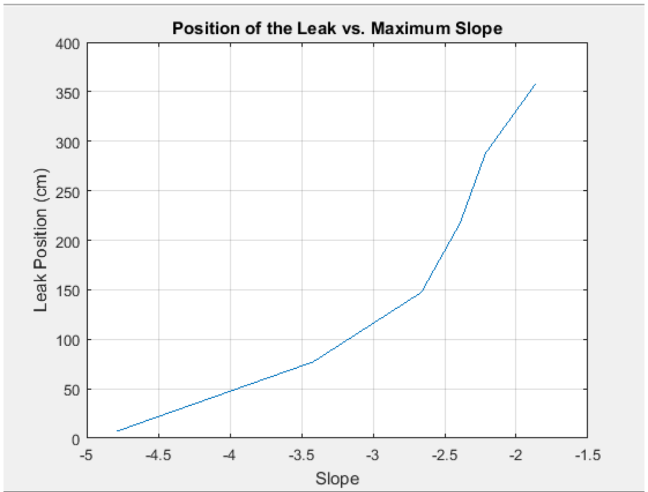

Figure 13: Position of the Leak vs. Maximum Slope Attained

VII. Results and Discussions

Since there is a significant relationship which has been established from the previous observation, this relationship can be used to determine the position of the leak. Based on Figure 13, leaks which occurred closer to Sensor 1 will have a steeper slope (more negative) compared to leaks which are located farther from Sensor 1. By using the Interpolation/Extrapolation Function, leakage localization would be possible in determining leakages along the pipeline by using the database from the previous runs.

From Table III, to test the performance and accuracy, three random holes/leakages were established having an actual position of 33.5 cm, 160 cm, and 386 cm. Three trials were made per leak. Upon acquiring the slopes, *Test Leak 1* projected the maximum slope since this was the nearest of all leaks. By using interpolation/extrapolation function, the approximate position of the leakages was evaluated having at most 20.4278% error.

Table III. Leak Localization Testing

Test Leak	Actual Position	Trials	Max Slope	Approximate Position	Difference	Percentage Error
1	33.5 cm	Trial 1	-4.18085	38.15cm	4.65 cm	13.9017%
		Trial 2	-4.1959	37.38cm	3.88 cm	11.6041%
		Trial 3	-4.1381	40.34cm	6.84 cm	20.4278%
2	160 cm	Trial 1	-2.6337	154.82cm	5.17 cm	3.2360%
		Trial 2	-2.7177	142.31cm	17.68 cm	11.0549%
		Trial 3	-2.6972	144.21cm	15.78 cm	9.8627%
3	386 cm	Trial 1	-1.8309	364.79cm	21.20 cm	5.4946%
		Trial 2	-1.8380	363.30cm	22.63 cm	5.8632%
		Trial 3	-1.7829	374.40cm	11.59 cm	3.003%

$$Percentage\ Error\ (\%) = \frac{|Actual\ Position - Approximate\ Position|}{Actual\ Position} x\ 100$$

VIII. Conclusion

Flow rate reading was utilized to detect and locate leakages along a water pipe. This method is efficient to implement on household setting; since existing methods might impose erroneous results or might fail in detecting leakages due to various human activities around the household.

However, a suitable method such as continuous reading of the changes in flowrate or pressure along water pipes can be utilized in order to efficiently detect and/or locate leakages on household setting.

This paper aims to locate leakages along pipeline by reading flowrate changes in the pipeline. Differential Reading and transient analysis were utilized to detect and localize the position of the leakage. When there is a discrepancy between the readings of the two sensors, it means that there is a leak between them. Following the occurrence of leak, a transient drop of flowrate can be observed and used to analyze and to locate position of the leak.

For the experimental setup, the effect of the position of the leak to its transient flowrate drop was first established. It was found out that, as the water reading drops due to the presence of leak, the maximum slope or rate of change of flowrate in reading becomes steeper on leakages that nearer to sensor 1 (Output) . Using the established relationship, random leaks were made along the pipe, and by determining the maximum slope of each leak, its position can be approximated using interpolation/extrapolation function.

References

[1] M. Farley, *Leakage management and control.* Geneva: World Health Organization.

[2] Hieu, B.; Choi, S.; Kim, Y.U.; Park, Y.; Jeong, T. Wireless transmission of acoustic emission signals for real-time monitoring of leakage in underground pipes. *KSCE J. Civ. Eng.* 2011, *15*, 805–812.

[3] J. Vlachopoulos and D. Strutt, “Basic HeatTransfer and SomeApplications in Polymer,” vol. 2, pp. 21–33, 2002.

[4] Shakmak and A. Al-Habaibeh, "Detection of water leakage in buried pipes using infrared technology; A comparative study of using high and low resolution infrared cameras for evaluating distant remote detection," *2015 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT)*, Amman, 2015, pp. 1-7.

[5]. Kingajay, M.; Jitson, T. Real-time laser monitoring based on pipe detective operation. *Proc. World Acad. Sci. Eng. Technol.* 2008, *44*, 127–132.

[8] “Maynilad Water Services Inc.". *Mayniladwater.com.ph*.N.p., 2017. Web. 30 Apr. 2017.

[6]. Sinha, S.K.; Knight, M.A. Intelligent system for condition monitoring of underground pipelines. *Comput. Civ. Infrastruct. Eng.* 2004, *19*, 42–53.

[7] Gao, Y.; Brennan, M.; Joseph, P.; Muggleton, J.; Hunaidi, O. On the selection of acoustic/vibration sensors for leak detection in plastic water pipes. *J. Sound Vib.* 2005, *283*, 927–941.

[8]. Yan, S.Z.; Chyan, L.S. Performance enhancement of BOTDR fiber optic sensor for oil and gas pipeline monitoring. *Opt. Fiber Technol.* 2010, *16*, 100–109.

[9] “Leakage Control,” SSWM, 2017. [Online]. Available: http://www.sswm.info/content/leakage-control.html. [Accessed: 30-Apr-2017].

[10] “Data Profiling,” Technopedia, 2017. [Online]. Available: https://www.techopedia.com/definition/25986/data-profiling.html [Accessed: 30-Apr-2017].

[11] S.C. Hsia, S.W. Hsu, Y.J. Chang, "Remote monitoring and smart sensing for water meter system and leakage detection", *IET Wirel. Sens. Syst.*, vol. 2, no. 4, pp. 402-408, 2012.

[12] W. Moczulski, R. Wyczolkowski, K. Ciupke, “A Methodology of Leakage Detection and Location in Water Distribution Networks – The Case Study”, 2016 3rd Conference on Control and Fault-Tolerant Systems.

[13] M. JayaLakshmi and V. Gomathi, "An enhanced underground pipeline water leakage monitoring and detection system using Wireless sensor network," *2015 International Conference on Soft-Computing and Networks Security (ICSNS)*, Coimbatore, 2015, pp. 1-6.

[15] Sharma D., Verma, S. “Network Topologies in Wireless Sensor Networks: A Review.” *International Journal of Electronics &Communication Technology.* 2013, pp. 95-96.

[16] S. Saseendran and V. Nithya, "Automated water usage monitoring system," *2016 International Conference on Communication and Signal Processing (ICCSP)*, Melmaruvathur, 2016, pp. 0099-0103.

[17] Myles, A. Permanent Leak Detection on Pipes using a Fiber Optic Based Continuous Sensor Technology. In Proceedings of Pipelines Conference 2011: A Sound Conduit for Sharing Solutions, Seattle, WA, USA, 23–27 July 2011; pp. 744–754.

[18] Boundless. (2017). Flow Rate and the Equation of Continuity. [online] Available at: https://www.boundless.com/physics/textbooks/boundless-physics-textbook/fluids-10/fluids-in-motion-95/flow-rate-and-the-equation-of-continuity-348-6252/ [Accessed 25 Jul. 2017].

[19] Sadeghioon, A., Metje, N., Chapman, D. and Anthony, C. (2014). SmartPipes: Smart Wireless Sensor Networks for Leak Detection in Water Pipelines. Journal of Sensor and Actuator Networks, 3(1), pp.64-78.

[20] A. R. David Thorley, “Fluid Transients in Pipeline Systems”, 2004, Professional Engineering Publishing Ltd, Pg 119-130

[21] K. Brown (2007). Modeling Leakage in Water Distribution Systems. Florida State University Libraries pg. 68-69.

[22] Adedeji, K., Hamam, Y., Abe, B. and Abu-Mahfouz, A. (2017). Towards Achieving a Reliable Leakage Detection and Localization Algorithm for Application in Water Piping Networks: An Overview. IEEE Access, 5, pp.20272-20285.