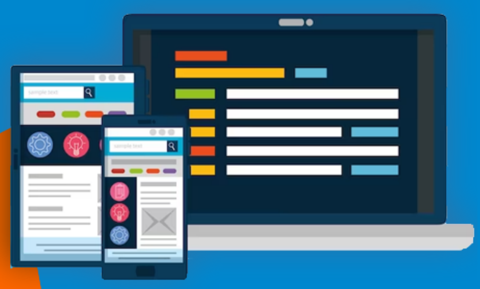

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RESEARCH ARTICLE OPEN ACCESS

Underground Water Pipe Leak Detection System Based on Soil Moisture Values with Fuzzy Logic

O C Murtikusuma, A B Primawan[1], L Sumarno
Department of Electrical Engineering, Universitas Sanata Dharma, Yogyakarta-Indonesia
[1]) correspondence author

ABSTRACT
Water pipe underground leakage detection was very important reduces water loss in the plumbing system. The occurrence of leakage in underground water pipelines represents a considerable challenge to the effective conservation of water resources and the maintenance of associated infrastructure. This study proposes a novel detection system based on soil moisture monitoring and fuzzy logic to accurately identify and classify leak severity in subterranean water pipelines. Soil moisture sensors situated in close proximity to the pipeline are employed to ascertain the real-time moisture levels, which are then processed by a fuzzy logic algorithm to determine the leak condition with high accuracy. The system's efficacy was validated through a prototype that achieved an average error rate of 6.64%, thereby demonstrating reliable performance in simulated leakage scenarios. This methodology offers a cost-effective, scalable solution to detect pipeline leaks and minimize water loss, with promising applications in urban and rural water distribution systems.

Keywords – underground water pipe, leakage detection, soil moisture, fuzzy logic, monitoring system

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I. INTRODUCTION

Water is a primary necessity for human life, necessitating effective management and distribution of this vital resource. The distribution system is responsible for transporting treated water from the treatment plant to settlements, offices, and industries that utilize water. To ensure the adequate distribution of water to consumers, a reliable piping system is essential. However, during the distribution process, instances of water loss due to pipe leaks may occur.

Water is a vital natural resource that is indispensable to human life. In addition to consumption for hydration, water is also required for several other domestic tasks, including cooking, washing, bathing, and numerous other activities. It is therefore evident that drains in the house have a significant role in everyday life. It is of paramount importance to consider and maintain the irrigation and plumbing system in the house to prevent damage or leakage. Leaking or damaged pipes have the potential to disrupt our daily activities[1], [2]. Consequently, we must gain an understanding of the factors that may lead to pipes becoming leaky or damaged in our residence. This will enable us to be more vigilant and avoid plumbing leaks in the future.

The effective and efficient distribution of potable water is a fundamental necessity to support the continued development and operation of modern infrastructure and to meet the increasing global demand for water. A significant challenge in the field of water distribution is the undetected leakage of water, which results in considerable water loss, infrastructure damage, and environmental strain[3]–[6]. A substantial body of research indicates that in many urban water systems, up to 30% of treated water is lost due to leakages in distribution pipelines. Conventional techniques for identifying these leaks, such as acoustic sensing and pressure monitoring, frequently lack the requisite sensitivity to detect minor leaks in subterranean pipelines. Furthermore, they are often financially impractical for extensive implementation.

Water pipe leaks are common and result in considerable financial and environmental losses. Consequently, there is a pressing need for an innovative solution to detect them[6], [7]. The use of fuzzy methods to create a pipe leak detection system based on water flow[8][9], however, a pipe leak detection system based on soil moisture has also been done. Therefore, it is necessary to build a system that combines both systems.

The recent advancements in sensor technology and computational intelligence have provided new opportunities for the development of more efficient and accurate methods for the detection of leaks. One promising approach involves the utilization of soil moisture sensors in conjunction with fuzzy logic for the classification of leak severity based on soil moisture data. Soil moisture values in the vicinity of a buried pipeline offer an indirect indication of leakage, with higher-than-normal moisture levels suggestive of a potential water leak.

This paper presents a soil moisture-based leak detection system using a fuzzy logic framework designed to assess moisture levels and classify leaks as "small," "moderate," or "large." By implementing a fuzzy logic approach, the system is capable of handling the inherent uncertainty and variability of real-world conditions, thereby providing a robust mechanism for leak detection. The system's performance is evaluated using a prototype model, and its error rate and potential limitations are analyzed to assess practical feasibility.

II. RESEARCH METHOD

The proposed system is based on the use of soil moisture sensors positioned at fixed intervals along a prototype water pipeline. Each sensor has been calibrated to measure soil moisture within a range of 0–1023, where a lower value indicates soil moisture levels that are above the desired level (which is likely due to a leak), and a higher value indicates soil moisture levels that are below the desired level. In order to enhance the accuracy and reliability of the readings, the sensors have been embedded at three critical points: close to the water source, along the pipeline, and near the endpoint..

The fundamental component utilized in the construction of this subterranean pipe configuration is a water pipe with a diameter of ½ inch. The water reservoir has a diameter of 50 cm and a height of 70 cm. It is situated on the left side of the prototype, while the final reservoir is located on the right side of the prototype, as illustrated in Figure 1. The sensor network model that will be employed in this research employs a dry soil medium, which will be situated within a box measuring 100 cm in length, 30 cm in height, and 32 cm in width. The pipes are situated within a dry soil medium or buried. The aforementioned design will be situated on a table measuring 150 cm in length. On the left side of the table will be placed a water pump, which will serve as a tool for the distribution of water.

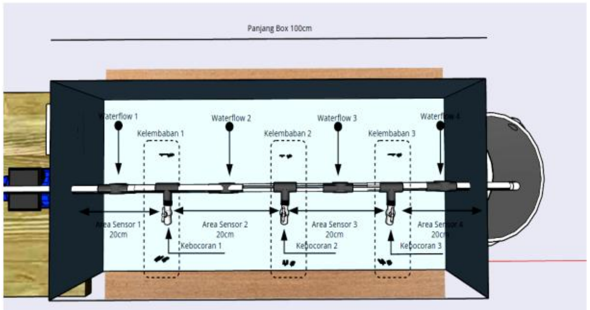

Fig.1 Ground Water Pipe Prototype

The membership function of the input is the measured value of the soil moisture sensor[10]. The resulting value is in the range of 0 to 1023. A value of 0 indicates a soil moisture level of 100% or wet soil conditions, while a value of 1023 indicates a soil moisture level of 0% or dry soil. This is the 10-bit ADC value of the sensor. The membership function for the input soil sensor was described as:

X : Soil moisture level
T : { wet, moist, dry}
X : [0 , 1023] soil sensor level
M :
Wet = Λ (x ; 0, 0, 200, 400)
Moist = Λ (x ; 300, 500, 700)
Dry = Λ (x ; 600, 800, 1023, 1023)

The leak detection system relies on a fuzzy logic algorithm that processes soil moisture data to assess leak severity. The soil moisture readings are categorized into three membership functions:

- Wet (0–400): Strong indication of potential leakage.
- Moist (300–700): Moderate likelihood of leakage.
- Dry (600–1023): Low likelihood of leakage.

In the other hand, the membership function for pipe leakage output detection is as follows:

x : leakage level
T : { small, medium, large}
X : [1 , 10] leakage level
M :
Small = Λ (x ; 0, 0, 2, 4)
Medium = Λ (x ; 3, 5, 7)
Large = Λ (x ; 6, 8, 10, 10)

For the output, leak severity is classified into three levels based on the fuzzy rules applied:

- Small Leak: Minor increase in moisture at a single sensor.
- Moderate Leak: Moderate moisture increase detected across multiple sensors.
- Large Leak: Significant moisture increase at all sensors, indicating severe leakage.

Table 1. Fuzzy Rules

No	Soil Sensor1	Soil Sensor2	*Output*
1	Wet	Wet	Large Leaks
2	Wet	Moist	Large Leaks
3	Wet	Dry	Moderate Leaks
4	Moist	Wet	Large Leaks
5	Moist	Moist	Moderate Leaks
6	Moist	Dry	Small Leaks
7	Dry	Wet	Moderate Leaks
8	Dry	Moist	Small Leaks
9	Dry	Dry	No Leaks

The fuzzy logic process comprises three steps:

a. Fuzzification: Converts sensor input data (moisture levels) into fuzzy values.
b. Inference: Applies a set of predefined rules to determine leak probability.
c. Defuzzification: Transforms fuzzy outputs into specific leakage categories (small, moderate, large). The main algorithm shown in Fig.2

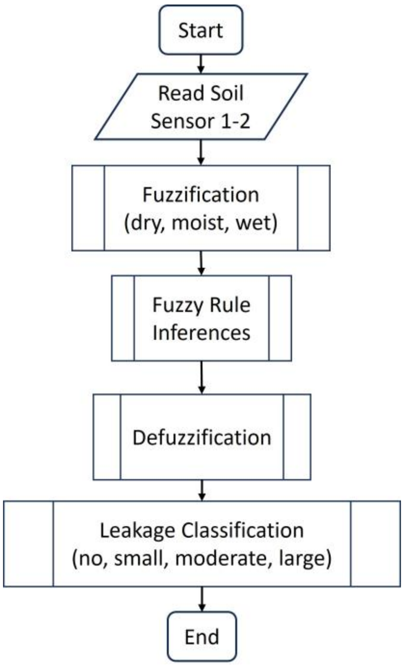

Figure 2. Main Algorithm

III. RESULT AND DISCUSSION

Fuzzy logic testing is performed to determine the correctness of the fuzzy logic results of the tool by comparing it with a software simulation that is given input of the original reading value or the sensor reading value in percent that has been converted to the original reading value. This comparison has provisions for the classification of the level of leakage with a range of fuzzy logic results of 0 (if there is no leakage), <3 (small leakage), <6 (moderate leakage), and> 6 (large leakage). A series of controlled leakage tests were conducted to evaluate the accuracy and response time of the detection system. Each test scenario was designed to simulate a different leak intensity, allowing for the observation of the system's ability to classify leak severity accurately.

Table 4. Comparison Result

Areas	No.	Test Results		Simulation Results		The final result		
		Test Value	Leak Status	Simulation Value	Leak Status	Status Judgement	Value Difference	Errors (%)
Area 1	1	0	No Leaks	0	No Leaks	Equal	0	0
	2	1.36	Small Leaks	2.78	Small Leaks	Equal	1.42	51.08
	3	5	Moderate Leaks	5	Moderate Leaks	Equal	0	0
	4	5	Moderate Leaks	5	Moderate Leaks	Equal	0	0
	5	7.78	Large Leaks	7.73	Large Leaks	Equal	0.05	0.65
Area 2	1	0	No Leaks	0	No Leaks	Equal	0	0
	2	0	No Leaks	0	No Leaks	Equal	0	0
	3	2.59	Small Leaks	2.37	Small Leaks	Equal	0.22	9.3
	4	6	Moderate Leaks	5.82	Moderate Leaks	Equal	0.18	3.1
	5	8	Large Leaks	7.57	Large Leaks	Equal	0.43	5.7
Area 3	1	0	No Leaks	0	No Leaks	Equal	0	0
	2	2.64	Small Leaks	2.44	Small Leaks	Equal	0.2	8.2
	3	4	Moderate Leaks	3.76	Moderate Leaks	Equal	0.24	6.4
	4	8	Large Leaks	7.34	Large Leaks	Equal	0.66	9
	5	9	Large Leaks	8.47	Large Leaks	Equal	0.53	6.25
						Average	0.262	6.64

From Table 4. it can be seen in area 1, there is a value of the fuzzy logic result of the soil moisture sensor reading which produces a value of 0 which indicates that there is no pipe leak in area 1. However, over time, the fuzzy logic result of the sensor reading value in that area changed to 1.36, meaning that a small leak occurred. Finally, the fuzzy logic result of the sensor reading value changed to 7.78 which means that there is a large leak in that area. The results of the tool test are then compared with the measurement or software simulation test to determine the level of accuracy and accuracy of the output or output of the pipe leak level that occurs. The same thing happens for area 2 and area 3, but in testing area 2 there are more errors than in area 1. This is understandable because the conditions of area 2 are influenced by area 1 conditions. Likewise, it was accumulated in area 3 where it was influenced by area 2 and area 1. In the leak test in the table above, there is a difference in the fuzzy logic result value between the tool test results and the simulation results which have an average fuzzy logic difference value of 0.262 and an average error value of 6.64%.

IV. CONCLUSION

The findings of this study indicate that the system is capable of detecting the extent of leakage in areas 1, 2, and 3, contingent on the specified time range and prevailing soil moisture conditions. It was observed that as the soil continues to receive a source or flow of water due to a leak in the pipe, the resulting leak rate tends to increase.

The soil moisture sensor, which is designed to detect the level of leakage concerning a reference soil moisture level, is operational when the sensor value of water-flow 2 is less than that of water-flow 1, indicating a leak. The implementation of fuzzy logic in leak testing in each area, from the fuzzification stage to the defuzzification stage, has an average number of fuzzy logic differences of 0.262 and an average error of 6.64 percent.

Acknowledgements

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