2021 IEEE International Symposium on Circuits and Systems (ISCAS) | 978-1-7281-9201-7/20/$31.00 ©2021 IEEE | DOI: 10.1109/ISCAS51556.2021.9401106

Leak Detection and Location Pinpointing in Water Pipeline Systems using a Wireless Sensor Network

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***Abstract*— Wireless Sensor Networks (WSNs) consist of wireless devices that are installed above the ground, buried under the dense soil, or placed in any underground spaces. WSNs have an immensely promising future which could impact diverse applications including water, oil, and gas pipeline leak detection. Any leak in the pipeline can trigger major financial losses and possible environmental damages. Almost twenty percent of the US water supply is lost annually because of pipe leakage. WSNs can be extremely useful in providing a solution for this problem. This paper presents a sensor network design method that uses pressure sensors to measure water pressure inside a pipe in different locations. Arduino and XBee (Zigbee) collect the pressure data, and exponential curve fitting technique determines leak and its location by analyzing the data. It demonstrates acceptable accuracy in predicting a leak and leak location under real world conditions for a given network. Moreover, it advises the acceptable distance between pressure sensors in a pipeline.**

Keywords*— wireless sensor network, pressure drop measurement, Arduino and XBee communication, exponential curve fit, leak detection.

I. Introduction

The pipeline system is a very important medium for transporting vital materials such as water, oil, and gas. Performance of the pipelines can be highly impacted by corrosion, cracking, accidental damage, and manufacturing flaws. Most of the pipelines, particularly underground pipelines, are operated at high pressure and temperature, which can often result in pipeline malfunction. Even a small water or oil pipeline leak can cause serious problems. Hence, continuous remote monitoring and assessment of the pipelines are necessary to prevent losses. The nature of the problem was emphasized in a World Bank investigation, which estimated the total global annual cost of leakage is $14 billion [1]. At the same time, with each new generation of electronics, sensors have become smaller, less expensive, and more sophisticated. As a result, sensors are producing more data, allowing for a more accurate assessment of a system, warning of environmental threats, and sensing of problems. Researchers have used various methods to detect and locate leaks in pipeline systems. Acoustic measurements, pressure measurements, fiber optic monitoring, and multimodal system analysis are the most common methods. Sensors play a pivotal role in detecting a leak in the pipeline system. Liu and Kleiner [2] study the sensor technologies used in monitoring pipe structural failure.

An extensive amount of research has already been done on acoustic or vibration measurements for pipeline monitoring [3], [4], [5], [6]. The most of these methods are based on the detection of the acoustic emissions from the pipe. Leakage in pipes creates vibrations which are transmitted along the pipe walls. These waves can be detected by using acoustic sensors or accelerometers installed on the pipe wall for analysis [5]. The location of the leak can be detected by using different cross-correlation methods. Although there are several advantages to using this technique, it does have some disadvantages that make it unsuitable to use, especially when considering the underground wireless network system. It requires a high sampling rate to measure the acoustic signal. Thus, due to the high consumption of power in the nodes, the lifetime reduces significantly. Moreover, the system requires a complex algorithm to process a large data set that also increases power consumption in the nodes. An exponential curve fit method works by analyzing a large set of data, and the analysis gives an idea about the leak position. It also provides the right distance between two sensors.

Fiber optic technology has a different level of success regarding the leak detection [7], [8]. A leak can be detected using this method by installing optical cables over large distances. However, the system is very difficult to install. In addition, in many cases fiber cable needs to be installed during pipe installation. Moreover, if a pipe section needs to be repaired or replaced, the fiber optic system could be out of service in that area.

The multimodal wireless sensor network is becoming more popular as it uses low power sensors. These sensors are very easy to install, and the system is very reliable. In this paper, analysis of a wireless sensor network using pressure sensors is done to detect the leak and its location. The problem associated with leak detection is to predict the leak and its location accurately with different water pressure levels and leak sizes. Sometimes it becomes hard to identify leak location with less water pressure, particularly when the leak size is very small. This paper solves the problem of identifying a leak with less pressure and/or small leak size by designing a simple sensor network and analysis method. It also helps to identify the ideal

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distance between sensors to accurately determine a leak. The approach combines a pressure drop calculation and mathematical model of the exponential curve fit. Arduino and Zigbee are used to collect and transfer the pressure values of every sensor under various conditions. This provides many dataset of all possible conditions. Accuracy is then calculated using an exponential curve fit method by analyzing a large set of data. The analysis gives an idea about the leak position. It also provides the right distance between two sensors.

II. RELATED WORK

For over a decade, the concept of a wireless sensor network has been investigated for the leak detection. In most studies, researches considered the multimodal system to detect a leak. To our best knowledge, one of the most relevant works was done by Sadeghioon et al. [9]. They used the combination of Force Sensitive Resistor (FSR) and temperature sensor to detect a leak. They collected pressure data generated from the FSR sensor and temperature data from the temperature sensor for three days. They concluded there was a leak by observing the pressure profile of every sensors and temperature data. JayaLakshmi and Gomathi [10] studied the connectivity between wireless sensor network standards. They used five flow sensors in their experiment to determine the leak. As seen in [11], authors followed the same procedure as [10] but used more sensors such as humidity, temperature, pressure, and a gas detection sensor to determine a leak and its location. They also showed the connectivity between Arduino and XBee to transfer data wirelessly. As seen in [12], the best locations for flow sensors was calculated. Rehman and Nawaz [13] demonstrated how magnetic induction-based wireless sensor networks can be designed for underground communications at low cost. These are very important analyses that we used for our system.

III. SYSTEM DESIGN

This section describes the overall system design for the proposed leak detection method. System design can be divided into two main parts: a pipeline network model and a data acquisition system.

A. Pipeline Network Model

Our system consists of PVC pipes with three different diameters: 0.75-inch, 1-inch, and 1.5-inch; three leaks; six sensors; one water tank; and one water pump. Three leaks were created in three different locations. These leaks were created by Hose Bibb. The advantages of using Hose Bibb are: the size of the leak can be controlled manually, and the pressure drop generated by the leak is strong enough to be detected by the pressure sensors. The maximum diameter of the Hose Bibb we used is 0.5-inch. As diameter can be varied, we tested our system with five different leak sizes: 0.5-inch, 0.4-inch, 0.3-inch, 0.2-inch, and 0.1-inch.

The sensors used in the leak detection method are known as SKU237545 Pressure Sensors, specializing in the water and oil leak detection technology. This analog Pressure Sensor is a 5V sensor that can measure pressures up to 200 PSI. It outputs an analog voltage that is proportional to the measured pressure. These sensors are small, lightweight, and waterproof; thus easy to handle. These sensors have built-in carbon steel alloy, can be easily installed, and require no special handling. Most importantly, these sensors are cheap, which makes the leak detection system inexpensive yet efficient.

B. Data Acquisition System

We used Arduino Mega 2560 as a microcontroller board to collect and convert data into a usable format. Arduino Mega 2560 works at 5 volts and each of them can provide/receive a maximum 40mA. The pressure sensors we used work well with this device. As the board has an analog input, 16 pressure sensors can be connected to a mega board. In our experiments, six of 16 analog pins were used to collect data from six pressure sensors. Arduino read sensor value from all six sensors and converted them to a digital output. This digital data needed to be transmitted through wirelessly. To do that, we used XBEE-PRO 900HP embedded modules that provide best-in-class range wireless connectivity to devices. This module can transmit or receive data up to 10-100 meters and data rates of up to 200 Kbps. This module is ideal for extended-range applications requiring increased data throughput which was very important in our experiment. The module was configured using XCTU software and data was transferred from this module to another module connected to a PC. This whole process is illustrated in Figure 1.

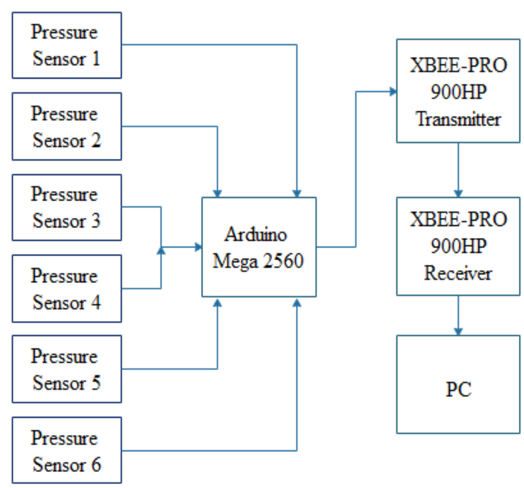

Fig.1. Data acquisition system

Both the XBEE modules were operated in AT command mode. One Zigbee was configured as Coordinator and other as Router. The router was connected at receiver side while coordinator was connected at the transmitter side. Data were collected and stored by the PC and processed for further analysis. The pipeline can be installed above or below the ground. XBEE-PRO 900HP is particularly important if we need to transmit data from the underground. Antenna plays a very pivotal role to transmit data from underground because typical radio frequency data transmission systems do not work well due to the difficulty of propagating RF signal through the soil. A 900MHz wire antenna was integrated with the XBee-

PRO 900HP module. Our system was tested using this integrated antenna and it was capable of transferring data from 2m below soil surface, which was enough to serve our purpose.

IV. EXPERIMENTAL ANALYSIS

A laboratory-based test bench system has been designed and developed to solve the problem and make the model effective and efficient. This system consists of U-shaped pipelines made of PVC pipes, as shown in Figure 2. Water was circulated in the system by a common water pump capable of providing up to 30 PSI of pressure. Three leaks were created in the pipe sections using Hose Bibb in three different locations. The first leak was created between sensors 1 and 2, the second leak was between sensor 3 and 4, and the third leak was between sensor 5 and 6.

Fig.2. laboratory-based test bench system

Pressure sensors were attached to the pipe through valves. These sensors are easily removable, so if any of them stop working, we can easily replace the new sensor with minimal effort. The whole experimental analysis can be divided into two sections: pressure drop analysis and exponential curve fit analysis.

A. Pressure Drop Analysis

The following illustration in Figure 3 illustrates the result for different scenarios. Here, we had only two sensors 860cm apart.

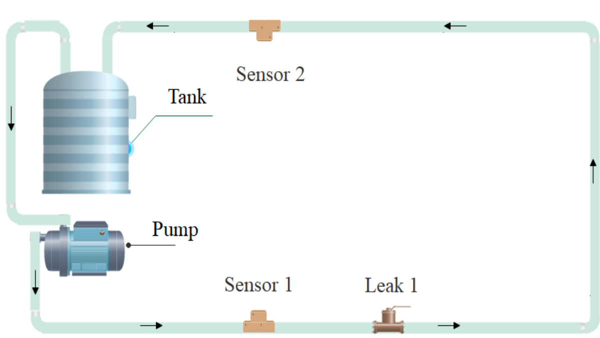

Fig.3. A system with 1 leak and 2 sensors

The other four sensors were not considered this time to explain the idea of calculating pressure drop. A leak in the size of 0.5-inch was created using Hose Bibb near sensor 1. Sensor 1 was located before the leak and sensor 2 was located after the leak. The leak was 90cm away from sensor 1 and 750cm from sensor 2. Data from the pressure sensors were recorded using Arduino at 500ms intervals and transmitted through Zigbee. Raw data from the sensors in laboratory tests is illustrated in Figure 4. This process can be divided into four main phases: the pumps start, stabilization, leak, and pumps off, which are clearly visible from the output of the pressure sensors. These include the pressure before the pump was switched on, the increase in pressure when the pump was switched on, the reduction in pressure due to the development of the leak, and finally, the drop-in pressure due to the switching of the pump shortly after the development of the leak.

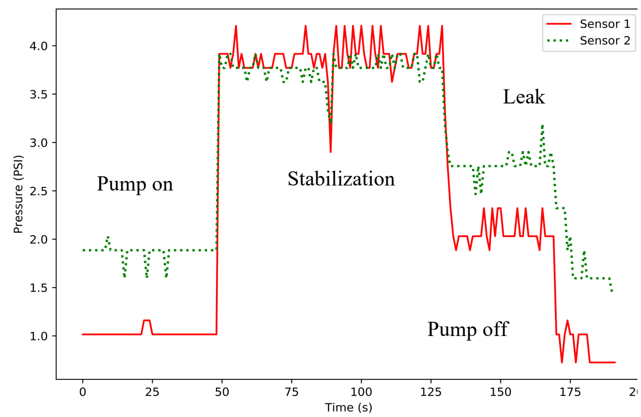

Fig.4. Raw data of two sensors

Based on Figure 4, it is difficult to determine the exact position of the leak because all the pressure sensors appear to respond similarly to the leak. Figure 5 shows a close range pressure profile due to the leak which contains stabilization, leak and pump off phases.

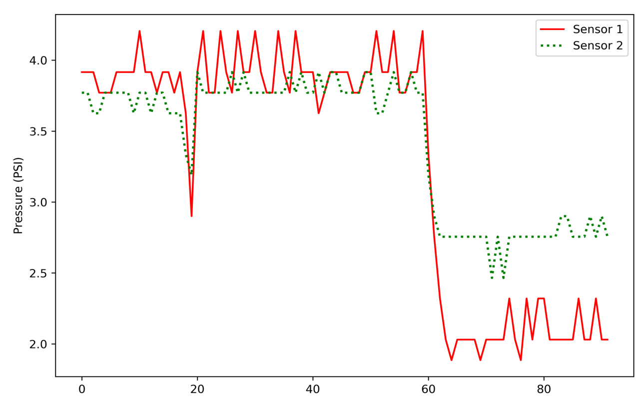

Fig.5. Close-range pressure profile of 2 sensors

In this figure, it is clear that the pressure profiles of sensors 1 and 2 are somewhat different from each other. The profile for sensors 1 exhibits more downstream pressure drop characteristics than sensor 2. This indication can be used to determine the approximate location of the leak, i.e., it is somewhere near sensor 1 in this case. However, it is also very difficult to pinpoint leak location by looking at downstream pressure drop, especially when the leak size is very small. To overcome this problem, the pressure drop has been calculated to pinpoint leak location is shown in Figure 6. To do this, average data of the stabilization portion is calculated and subtracted every data from the average in the array of an individual pressure sensor.

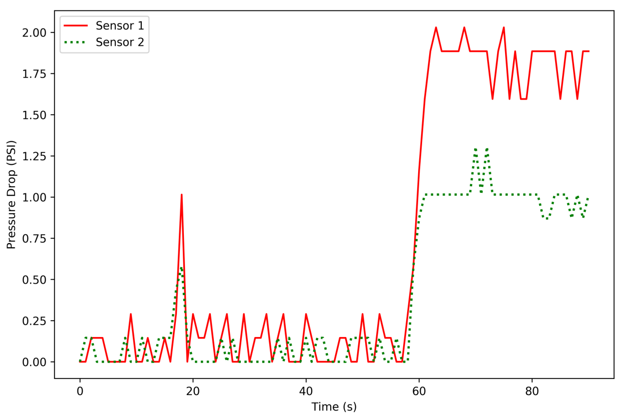

Fig.5. pressure drop calculation of 2 sensors

It is clear from the figure that sensor 1 exhibits more pressure drop than sensor 2. Based on this, we can assume that the leak is located somewhere near sensor 1. This idea can be explained more precisely when more sensors are implemented. Figure 6 shows six pressure sensors attached to the PVC pipe sections. Sensors 1 was located before the leak with a diameter of 0.5-inch and sensors 2, 3, 4, 5, 6 were located after the leak.

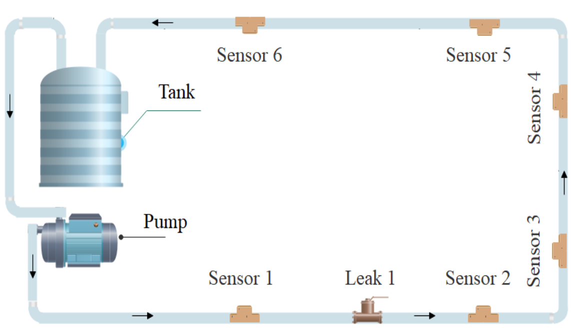

Fig.6. System with 1 leak and 6 sensors

Data from the pressure sensors were recorded at 500ms intervals. Raw data from the sensors in laboratory tests are illustrated in Figure 7. Figure 8 shows close-range pressure profiles due to the leak which contains stabilization, leak and pump off phases. Figure 9 exhibits a pressure drop of six sensors due to a leak. It is clear from Figure 9 that sensor 1 & 2 exhibits more pressure drop than sensor 3, 4, 5, 6. So, we can assume that the leak is located between sensor 1 and 2.

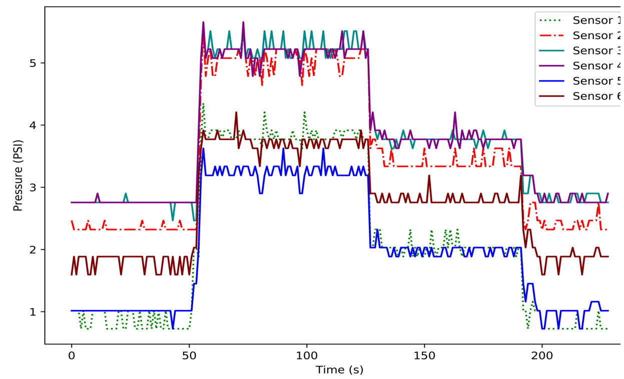

Fig.7. Raw data of 6 sensors

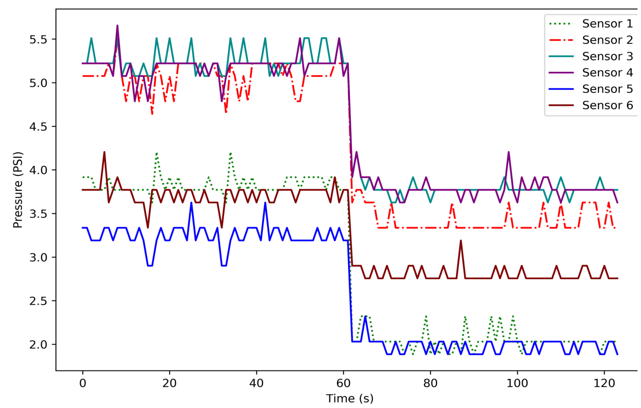

Fig.8. close-range pressure profiles of 6 sensors

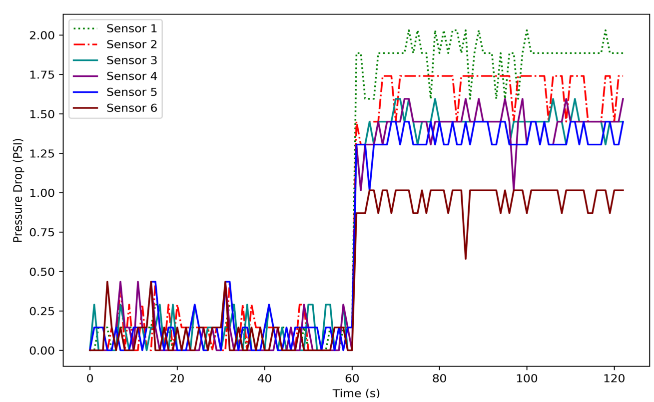

Fig.9. pressure drop of 6 sensors

This process works well unless until the leak size is very small. When the leak size is small, the pressure drop is much less for each sensor. Accordingly, it becomes very hard to determine leak location by calculating the pressure drop for each sensor. In our next experiment we used the same setup as previous experiment. However, this time the leak diameter was 0.1-inch. Data from the pressure sensors were recorded at 500ms intervals and the pressure drop was calculated. Figure 10 exhibits a pressure drop with 0.1-inch leak sizes while the leak was created between sensor 1 & 2.

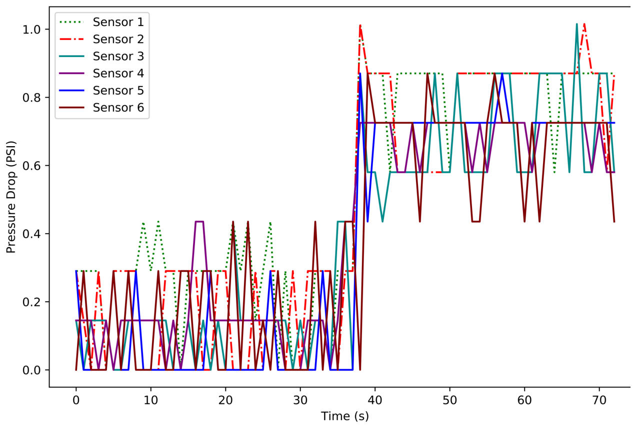

Fig.10. pressure drop of 6 sensors with 0.1-inch leak

It is very clear from the figure that it is difficult to distinguish pressure drops of every sensor this way. This problem can be solved by exponential curve fitting method.

B. Exponential Curve Fit Analysis

The trend in the dataset can be captured using curve fitting by allocating a single function across the entire range. A process of approximating the trend of the result is known as curve fitting. Exponential curve fitting is often used when the rate of change of a quantity is proportional to the initial amount of the quantity. In our case, pressure value generated by the sensor drops immediately after the development of the leak. This is true for all of the sensors as pressure value of all six sensors drop immediately and at the same time after the leak. Thus, the rate of change in pressure value with time can be modeled by following a simple exponential relationship:

$$y = ae^{bx}$$

y is the pressure value where x is the time, and b is a negative constant which can be called as decay rate that denotes how rapidly the pressure value decreases with time. By comparing the decay rate, we can predict the leak location.

In this case, we have created a leak of 0.5-inch between sensor 1 and 2. Sensor 1 was located before the leak and sensors 2, 3, 4, 5, 6 were located after the leak. Data from the pressure sensors were recorded at 500ms intervals. The exponential curve fitting model was then applied using MATLAB is illustrated in Figure 11.

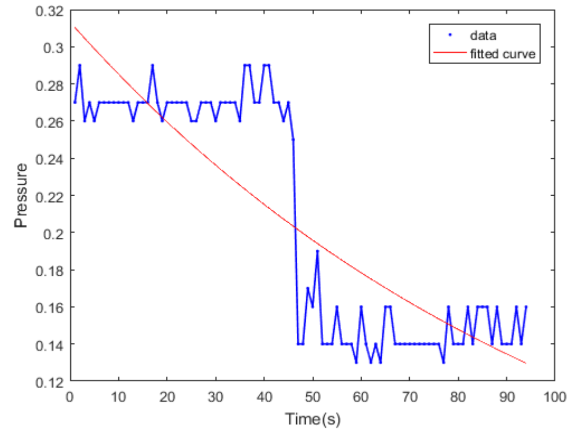

Fig.11. exponential curve fit applied to sensor 1 data for 0.5-inch leak

In this figure, we have applied exponential curve fit to sensor 1 data, providing us with a single decay rate. For the six sensors we got six decay rates. In other words, for a single dataset, we found six decay rates as we had six sensors in our system. The decay rate of six sensors is given in Table 1.

TABLE I. DECAY RATE

Sensor	1	2	3	4	5	6
Decay	0.0104	0.0078	0.0068	0.0056	0.0052	0.0050

It is clear from Table I that sensors 1 and 2 have more of a decay rate than other sensors. Based on this, we can assume that the leak is located between sensors 1 and 2. Now this idea can be justified if it can detect leak with a small diameter. In our next experiment, we used the same setup as the previous experiment. However, this time the leak diameter was 0.1-inch. The exponential curve fit model for a single sensor is shown in Figure 12.

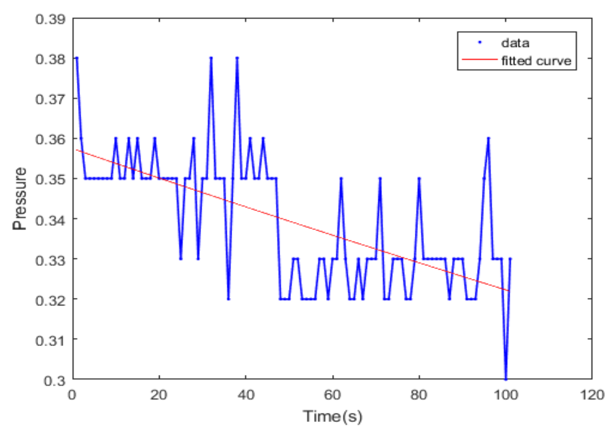

Fig.12. exponential curve fit applied to sensor 1 data for 0.1-inch leak

A decay rate of six sensors for 0.1-inch leak is given in Table II.

TABLE II. DECAY RATE

Sensor	1	2	3	4	5	6
Decay	0.0010	0.0009	0.0009	0.0008	0.0007	0.0006

It is clear from the table that sensors 1 and 2 have more of a decay rate than other sensors. We can then assume that the leak is located between sensors 1 and 2. In this way, the leak and its location can be precisely detected. The whole leak detection process can be summarized by the following figure.

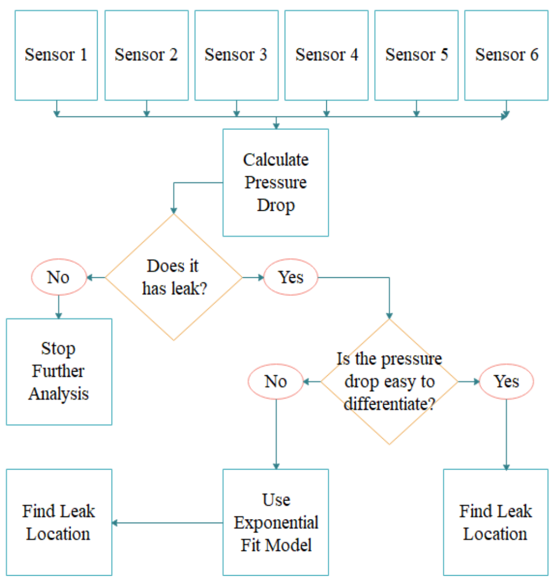

Fig.13. overall leak detection process

Although simple pressure drop calculation can give an indication of leak location, exponential curve fitting can accurately predict leak location.

V. RESULT

We collected a large dataset to verify our system. We used PVC pipes with three different kinds of diameters: 0.75-inch, 1-inch, and 1.5-inch; 3 leak locations and five different leak sizes: 0.5-inch, 0.4-inch, 0.3-inch, 0.2-inch, and 0.1-inch to collect data with different conditions is illustrated in Figure 14.

Sensors 1 and 2 are 180cm apart, sensors 3 and 4 are 100cm apart, sensors 3 and 4 are 180cm apart, sensors 2 and 5 are 500cm apart, and sensors 1 and 6 are 860cm apart. Leak 1 is halfway between sensors 1 and 2, leak 2 is halfway between sensors 3 and 4, and leak 3 is halfway between sensors 5 and 6. The overall system is shown in Figure 15.

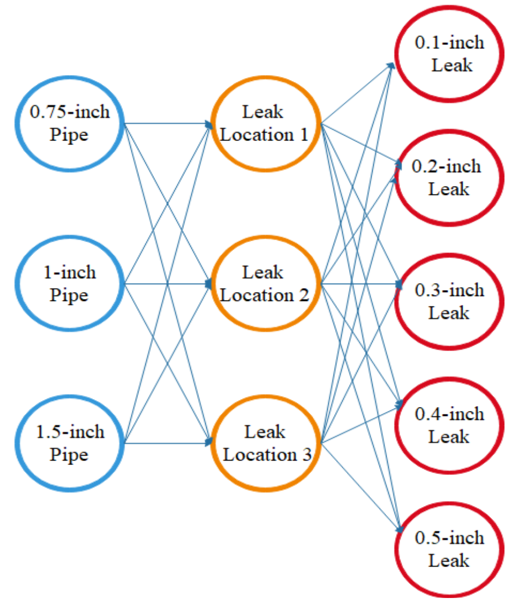

Fig.14. data collection conditions

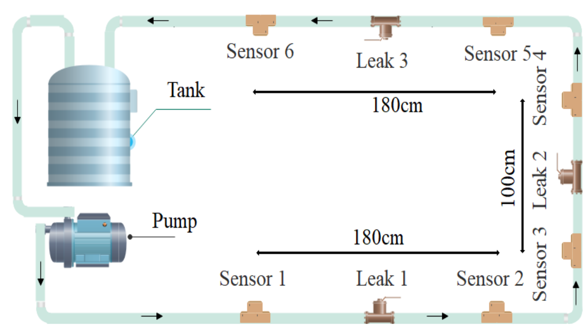

Fig.15. Data collection system

We collected 900 sets of data by creating various leaks in different locations with different pipes. We examined every dataset using an exponential curve fitting model and then compared the result with the actual outcome to get the accuracy. Overall accuracy was calculated as shown in Table III.

TABLE III. ACCURACY RATE

Leak Location	1	2	3
Overall Accuracy	82.5%	52.5%	80.7%

It is clear from the table that leak location 2 produces less efficiency compared to other locations. We can reach a conclusion that 100cm is not the right distance between sensors. To verify this, we nullified the effect of sensors 3 and 4 and collected data from sensors 1, 2, 5, and 6. Now the leak is between sensors 2 and 5, and both sensors are 500cm away. We have collected 125 datasets and then calculated the efficiency of leak location identification. In this case, we achieved accuracy 85.6%. Therefore, it is clear that the distance between sensors plays a pivotal role in accurately detecting leaks. We can conclude that the distance between sensors should be around 180cm or more, but we could not calculate the maximum distance from our system.

As leak 2 is showing less efficiency because of the incorrect distance between sensors, we only considered data sets related to leaks 1 and 3. We collected a total of 750 datasets with different conditions. All of the accuracy data is listed in Table IV.

TABLE IV. SYSTEM ACCURACY

Pipe / Accuracy	1.5-inch pipe	1-inch pipe	0.75-inch pipe
Overall	79.4%	81.2%	84.2%
0.1-inch leak	76%	76%	78%
0.2-inch Leak	73%	77%	80%
0.3-inch Leak	80%	82%	85%
0.4-inch Leak	83%	85%	88%
0.5-inch Leak	85%	86%	90%

It is clear from the figure that leak detection accuracy increases with the decrease of pipe diameter. The smaller diameter pipe has more water pressure than another diameter pipe, as the source is producing the same water pressure. Based on this, we can say that accuracy increases with the increase of pressure inside the pipe. A 0.75-inch pipe has the highest overall accuracy because it has more water pressure inside it. In other words, if we increase the water flow rate using a more powerful water pump, leak detection accuracy will be higher. Another outline can be drawn from the table that accuracy increases when the leak size increases, because higher leak size creates a higher pressure drop, hence leak detection accuracy is high.

VI. CONCLUSION

This paper represents a new method of detecting leaks in water pipeline networks. We have demonstrated system efficiency under some practical circumstances. Researchers can use this method to determine leak detection analysis in other systems, wherever it best suits them. We have also shown the minimum distance researchers should use between two sensors to get optimum results.

In future work, we intend to broaden the network models considering multiple leaks in a network. In addition, leak size cannot be predicted by our designed system, so predicting leak size could be another option for future work. Other applications that could take advantage of our approach include leak and leak location detection in oil and gas pipeline systems. Prediction accuracy could be improved by using Artificial Neural Network (ANN) algorithm.

ACKNOWLEDGMENT

This research is part of Project: 'Through-The-Earth Data Transmission Systems to Enable Buried Environmental Sensors' funded by the NEC Corporation of America.

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