Natural Gas Distribution Pipeline Security System Using Wireless Sensor Network Based on Internet Of Things

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Abstract. Increasing security in the natural gas distribution pipeline system is one of the essential requirements in the energy industry. To fulfil this requirement, in this study an Internet of Things-based Wireless Sensor Network was designed to improve the security system of natural gas distribution pipelines. The WSN consists of 3 transmitter nodes and 1 receiver node connected to the NodeMCU ESP8266 gateway as a sensor network connector with the Ubidots IoT platform. This research aims to develop an efficient and accurate security system by representing sensor data into linguistic values such as at normal tem- perature (20 – 38°C), warm (32 -50°C), and hot (44 - 62°C). Gas Leaks: no leaks (0 – 225 ppm), moderate (150-375 ppm) and large leaks (300-525 ppm). Presence of fire: no presence of fire (600-1024), presence of little fire (300 -750) and pres- ence of big fire (0-450). As for the results of system analysis in response to vari- ous potential hazards; safe (0-110), alert (88-198) and dangerous (154-255). The application of sensor analysis in WSN uses fuzzy logic analysis by using fuzzy sets and fuzzy rules; the Mamdani method can describe the level of uncertainty in the input data and provide output based on human knowledge flexibly. The research using MATLAB and manual calculations as a comparison that the de- sign of the system has the right calculation with a standard of not more than 1 between MATLAB and manual calculations. Obtained a difference of 0.3 - 0.78 from 3 experimental conditions between MATLAB and manual calculations.

Keywords: Natural Gas Distribution, Pipeline Security, Wireless Sensor Network, Internet of Things.

1 Introduction

Natural gas line installations have high potential safety risks. Gas leaks or other security threats can cause serious impacts such as explosions, fires, or harm to the environment. Therefore, it is necessary to develop an effective and reliable security system to identify and respond to such threats. Wireless Sensor Network (WSN) offers an attractive solution in improving the security system of natural gas line installations. Using WSN, small and energy-efficient sensors can be installed wirelessly at various points on the natural gas line. This enables real-time data collection on temperature, humidity, and potentially harmful gases. This research aims to design and implement an Internet of

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Things (IoT)-based wireless sensor network (WSN) on a natural gas line installation security system. This wireless sensor network is designed to monitor and detect potential gas leaks and other security threats in real-time. The implementation of WSN in IoT-based natural gas line installation security system also involves several challenges such as power management, network reliability, and data security. However, the opportunities are enormous in improving the reliability, early detection, rapid response, and operational efficiency of natural gas line installation security systems.

Previous studies related to gas leak detection with the MQ-6 sensor on the main gas channel, the results showed that the data sent had an average gas leak value of 640 ppm with a time span of 6-9 seconds for data received on a smartphone [1]. Monitoring the LPG gas leak system with the MQ-6 sensor by sending gas leak warnings via SMS to cellphones, using load sensors to monitor the specified threshold levels, so that users have an idea of how long LPG gas can last for replacement. The use of the GSM network to transmit gas leak data with load sensor detection is proposed to ensure the availability of LPG gas and detect gas leaks [2].

Wireless Sensor Network or often abbreviated as WSN is an embedded system equipment that communicates without cables which contains one or more sensors and is equipped with communication system equipment. Sensors here are used to capture information according to the characteristics and presentation of information via internet communications [3], [4].

The Mamdani Fuzzy Method is one part of the Fuzzy Inference System which is useful for drawing conclusions or the best decision in uncertain problems. The Mamdani Fuzzy Method was introduced by Ebrahim Mamdani in 1975. The Mamdani Fuzzy Method in its process uses linguistic methods and has a fuzzy algorithm that can be analyzed mathematically, making it easier to understand [5].

In the Mamdani method there are 4 stages to get an output, namely:

- Fuzzy set formation, Fuzzification is a crisp number generator that has a fuzzy value in it which will be converted into a fuzzy value which can later be grouped.
- Application of the implication function, the implication function used is Min.

$$\mu AUB(X) = \min(\mu A[x], \mu B[x]) \quad (1)$$

- Rule composition, Aggregation is the process of combining the output values of all rules. At this stage, the Max method is used.

$$\mu_{sf}[x_i] = max(\mu_{sf}[x_i], \mu_{sf}[x_i]) \quad (2)$$

- Defuzzification is to change the output fuzzy value of the rule aggregation in a crisp number which will produce a certain range. In this system using the centroid method, besides centroid there are 4 other methods, namely Bisector, Mom, Lom, and Som.

The aim of this research is to improve the safety of natural gas line installations. By implementing a wireless sensor network connected to an IoT platform, this system can detect early potential gas leaks or other security threats. This enables a fast and effective response to prevent dangerous events. Wireless sensor networks enable real-time monitoring of critical parameters such as gas concentration, temperature, pressure, and humidity.

2 Experimental Setup

2.1 Analysis of System Requirements

Before designing, an analysis of system requirements was carried out in this study. The analysis determines what the system can do, and the various components needed in the system. The needs of this system include:

1) Functional requirements
   - The wireless sensor network system only sends data information from each transmitter node to the receiver node and the system consists of 3 transmitter nodes and 1 receiver node.
   - The system can detect fire hazards and gas leaks
   - The system can transmit and receive data between nodes wirelessly under 30 metres distance between transmitter nodes to receiver nodes.
   - The system can display sensor data on the OLED display
2) Non-functional requirements
a) Software requirements
   - Arduino IDE
   - Fritzing
   - Ubidots
   - Matlab
b) Hardware requirements

2.2 System Block Diagram

General description the system will be made using a wireless sensor network where each node has 3 sensors, namely the MQ-6 sensor, fire sensor and temperature sensor. There is an illustration of the system created in the picture above. The three sensors can provide information on hazards that occur in the gas distribution network, both gas leaks and fires that occur in the gas pipeline network area. Each node is equipped with an NRF24L01 communication module that functions to communicate between nodes.

The system uses 4 nodes named: node 00, node 01, node 02 and node 03. Node 00 has a function as a system gateway to the database to store measurement data. NodeMCU which is node 00 is only equipped with the NRF24L01 module and OLED display because it functions as a system gateway. Data on the ubidots server will be processed and displayed as information through tables, charts and others. If there is a leak or indication of a fire around the gas network area, the system provides a warning either via email, OLED display, web server and buzzer. Figure 1 shows the system block diagram.

2.3 Hardware Implementation

In this study using 2 kinds of nodes, namely transmitter nodes and receiver nodes. Figure 2 shows the transmitter node.

There are 3 sensors connected to the arduino then the sensor data will be forwarded to the receiver node by the arduino using NRF24L01. Here it only functions as a sender. The hardware implementation of the receiving node is shown in Figure 3.

In the receiver node, there is an LED monitor to display the data received from the transmitter node. Then, this data is uploaded to the Ubidot server for display purposes. Additionally, it sends a danger signal through email and activates a buzzer on the receiver node circuitry.

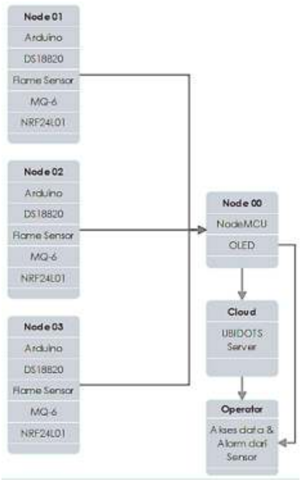

Fig. 1. Block Diagram System

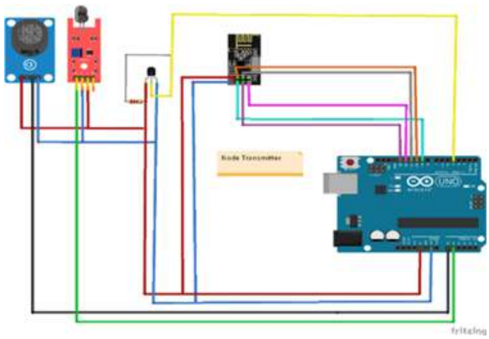

Fig. 2. Transmitter Node Wiring

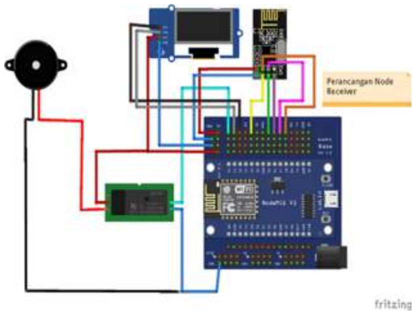

Fig. 3. Receiver Node Wiring

2.4 Fuzzy Logic Mamdani Method

In designing this system, the selected membership is 1st order fuzzy logic referring to a fuzzy logic model that uses a membership function with a more complex form and takes into account the degree of membership. The 1st order membership function allows partial membership values between 0 and 1. Figure 4-9 shows the application of fuzzy logic using variables, namely temperature (normal, warm, hot), gas sensor (no leak, warm, hot), fire presence sensor (big fire, small fire, no fire) and risk (safe, alert and dangerous).

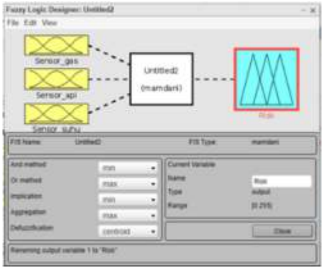

Fig. 4. Fuzzy Logic Mamdani

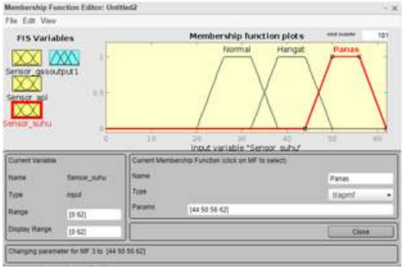

Fig. 5. Temperature Membership

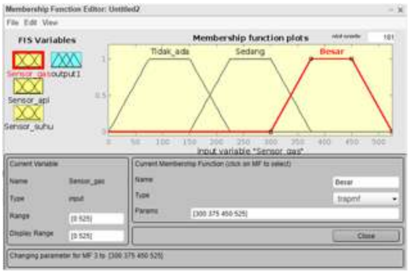

Fig. 6. Gas Membership

Fig. 7. Flame Membership

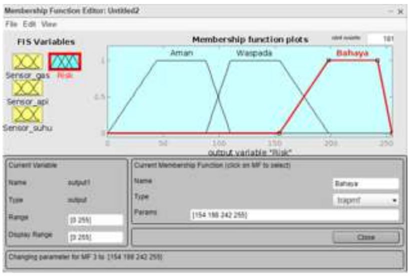

Fig. 8. Output Risk Membership

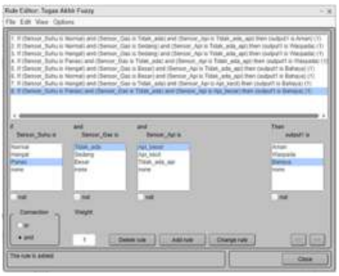

Fig. 9. Rule Fuzzy

Membership normal (20-38), warm (32-50) and hot (44-62). Membership is none (0 - 225), medium (150 - 375) and large (300 - 525). Membership big fire (0-450), small fire (300-750) and no fire (600-1024). Membership safe (0-110), alert (88-198) and danger (154-255). Figure 9 shows the fuzzy editor rules.

3 Result and Analysis

Results and analysis of Wireless Sensor Network design in gas distribution network security systems using the internet of things. This testing and analysis aim to determine the suitability of the tool's performance with the design that has been created. The results of observations and data analysis from testing are used to evaluate the system and can be used as a reference for further development. Figure 10 shows the Transmitter device & Receiver device.

Fig. 10. Transmitter Node & Receiver Node

3.1 Wireless System Network Testing

This test aims to find out how the NRF24L01 communicates with the system. Data collection is carried out by installing the NRF24L01 on the microcontroller pin according to the system design of the transmitter node and transceiver node. Each node will communicate and exchange data using the RF Network library programmer for this test. In a wireless sensor network system, to differentiate one node from another node, a different node header ID is used for each module. Table I shows Wireless System Network Testing data.

Table 1. Wireless Sensor Network Testing Based on Multiple Distances.

No	Distance (Meter)	Node Transmitter			Node Receiver	Result
		Node 01	Node 02	Node 03	Node 00	
1	1 m	Data Sent	Data Sent	Data Sent	Data received	Data on the sensor network in the system only has a good data reception distance ranging from 0 metres to 30 metres. If it is more, the data transmission will not be received by the receiver node.
2	5 m	Data Sent	Data Sent	Data Sent	Data received	
3	10 m	Data Sent	Data Sent	Data Sent	Data received	
4	15 m	Data Sent	Data Sent	Data Sent	Data received	
5	20 m	Data Sent	Data Sent	Data Sent	Data received	
6	25 m	Data Sent	Data Sent	Data Sent	Data received	
7	30 m	Data Sent	Data Sent	Data Sent	Data received	
8	31 m	Data not sent	Data not sent	Data not sent	Data not Receive	

3.2 Ubidots Webserver Testing

Figure 11 shows the results of website testing which aims to find out whether all node data has been sent to the ubidots website. NodeMCU ESP8266 is used as a wireless sensor data transmission device.

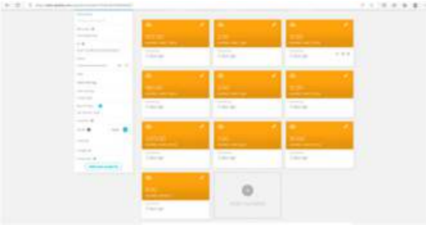

Fig. 11. Ubidots Web Server

Fig. 12. Ubidots web data

In this test it is said to be successful if the value displayed on the ubidots web is in accordance with the value listed on the local display. On the website a diagram is also created to make it easier to observe the value of each sensor which is presented in the form of a table and dashboard diagram shown in Figure 12 and 13.

Fig. 13. Dashboard Data Ubidots

Fig. 14. Email Alarm From Ubidots

Then, to provide fast notifications to users, ubidots in this system will provide email notifications if there are sensor values that indicate a danger to the gas distribution network system. Figure 14 shows the receipt of a danger notification email from one of the fire sensor presence sensors.

3.3 Testing the Overall System

Testing of the entire system is carried out by providing several conditions to each node then the sensor data values will be sent to ubidots and if a danger occurs it will provide a buzzer warning and close the valve according to the level of risk. Table 2 shows the test results data on each node.

Table 2. Result Overall Wireless System Network Testing

No	Parameter	Node 01	Node 02	Node 03	Transmitter			Indicator (Buzzer)	Ubidots
					Node 01	Node 02	Node 03		
1	Flame Sensor	998	996	994	998	996	994	Buzzer is off	Node 1: Safe
	Gas Sensors	2 ppm	1 ppm	2 ppm	1 ppm	1 ppm	1 ppm		

	Temperature Sensor	31 °C	32 °C	32 °C	31 °C	32 °C	32 °C		Node 2: Safe
	Output Risk	55,00	55,00	55,00	55,00	55,00	55,00		Node 3: Safe
2	Flame Sensor	172	175	173	172	175	173	Buzzer Active	The received data corresponds to Node 0
	Gas Sensors	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm		
	Temperature Sensor	50 °C	51°C	51 °C	50 °C	51 °C	51 °C		
	Output Risk	204,78	204,78	204,78	204,78	204,78	204,78		
3	Flame Sensor	933	936	934	933	936	934	Buzzer Active	
	Gas Sensors	475 ppm	475 ppm	475 ppm	475 ppm	475 ppm	475 ppm		
	Temperature Sensor	31 °C	32 °C	32 °C	31 °C	32 °C	32 °C		
	Output Risk	209,04	209,04	209,04	209,04	209,04	209,04		

3.4 Discussions

In the overall system test results, it can be concluded that the system as a whole can successfully work very well. In addition, the results of the design and implementation of this wireless sensor network with NRF24L01 have fulfilled the planned functional requirements. Based on several Fuzzy calculations both MATLAB and manual calculations of the response of the temperature sensor, gas sensor and fire sensor there are differences in the defuzzification response results. However, the difference in these results can still be tolerated because the difference in calculations is still below 1 so it is concluded that the system can monitor the security of the gas distribution pipeline network. The results of the defuzzification response in each experiment are shown in the Table 3.

Table 3. Comparison Of Fuzzy Results from Arduino, Matlab and Manual Calculation

No	Parameter	Arduino	Matlab	Manual	Error Output
1	Flame Sensor	998	996	994	0,4 - 0,6
	Gas Sensors	2 ppm	1 ppm	2 ppm	
	Temperature Sensor	31 °C	32 °C	32 °C	
	Output Risk	55,00	55,00	55,00	
2	Flame Sensor	172	175	173	0,5 - 0,78
	Gas Sensors	1 ppm	1 ppm	1 ppm	
	Temperature Sensor	50 °C	51°C	51 °C	
	Output Risk	204,78	204,78	204,78	
3	Flame Sensor	933	936	934	0,04 - 0,3
	Gas Sensors	475 ppm	475 ppm	475 ppm	
	Temperature Sensor	31 °C	32 °C	32 °C	

Output Risk	209,04	209,04	209,04

One of the first tests in the table will be tested against Arduino, Matlab and the following manual calculation of the fuzzy logic results on Arduino is shown in Figure 15.

Fig. 15. Fuzzy Calculation from Arduino

Fig. 16. Fuzzy Calculation from Matlab

Figure 15 shows the results of fuzzy calculations on Arduino where 3 sensors are input and one output which has 3 explanations, namely safe, alert and dangerous. The three outputs above are responses made if various possible dangers are detected in the gas distribution pipe. It can be seen that the degree of membership in the fuzzy input produces a defuzzification of 55.00 which is obtained from the inference/rules that have been created in the fuzzy design.

Figure 16 shows the results of calculations with Matlab. To ensure the correctness of the calculations, the same parameters were tested in Matlab software with the following results:

Testing in matlab is done by creating mamdani fuzzy logic in accordance with the design that has been made then opening the rule viewer, it will display the image as above. Then input the values 31, 2 and 998 as a representation of the value of the temperature sensor, gas sensor and fire sensor. Matlab will calculate the output after the input value is entered. In the picture, the output has a value of 55.6, meaning that if the distribution pipe has a temperature of 31 Celsius, the gas in the air is 1 ppm and the fire sensor has a value of 998, the fuzzy output has a safe degree of membership with a value of 55.6.

4 CONCLUSION

The thesis "Natural Gas Distribution Pipeline Security System Using Wireless Sensor Network Based on Internet of Things with NodeMCU ESP8266 Gateway" successfully develops an effective security system for natural gas distribution pipelines. Utilizing a multi-transmitter setup with three transmitter nodes and one receiver node, the system enables efficient wireless data collection. The receiver node aggregates data from the sensors and transmits it to the Ubidots IoT platform via the NodeMCU ESP8266 gate-

way, eliminating the need for individual internet connections for each sensor. The system reliably detects LPG gas, fire, and temperature, translating numerical sensor readings into user-friendly linguistic values that enhance understanding of potential hazards.
Additionally, the research employs fuzzy logic analysis using the Mamdani method, which effectively manages uncertainty and ambiguity in data interpretation. This approach allows for intuitive categorization of readings into defined ranges—such as safe, alert, and danger—making it easier for users to respond to threats. Validation through comparisons between MATLAB simulations and manual calculations revealed minor discrepancies, confirming the accuracy of the system design. Overall, the research demonstrates a robust integration of IoT and wireless sensor technologies, providing a reliable solution for natural gas pipeline security.

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