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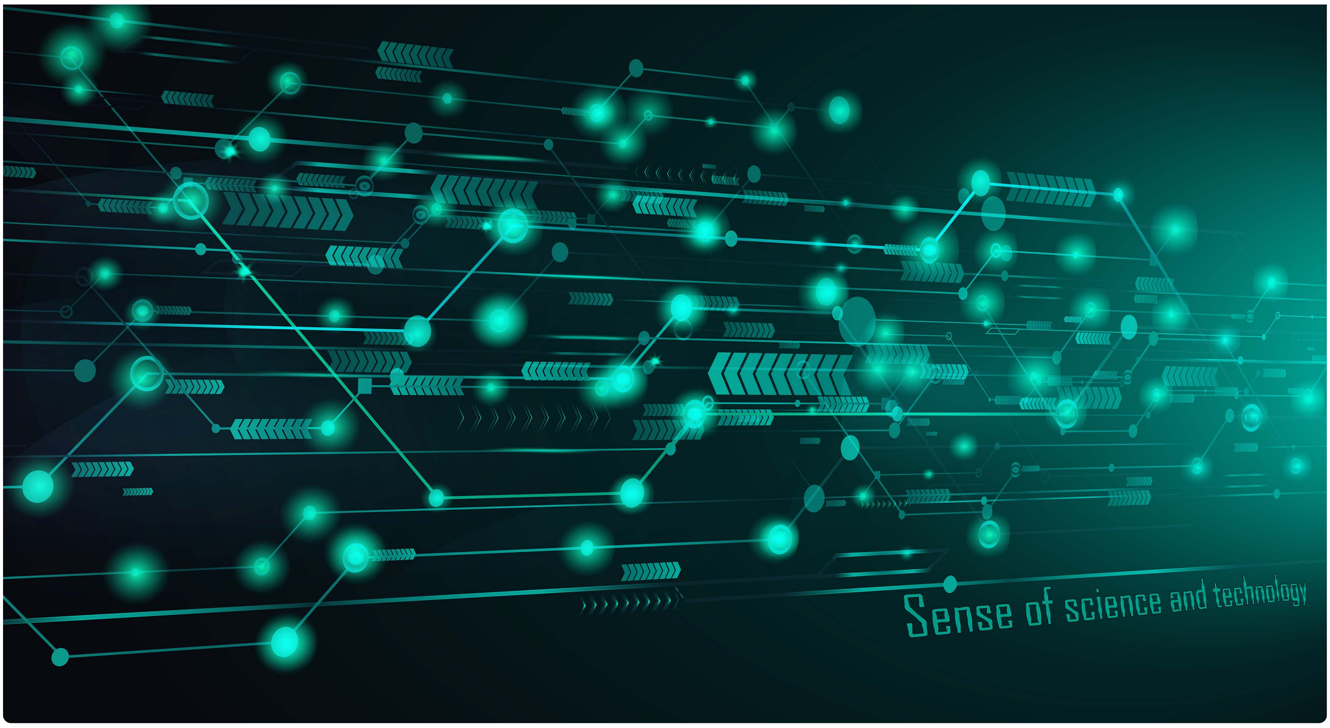

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Original Article

Water Pipe Leakage Detection System based on Fuzzy Logic and Sensor Network

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Abstract *- A water pipe leak detection system is a system needed to overcome the problem of loss of water resources in pipelines. Therefore, a leak detection system has been designed and implemented by utilizing the fuzzy logic method to determine the condition of pipe leaks based on the results of measuring water flow and soil moisture levels around the pipe location. The results obtained show that the system can measure water flow and soil moisture well, as well as make decisions about the condition of pipe leaks in a particular area. The accuracy level of the implemented detection system is 93% compared to the simulation. The proposed system combines the results of water flow and soil moisture measurements to make decisions based on fuzzy logic.*

Keywords *- Water pipe leakage, Fuzzy logic, Water flow sensor, Soil sensor, Wireless sensor network.*

1. Introduction

Detecting leaks in water pipes is one of the most important measures to ensure sustainability within distribution networks. Pipeline leaks can lead to the waste of a large volume of water with financial expense and environmental damage. Water pipe leak detection is an extremely valuable study area because leaks may be unseen and induce infrastructure damage. But more significantly, it results in water wastage. The cause of this issue lies in the record-length pipeline upgrades that must be constructed, which must meet backlogs from among the most extensive nationwide pipelines built initially. It may well have something to do with our severely failing clean water lines. Some detection systems have been developed with audio signals [1],[2] or flow water[3],[4]. The accuracy and speed of traditional leakage detection are usually not high enough; therefore. It is necessary to develop more refined systems. Intelligent systems like fuzzy logic might improve detection by efficiently processing ambiguous and obscure input. Flow sensors monitor the water flow rate via a pipe to identify leaks in water systems.

The sensor picks up on a sudden change in flow rate that can result from a leak. Leaks in water supply pipelines, both big and tiny, can be found with flow sensors. Typically. They are positioned strategically throughout the network of pipes to monitor water flow and identify any anomalies by looking for indications of water seeping out of an underground pipe leak. Soil sensors are essential for finding leaks in water systems. When a leak occurs in a pressurized water pipe. The water rushes into the ground quickly. Creating a variety of impacts that soil sensors can identify. One way to detect leaks in water pipe networks is using a clever leak detection system based on fuzzy logic algorithms. This system examined data from sensors placed throughout the network. Using fuzzy logic to figure out if there's a leak. The whole idea behind this system is that a leak will cause changes in water pressure and flow rate within the network.

The system relies on the fuzzy logic approach to determine if there's a leak. It evaluates these changes and decides whether a leak is present. Fuzzy logic algorithms have recently become quite popular for boosting leak detection accuracy in water pipelines [5],[6]. Fuzzy logic is a fancy math method that can spot leaks in water distribution systems by mimicking complex systems with imprecise and uncertain data. A good monitoring system can detect leaks early and inform users. Water pipe leaks are a significant problem that causes major losses to society and the environment. We need innovative solutions to detect water pipe leaks early and notify users. Many techniques are used to find pipe leaks, including electromagnetic, infrared, and acoustic. However, few have developed pipe leakage systems based on the moisture potential of the soil around the pipe. Moreover, there is a need for a system that combines soil moisture and water flow parameters in monitoring pipeline leakage issues. This study aims to make advanced detection techniques by introducing fuzzy logic into leak detection systems. According to Sayees[7], implementing the water pipe leak detection system with wireless sensor networks has not implemented machine learning techniques; therefore, fuzzy logic techniques can be applied as a basis for system development. Meanwhile, based on the results of Ahmed's review[8], it is stated that the fuzzy inference system technique can be used to predict the possibility of leakage; therefore, it is necessary to further develop the technique by utilizing a combination of water flow sensor data and soil moisture. This study explores the potential of fuzzy logic systems in pinpointing leaks in water pipes and thoroughly assesses how well they improve the accuracy of leak detection while reducing false alarms.

2. Literature Review

The water leak system was built to detect the phenomenon that occurs in closed water channels such as pipes. This system measures the reduction in water flow or the condition of increased soil moisture caused by increasing water content at a location. The reviewed model and leakage detection method have been discussed by [9] [10]. The evolution of research methodologies has seen a transition from human experience-based methods to automated techniques that utilize machine learning (ML) and the Internet of Things (IoT) technologies.

There is a growing emphasis on experimental data collection, with 64% of reviewed studies being based on experimental data. Vibration and acoustic sensors are the most commonly used due to their low cost and ease of installation. ML algorithms are increasingly being adopted for their flexibility and accuracy. Its implementation was discussed by Phua et al., who created a pipeline leak detection method based on acoustic signals with an infrasonic sensor[11], as did Ullah et al. by measuring acoustic emissions[2]. Meanwhile, Rosman et al. implemented a pressure sensor to detect plastic pipe leaks[12]. Chen et al. developed a pipe crack detection robot using a color sensor[13]. A pipe leakage monitoring system was developed by Kwietniewski et al. using a geographic information system[14]. Alzubaidi et al. developed a pipeline telemonitoring system for FPGA devices[15]. A detection system utilizing geo-electrical resistance was developed by Pratap et al. [16]. Furthermore, the algorithm for leakage detection was explained by Hu et al., which classifies the condition of water pipelines based on spatial clustering[17], while Sousa et al. utilizes machine learning to determine leakage conditions in water distribution pipelines[18].

3. Materials and Methods

The basic material in the water distribution section uses pipes that are 1/2 inch in diameter. A 50 cm diameter reservoir with a height of 70 cm as a water source will be placed on the right side of the prototype, and the final water storage box will be placed on the left side of the prototype. Planning for the sensor network model used in this research uses dry soil media, which will be placed in a box measuring 100 cm. The height of the box was 30 cm with the box width was 32 cm. The pipe will be laid in the ground. This design will be placed on a table measuring 150 cm to the left of the prototype; the pump will be placed water as a tool to distribute water.

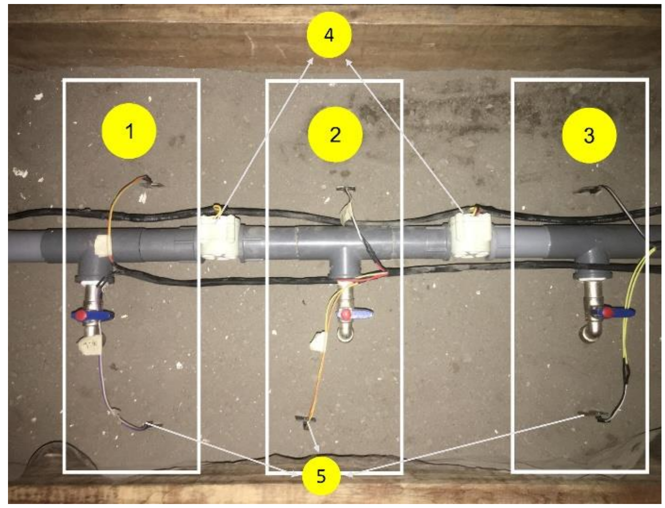

Fig. 1 Water pipe leakage model

3.1. Water Distribution Model

There were 7 sensor points, namely 4 water flow sensor points and 6 soil moisture sensor points. In this study, a soil moisture sensor was used to detect leaks in pipes by measuring soil conditions around the pipes. The NodeMCU will be placed in a small box above the simulation box leaks to avoid exposure to water. There are two water faucets available to simulate the occurrence of pipe leaks, namely at points (A) 33 cm and (B) 66 cm, which are located opposite the soil moisture sensor. The water faucet will be provided with a pipe protector 9 cm in diameter to make it easier to carry out simulations. Soil moisture sensors will be placed at 33 cm and 66 cm, as in Figure 1, and the sensor will be placed into the ground approximately 15 cm from the ground surface. This model was divided area into Area (1), Area (2), and Area (3), which placed water flow sensors on the pipe (4) and soil sensors (5) into the surrounding underground pipe.

3.2. Fuzzy Detection Model

Each soil sensor has a membership set value with 3 conditions of soil moisture level, namely wet soil with a membership function (0. 200. 400). Then moist soil with a membership function (300. 500. 700) and dry soil with a membership function (600. 800. 1023), which was written as:

X : Soil Moisture
T : {wet. moist. dry}
X : [0. 1023]
M :
wet = Λ (x; 0. 0. 200. 400)
moist = Λ (x; 300. 500. 700)
dry =Λ (x; 600. 800. 1023. 1023) (1)

Meanwhile. the system built has 4 fuzzy membership functions i.e. Sensor 1. Sensor 2. Sensor 3. and Sensor 4. The variable membership for each sensor is divided into 4 sets of water flow. Namely small (0-9.5). Medium (9. -10.35). Large (10-11). and very large (10.7-12). which was written as:

X : Flow rate
T : {small. medium. large. very large}
X : [0. 12]
M :
small = Λ (x; 0. 0. 9.5)
medium = Λ (x; 9. 10. 10.35)
large = Λ (x; 10. 10.5. 11)
very large = Λ (x; 10.7. 11.5. 12. 12) (2)

The output detection system was designed to find the leakage conditions associated with the membership function as follows:

X : Leakage condition
T : {small. medium. large}
X : [0.10]
M :
small = Λ (x ; 0. 0. 0.5.1)
medium = Λ (x; 1. 1.5. 2)
large = Λ (x; 2. 2.5. 3. 10) (3)

The leakage area detection is described in Table 1. This model is divided into three areas, i.e. Area 1. Area 2. and Area 3. Each area will be determined by two flow sensors and two soil sensors.

Table 1. Leakage area detection

Area	Flow Sensor		Soil Sensor	
Area1	Flow_1	Flow_2	Soil_1	Soil_2
Area2	Flow_2	Flow_3	Soil_3	Soil_4
Area3	Flow_3	Flow_4	Soil_5	Soil_6

Table 2. Fuzzy rules

Flow_1	Flow_2	Soil_1	Soil_2	Leakage Status
Very large	Large	Moist	Dry	Small
Large	Medium	Moist	Dry	Small
Large	Small	Moist	Dry	Small
Very large	Large	Dry	Moist	Small
Large	Large	Dry	Moist	Small
Large	Small	Dry	Moist	Small
Very large	Large	Wet	Dry	Medium
Big	Small	Wet	Dry	Medium
Very large	Large	Moist	Moist	Medium
Large	Small	Moist	Moist	Medium
Very large	Large	Dry	Wet	Medium
Large	Small	Dry	Wet	Medium
Very large	Small	Wet	Wet	Large
Very large	Small	Wet	Moist	Large
Very large	Small	Moist	Wet	Large

In this research, the rule base determines the output of water pipe leaks in each Area. A knowledge/rule database can be formed from the fuzzification results of the soil moisture sensor, which are listed in Table 2. The fuzzy rule for Area 2 and Area 3 is the same as for Area 1.After the results of fuzzification are acquired, the maximum value of each input is obtained. Thereafter, the minimum implication is executed using the formula as follows:

$$\mu A \cap B = \min (\mu A[x], \mu B[y]) \quad (4)$$

At the defuzzification stage, the centroid method is utilized to obtain the value of the affirmation function, which becomes the output value of the system. The system output, as determined by the defuzzification process, is classified as small, medium, or large. The following equation represents the defuzzification stage:

$$t(A) = \frac{\int_x \mu_A(x) x dx}{\int_x \mu_A(x) dx} \quad (5)$$

3.3. Node Sensor

In this research a water flow sensor and soil sensor are used in a pipe leak detection system. The sensor node design in this research uses 4 water flow sensors connected to an Arduino Mega connected to the network via the ESP8266 WiFi module. This design was carried out by connecting the water flow sensor and soil sensors with the pins on the Arduino Mega 2560 of each sensor network. The schematic diagram is displayed in Figures 2 and 3.

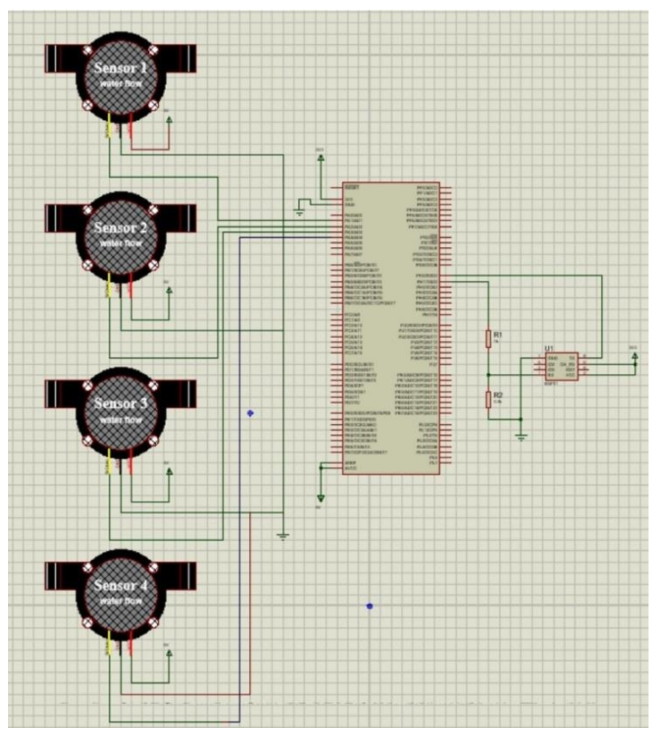

Fig. 2 Water flow sensors schematic diagram

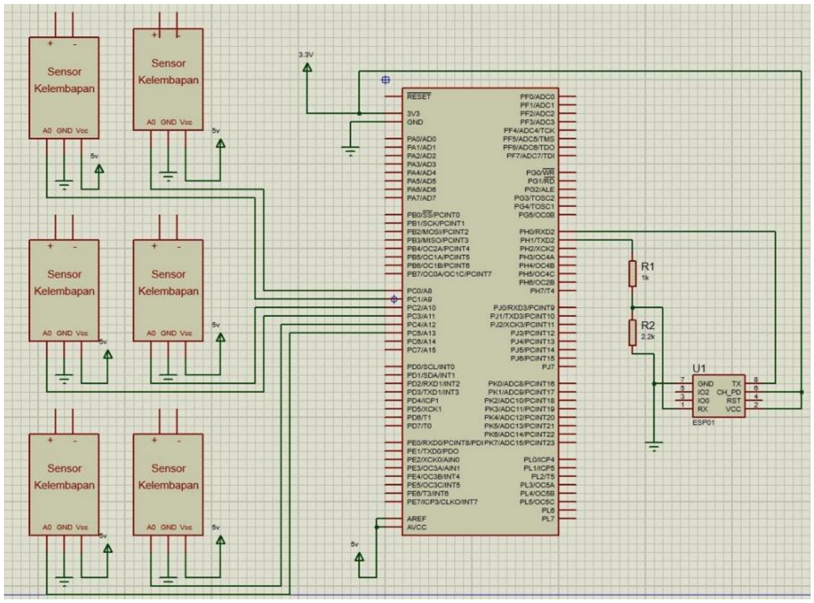

Fig. 3 Soil sensors schematic diagram

The implementation of sensors is conducted by evaluating sensor performance to standard meters. This evaluation aims to identify any discrepancies in the measurement results. The outcomes of this evaluation are illustrated in the accompanying figures, Figure 4 and Figure 5, which showcase the statistical analysis results for each sensor type.

The different values between the sensors and the standard meters are then determined. These values are subsequently incorporated into the input data acquisition program for water flow and soil moisture sensors. The soil moisture sensor shows that the highest deviation appears to be 4% (34% vs. 30%). The lowest deviation is 0%, indicating that both sensors give identical results in some cases. Most differences are within ±2%, suggesting a reasonable accuracy level.

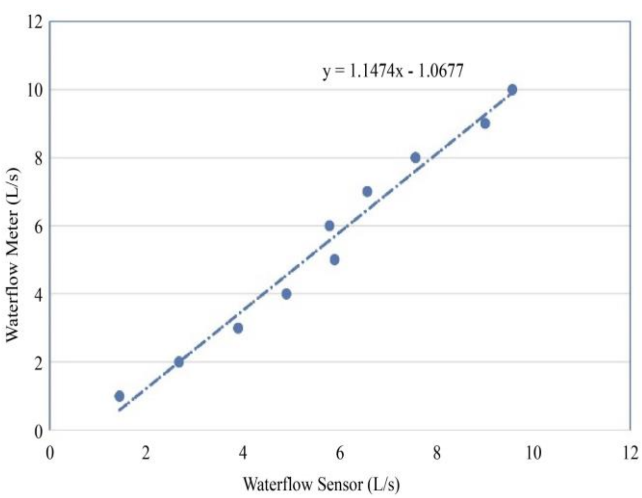

Fig. 4 Waterflow sensor calibration

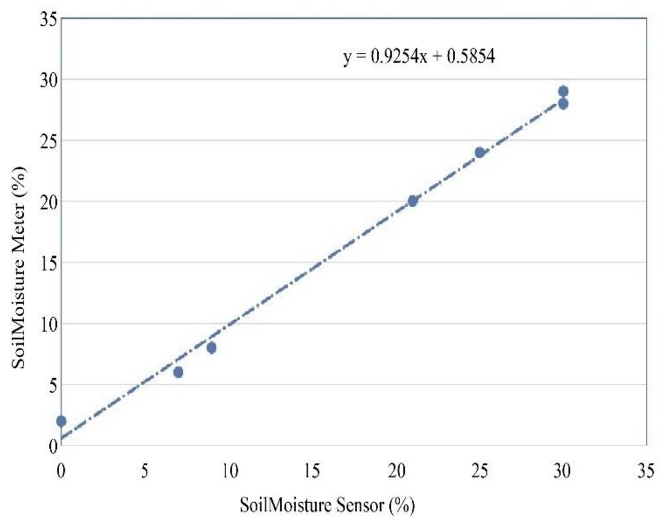

Fig. 5 Soil moisture sensor calibration

Furthermore, the water flow sensor shows high consistency due to the strong correlation (0.989) and low standard deviation. The accuracy is quite good, with an average error of only 8.09%. The maximum error is relatively low, indicating that the sensor does not have significant outliers or inconsistencies.

4. Results and Discussion

4.1. Sensor Performance

The application of a soil moisture and water flow sensor network in a leak detection system is useful for determining differences in water flow rates and soil conditions around water pipes. The sensor test results show that the sensor has worked according to its characteristics. The percent of error is the difference value of the data acquisition, whether the accuracy was defined as the error value compared to the maximum value of 100 percent. It shows the water flow sensor performance compared with the standard. It shows that the implemented sensor has a high level of accuracy of as much as 94% (see Table 3). Otherwise, the soil sensor has an accuracy of as much as 92 % (see Table 4).

Table 3. Waterflow sensor performance

No.	Standard Waterflow Sensor (L/m)	Waterflow Sensor (L/m)	Percentage of Error %	Accuracy %
1	10.00	9.56	4.40	95.6
2	10.00	10.00	0	100
3	10.00	9.56	4.40	95.6
4	10.00	9.56	4.40	95.6
5	10.00	9.78	2.20	97.8
6	10.00	10.89	8.90	91.1
7	10.00	10.89	8.90	91.1
8	10.00	10.89	8.90	91.1
9	10.00	10.89	8.90	91.1
10	10.00	10.89	8.90	91.1
11	10.00	10.67	6.70	93.3
Average			6.05	93.94

Table 4. Soil sensor performance

No.	Standard Soil Sensor (%)	Soil Sensor (%)	Percentage of Error %	Accuracy %
1	31	30	3.2	96.8
2	34	30	11.7	88.3
3	23	21	8.7	91.3
4	24	25	4.1	95.9
5	6	7	16.7	83.8
6	9.5	9	5.2	94.8
7	0	0	0	200
8	0.1	0	10	90
Average			7.45	92.5

4.2. Fuzzy Output

The system results in fuzzy detection algorithms, and a comparison with the simulation is shown in Table 5. In system testing, changes in water flow conditions and soil moisture were carried out to determine the response of the fuzzy logic system. Test results for water flow conditions and soil moisture indicate that the system responds as designed. The simulation and implementation results obtained the same conditions. When the water flow is constant. This is indicated by the absence of differences in the water flow sensor and high humidity values (dry soil conditions). The system detects that no leaks are occurring. Meanwhile, small leak detection occurs when there is a small difference in the water flow sensor value and the soil moisture value shows that one part is wet. Likewise, when the difference between the two water flow sensors is large enough, the ground conditions are wet or very wet. The system will detect a medium or large leak. The implemented output has been found to systematically deviate slightly above the simulated output, with an average percentage error of 8.97%. The error ranges from 6.38% to 12.00%, indicating that most values fall within a ±10% tolerance, except for the initial data point, which exceeds this limit. While the accuracy is relatively high, the consistent upward deviation suggests the presence of a systematic bias in the implementation. Assuming an acceptable margin of error of ±10%, the implementation can be considered reliable. However, if higher precision is required, adjustments must be made to mitigate the observed discrepancies.In comparison, the implemented system has advantages over similar systems created before. This system uses two types of sensors, namely water flow sensors and soil moisture sensors, while [4],[5], and [7] are only water flow sensors. Likewise [7], the use of fuzzy logic algorithms only uses water flow data without involving soil moisture data. In future work, the built system can detect leaks in each area. This represents a novel problem that can be investigated in future studies. The detection system can be developed to encompass the entire network as a single fuzzy leakage detection system model.

Table 5. Comparison result

Flow_1	Flow_2	Soil_1	Soil_2	Simulated Output		Implemented Output		Status
10.44	10.44	1003	992	0.5	No Leakage	0.56	No Leakage	Succeed
10.44	9.78	368	992	2.44	Small	2.64	Small	Succeed
10.44	10	368	992	2.37	Small	2.59	Small	Succeed
11.56	8.22	307	368	7.34	Large	8	Large	Succeed
10.89	9.11	450	573	3.76	Medium	4	Medium	Succeed

5. Conclusion

The present study has developed a detection system for pipe leakage based on the fuzzy method, with input parameters such as water flow and soil moisture. The sensor performance demonstrates an accuracy of 92-94 percent, and the fuzzy detection functions as intended. While the system has successfully detected pipe leakage, it has only been deployed in specific areas. Further exploration is necessary to investigate the system's capacity to detect diverse regions within a single calculation.

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