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Research Article

DESIGNING A PARTICLE SWARM OPTIMIZATION MODEL FOR EFFICIENT WATER MANAGEMENT

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Abstract

This paper proposes a real-time monitoring system for pressurized water networks capable of detecting, localizing, and pinpointing leaks by utilizing particle swarm optimization (PSO) with sensors. The particle swarm optimization technique was used to find the minimal sensor placement for the identification of leaks in pipe networks. This technique was developed and integrated for accurate pipe leak detection in a wide variety of situations, leading to high efficiency. The system response was observed, and false alarms were noticed. About 4 false alarm frequencies were noticed for the water flow and no leakage mode, and 100% of the false alarms represented no flow and no leakage. In the case of water flow and leakage mode, a total of 5 false alarms were observed, of which 55% represent no flow and leakage and 45% represent no flow and no leakage. Meanwhile, the system false alarm was observed to reduce significantly when the system is pressurized for a long period of time. The PSO-based approach for leak detection in pipes minimizes false alarms, improves the accuracy and efficiency of leak detection, reduces energy waste, saves money, and helps prevent environmental damage.

Keywords: Sensor, System Response, Leakage, Leak Detection, and Alarm Frequencies.

INTRODUCTION

The main goal of a water provider is to provide clean and safe water to taps of all customers; therefore, leaks in a water distribution system can increase the contamination of water that leaves the source or treatment facility before reaching the customer. Consequently, pipe leaks created a pathway for pathogen intrusion into the drinking water [1]. Leak detection is an essential tool for the management of water distribution systems around the globe. Accurate pinpointing of the location of leaks in water pipes within a supply system and subsequent repair serves to prevent water loss and conserve energy. Water that is lost after treatment and pressurization but before delivery to customers is money and energy wasted [2]. In many water distribution systems, a significant percentage of water is lost while in transit from treatment plants to consumers. The amount of lost or "unaccounted-for water" is typically in the range of 20–30% of production [3]-[4]. In the case of some systems, mostly older ones, the percentage of lost water could be as high as 50% [5]-[6]. Unaccounted-for water is usually attributed to several causes, including leakage, metering errors, and theft. Pipe leakage is a costly problem, not only in terms of wasting a precious natural resource but also in economic terms. The primary economic loss due to leakage is the cost of raw water, its treatment, and its transportation. Leakage inevitably also results in secondary economic loss in the form of damage to the pipe network itself. The environmental and economic losses caused by leakage and leaky pipes create a public health risk, as every leak is a potential entry point for contaminants if a pressure drop occurs in the system. Thus, managing these problems has become an important aspect for managers of water supply networks [7].

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Acoustic listening and ground-penetrating radar devices are the physical inspections of the leak in the pipeline [8]. These techniques require shutting down and isolating the affected part or whole system. Pipe failure types are classified into circumferential cracking, longitudinal cracking, bell splitting, bell shearing, blow-out holes, and spiral cracking. Figures 1 (a) to (f) below depict these different types of pipe failure. The diameter of the pipe influences these modes of failure [9].

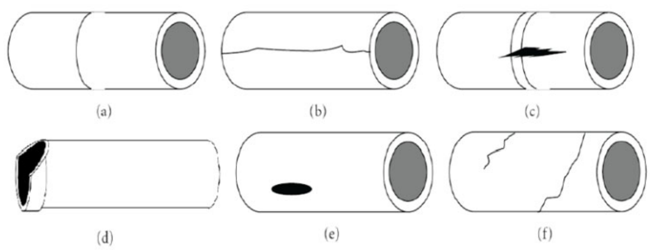


Figure 1. Pipe Failures (a-f)

Water loss occurs in all pipeline distribution systems; only the volume of loss varies. The volume of loss depends largely on the characteristics of the pipe network and is affected by the leak detection and repair policy practiced by the water company [10]. The main economic loss caused by leakage is the cost of raw water, transportation, and its treatment. In addition to environmental and economic losses due to leakage, leaky pipes also contribute to a public health risk, as leaks are possible access points for contaminants if a pressure drop occurs in the pipeline system [11]. Leaks that are left unrepaired are susceptible to growing and thus allow pathogens and contaminants from the environment into the water network, which results in a significant decrease in the quality of the provided water and might harmfully affect the lives of humans and other living species [12]. In response to these damages and negative impacts, many researchers have developed a real-time monitoring system within water distribution networks that allows early detection of leaks and eventually optimally-timed repairs [13]-[16]. Particle Swarm Optimization (PSO) has been used in many applications in various academic and industrial fields, including electrical and electronics engineering, automation control systems, communication theory, and mechanical engineering [17]. Proper monitoring with the help of sensors and automation is needed to ensure pipeline sustainability. Leakage control can be enhanced by incorporating sensors on the pipelines connecting each and every house to detect leakage [18]. The different types of sensors used for leakage detention, such as pressure, flow, acoustic, electrode, ultrasonic, and temperature Sensors. Multiple models were developed by researchers to address the issue; nevertheless, these models have limitations either in terms of accuracy or false alarms. This paper focused on the area of pipe leakage in water distribution networks using particle swarm optimization for effective monitoring and water distribution management.

MATERIALS AND METHODS

Two SEN0257 DFROBOT water pressure sensors, three-inch polyvinyl chloride values, 1 horse power water pump, and an Arduino microcontroller (ATMEGA328) were acquired and employed for the construction of the leakage experimental rig. The SEN0257 DFROBOT has a pressure range of 0–1.6 MPa, a voltage range of 0.5–4.5 V, and an accuracy of 0.5–1%. The Arduino ATMEGA328 microcontroller is an 8-bit automatic voltage regulator; it is one of the many IDEs utilized for Atmel automatic voltage regulator (AVR) controllers. Figure 2 shows the flowchart of the study methodology framework. The leakage detection scheme to be implemented required identifying the optimum leakage location along the pipeline. In order to obtain the optimum position, the Particle Swarm Optimization (PSO) algorithm was used.

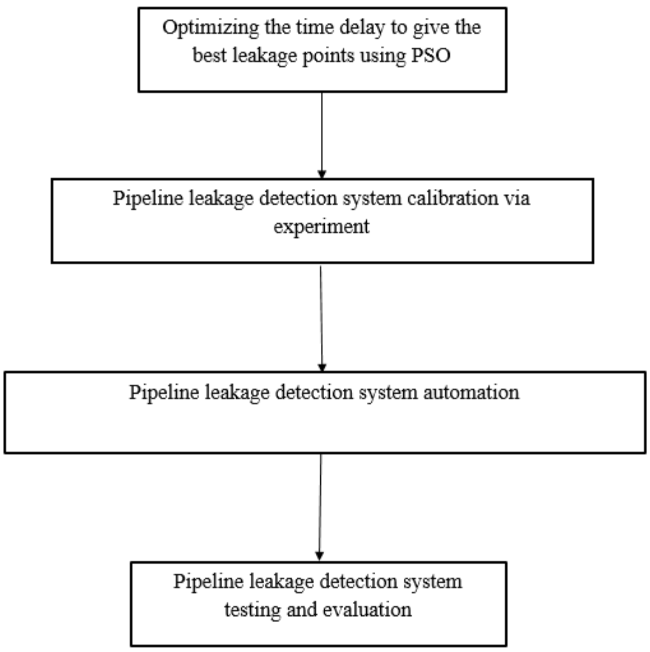


Figure 2. Flowchart of the Study Methodology

The Particle Swarm Optimization algorithm is a meta-heuristic algorithm that is implemented for optimization problems to mimic the behavior of swarms of particles' populations. The particle swarm optimization model involves solving the swarm's velocities and positions until convergence is reached. Polyvinyl Chloride (PVC) pipe material was used, and the velocity of sound in any material medium is given by equation 1 [19].

$$v = \sqrt{\left(\frac{1}{\rho} \cdot \frac{1}{\frac{1}{K} + \frac{D}{E.S}}\right)} \quad (1)$$

Where v is the sound velocity, ρ is the density of the fluid flowing through the pipe, K is the compressibility of the fluid, E is the modulus of elasticity of the material of the pipe, D is the diameter of the pipe, and S is the pipe wall thickness. Thus, solving for the sound velocity using the properties in Table 1 and equation 2, the objective function for the leakage scheme was determined by the algorithm work to optimize the values of time delay that minimizes the distance between the leakage point and d_1, for the given range of time delay τ $(seconds)$.

$$min\ d_1 = \frac{d - v\tau_i}{2} \quad (2)$$

Table 1. Parameters Used for Evaluating Sound Velocity in PVC Pipe

Parameters	Values	Units
Fluid density (ρ)	1,000	kg/m^3
Fluid compressibility (K)	44.0849	$(N/m^2)^{-1}$
Pipe material modulus of elasticity (E)	3.5×10^6	N/m^2
Pipe diameter (D)	0.0127	m
Pipe wall thickness (S)	0.034	m

An experimental rig, as shown in Figure 3, was constructed to predict leakages along water pipelines. The rig consists of water networks with leakage points as dictated by the outcome of the PSO, a water pump, and a water basin. Two modes of flow lines were studied: horizontal and vertical flow lines. The orthographic and isometric projection and parts description of the experimental rig developed for monitoring and detecting pipe leakage are shown in Figures 4 and 5.

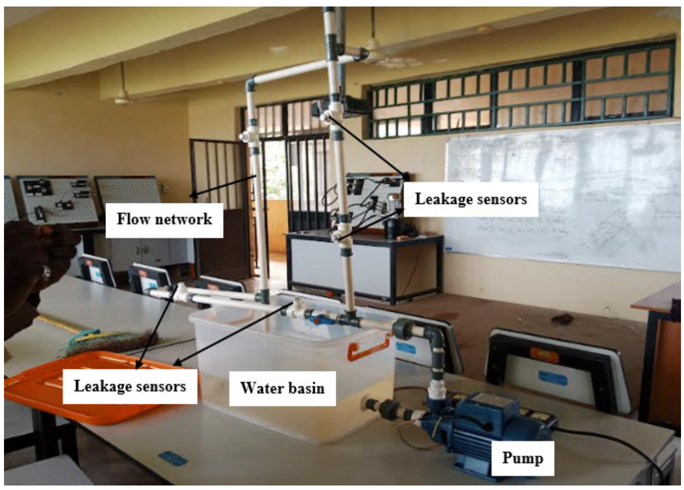


Figure 3. Leakage Detection Experimental setup for this Study

Calibration of the leakage detection scheme was done by installing the sensors along the length of the pipes for both orientations and interfacing the sensors with the microcontroller, which was facilitated via the Arduino sketch (program) developed. When calibrating for any of the flow orientations, a valve was used to isolate the flow from passing through the other orientation, which is not of interest. Different leakage positions with respect to the sensors and as obtained from particle swarm optimization, including no leakage condition, were investigated. In order to determine the flow parameter (basically negative pressure), which was used to automate the leakage detection scheme, the water flow network was pressurized, and data were recorded. Different conditions of the pipeline were used in the computer program to control the alarm state of the leakage system.

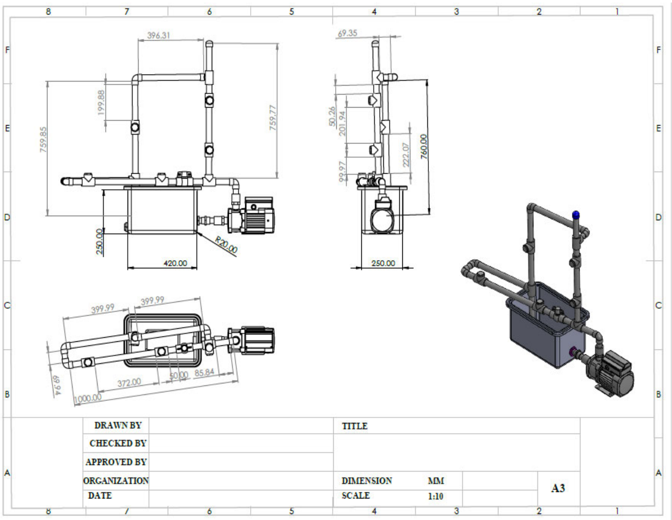
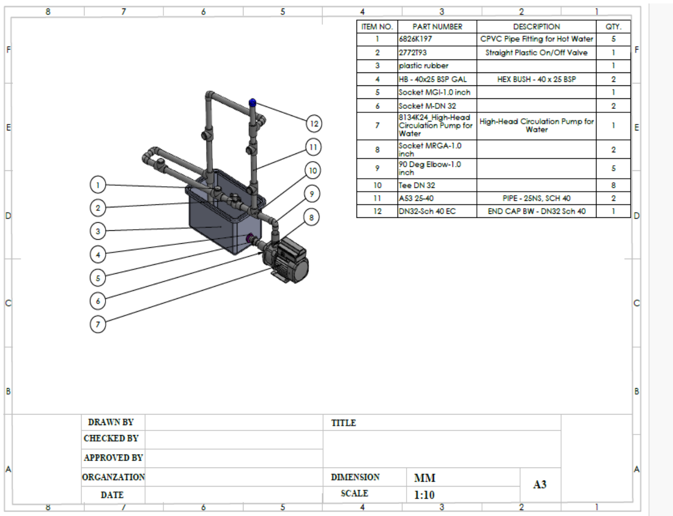


Figure 4. Orthogonal Projection and Parts Description of the Experimental rig



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6826K197	CPVC Pipe Fitting for Hot Water	5
2	2772T93	Straight Plastic On/Off Valve	1
3	plastic rubber		1
4	HB - 40x25 BSP GAL	HEX BUSH - 40 x 25 BSP	2
5	Socket MGI-1.0 inch		1
6	Socket M-DN 32		2
7	8134K24_High-Head Circulation Pump for Water	High-Head Circulation Pump for Water	1
8	Socket MRGA-1.0 inch		2
9	90 Deg Elbow-1.0 inch		5
10	Tee DN 32		8
11	A53 25-40	PIPE - 25NS, SCH 40	2
12	DN32-Sch 40 EC	END CAP BW - DN32 Sch 40	1

Figure 5. Isometric Projection and Parts Description of the Experimental rig

RESULTS AND DISCUSSION

The Particle Swarm Optimization (PSO) algorithm was utilized in determining the optimal position for the leakages with reference to the sensor, starting from the left for the horizontal orientation. Different values of time delay were optimized, establishing the leakage positions that were used for the automation of the leakage detection scheme. The results of the leakage positions as obtained from particle swarm optimization are shown in Figures 6, 7, 8, and 9, respectively.
Figure 6 shows that the fitness value converges at 10.118 cm, which is measured to the left of sensor 1. PSO revealed the optimal time delay of 0.018 seconds, which represents the time taken for the two sensors to see the signal at the same moment. Figure 7 shows a fitness value of 25.35 cm with an optimal time delay of 0.050 seconds, and Figure 8 shows a fitness value of 37.25 cm with an optimal time delay of 0.075 seconds. The optimal positions for the leakages with reference to the sensor starting from the bottom as determined from the PSO are shown in Figure 9.

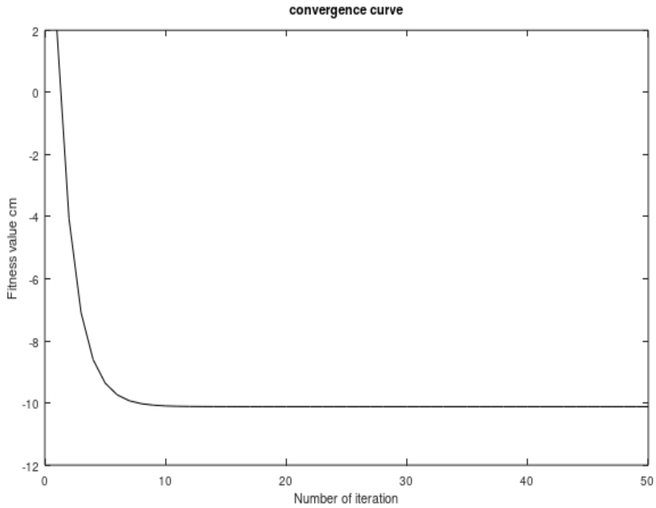


Figure 6. Convergence Curve for the First Leakage Point for the Horizontal Configuration

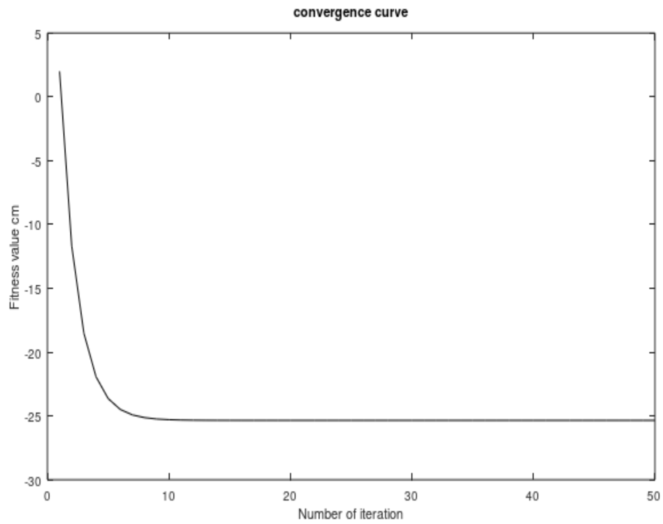


Figure 7. Convergence Curve for the Second Leakage Point for the Horizontal Configuration

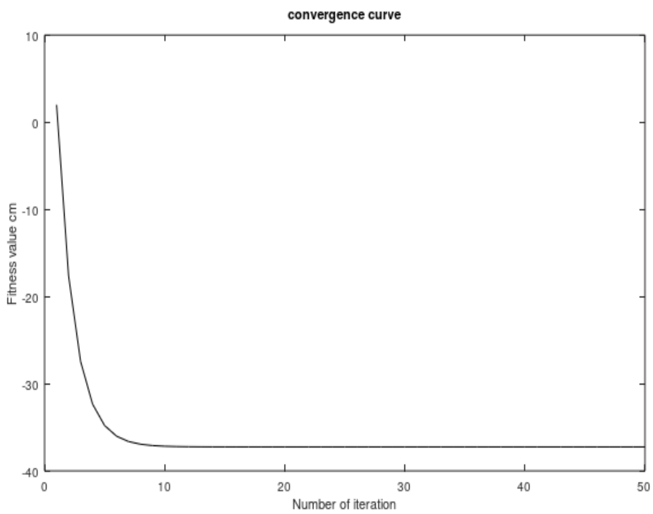


Figure 8. Convergence Curve for the Third Leakage Point for the Horizontal Configuration

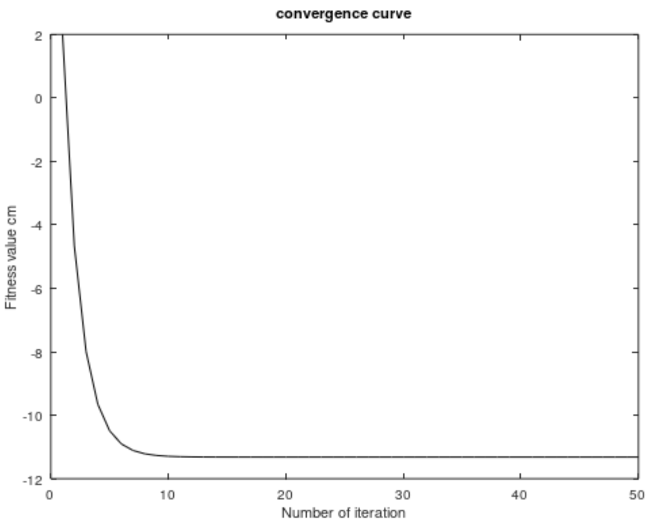


Figure 9. Convergence Curve for the Third Leakage Point for the Vertical Configuration

Pressure values were recorded for different cases of water flow in the pipeline. No leakage with no flow, no leakages with flow, leakage at 10 cm with flow, leakage at 25 cm with flow, and leakages at 35cm were investigated for the horizontal configuration. The water distribution line was pressurized for 60 seconds for each case considered. Figure 5.1 shows the profile of the pressure for no leakage with no flow.

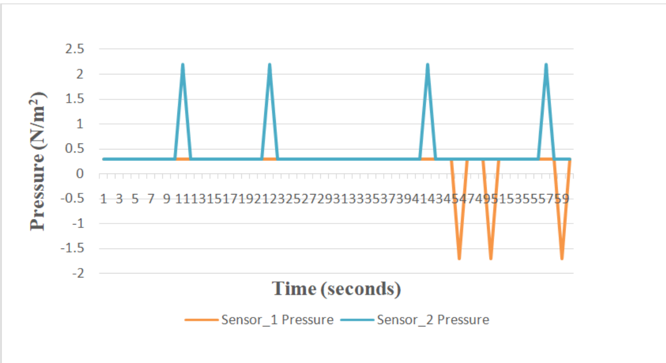


Figure 10. Pressure Values for Sensor_1 and Sensor_2 for no Flow and no Leakage Case (Horizontal Configuration)

Figure 10 shows that both sensors maintained a uniform pressure of around 0.3 N/m^2, except for a few occasions where pressure deviations were experienced. For sensor_1, a constant pressure peak of 2.2 N/m^2 was observed at 11, 22, 42, and 57 seconds, respectively, and for sensor_2, a constant pressure peak of negative 1.7 N/m^2 was observed at 46, 50, and 59 seconds, respectively. Figure 11 revealed the pressure values for both sensors for water flow and no leakage along the pipeline. The pressure value decreases along the downstream, where both sensor_1 and sensor_2 gave fluctuating pressure values, with sensor_1 registering a pressure value between 8 and 12 N/m^2 and sensor_2 registering a pressure value between 8 and 10 N/m^2. The pressure value of 10 N/m^2 as detected by sensor_1 is very pronounced, and for sensor_2, a pressure value of 8 N/m^2 occurs most frequently. Figure 12 shows a more stable value for sensor_1 with a uniform pressure value of 8 N/m^2 taking place, except at 2, 17, 29, 36, and 50 seconds, respectively, where the pressure values of 6 and 10 N/m^2 were recorded. However, sensor_2 pressure values were very unstable at 5–11, 17–23, 27–36, and 50 seconds, with a fixed pressure value of 8 N/m^2. For the no flow, no leakage case of the vertical flow orientation, the pressure values do not show a significant difference, as can be seen in Figure 13. Both sensors maintained a uniform pressure value of 0.3 N/m^2, except at times 19 and 30 seconds, where sensor 1 experienced pressure peaks of 2.2 N/m^2. A flow and no leakage condition were studied for the vertical configuration, and pressure rise was observed for both sensors. Sensor_1, which is closed to the upstream, registered a higher pressure, which is in the range of 6.2–8 N/m^2, compared to sensor_2, which has a pressure range of 2.2–6.2 N/m2, as revealed through Figure 14. A case of flow and a leakage at 11.5cm away from the upstream sensor for the vertical orientation were studied. The leakage size in this case was very small (in the order of 0.01mm). The choice of this size is because it is possible that leakages of such sizes occur, and to test the sensitivity of this scheme, it was important to investigate it. Figures 15 and 16 revealed the same pattern of flow with no leakage; however, the pressure values vary insignificantly. Sensor_1 shows a pressure range of 2.2–7.8 N/m^2, whereas Sensor_2 shows a pressure range of 3.8–5.8 N/m^2.

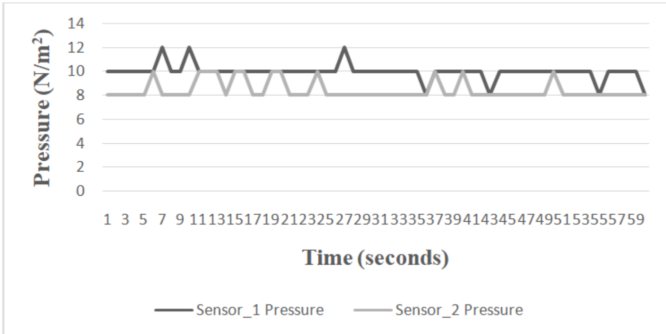


Figure 11. Pressure Values for Sensor_1 and Sensor_2 for Fluid Flow and Leakage Case (Horizontal Configuration)

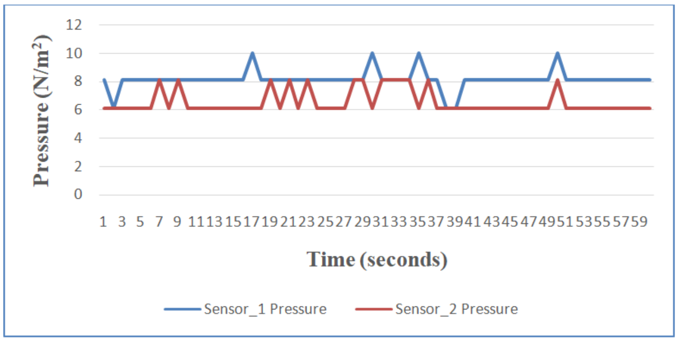


Figure 12. Pressure Values for Sensor_1 and Sensor_2 for Fluid Flow and Leakage at 10 cm Case (Horizontal Configuration)

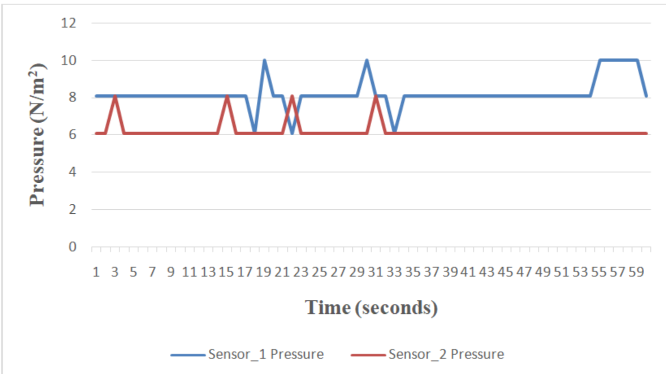


Figure 13. Pressure Values for Sensor_1 and Sensor_2 for Fluid Flow and Leakage at 25 cm Case (Horizontal Configuration)

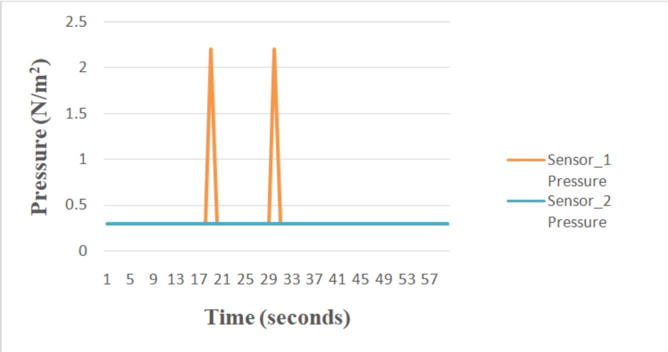


Figure 14. Pressure Values for Sensor_1 and Sensor_2 for no Flow and no Leakage Case (Vertical Configuration)

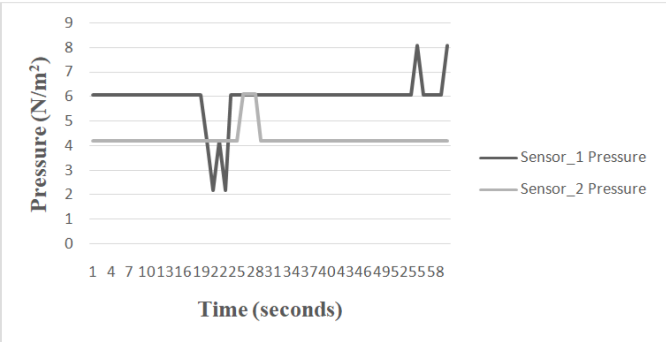


Figure 15. Pressure Values for Sensor_1 and Sensor_2 for Flow and no Leakage Case (Vertical Configuration)

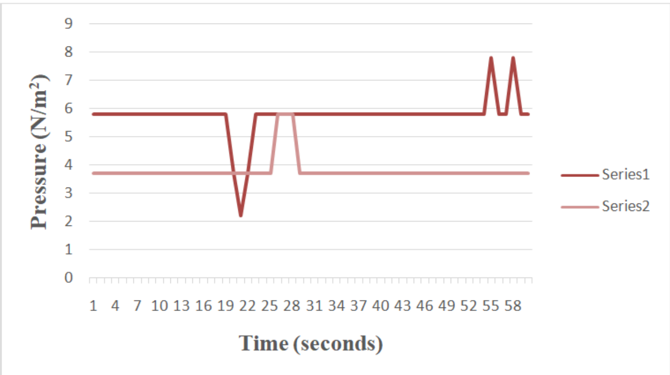


Figure 16. Pressure Values for Sensor_1 and Sensor_2 for Flow and Leakage at 15cm Case (Vertical Configuration)

Conclusion

Pipe leakages have been causing environmental challenges and water shortages, and it has led to spending huge amounts of money to clean the environment. This study used particle swarm optimization to optimize the best position to place the leakage point with respect to the sensors. An objective function was developed, and the time delays were optimized using PSO simulation. The developed experimental rig contains two sensors, PVC pipes, and an electric water pump. The leakage points based on the PSO were replicated on the experimental rig. The system was calibrated, data was extracted, and it was used for leakage automation. The results showed that the best leakage point is 10.118 cm, which is measured to the left sensor_1 for the first leakage point in the horizontal configuration with a 0.018 second time delay; 25.35 cm for the second leakage point in the horizontal configuration with a time delay of 0.050 seconds; and 37.25 cm for the third leakage point with a time delay of 0.075 seconds. The result of the generation of an acoustic model with high accuracy and efficiency for pipe leakage detection minimized false alarms, reduced energy waste, saved money, and the and the purity of liquid conveyed along the pipe network, which helped prevent environmental damage and low power and energy consumption. The outcome reduces leakages in the pipeline distribution network, improving pump efficiency and the purity of water conveyed along the pipe network due to less or no contamination and municipal treatment for all Nigerian industrialization.

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