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Analysis of Temperature Sensors in a Volcanic Detection System

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Abstract

Volcanoes are geological phenomena that can cause significant disasters to human life and the environment, such as eruptions, pyroclastic flows, and lahars. Therefore, early warning systems for volcanoes are crucial to reduce disaster risks and provide sufficient time for evacuation. Monitoring surface temperature and the surrounding air around volcanoes is one of the key parameters in detecting volcanic activity. Temperature increases often serve as an early indication of magmatic activity beneath the surface. This study proposes an early warning system for volcanoes based on temperature sensors integrated with fuzzy logic to monitor volcanic activity in real-time. The system consists of a wireless temperature sensor network based on the Internet of Things (IoT) connected to an IoT platform for data monitoring and analysis. The SHT31D, SHT2X, BME280 and DHT11 sensors are used to measure the ambient temperature, and the temperature data is processed using fuzzy logic methods to detect changes in volcanic activity. The system was tested in both simulation and field environments using sensor node devices consisting of several temperature sensors controlled by a microcontroller. The fuzzy logic algorithm built using 256 rules is able to classify new data from sensor nodes into one of the categories of volcano vulnerability levels, namely “Normal”, “Caution”, “Warning”, or “Evacuate”. This system has the potential to serve as a real-time temperature monitoring tool for volcanoes, supporting disaster mitigation and volcanic activity risk management.

Keywords: sensor, volcano, monitoring-system, fuzzy logic, internet of things

INTRODUCTION

Volcanoes are one of the geological phenomena that have a significant impact on human life and the environment. Volcanic activity can cause major disasters such as eruptions, pyroclastic flows, and lahars, which not only damage infrastructure but also threaten lives [1]. Therefore, an early warning system for volcanoes is crucial to reduce disaster risks and provide sufficient time for communities to evacuate [2] [3] [4]. The purpose of monitoring is to predict eruptions as an effort to determine when a volcanic eruption will occur, how long it will last, where the eruption center is located, and the characteristics of the eruption itself to minimize the effect of this disaster [5] [6]. Eruptions are usually preceded by several seismic activities, followed by lava dome growth, volcanic-tectonic earthquakes, and shallow volcanic (VB) earthquakes as a response to rock pressure caused by magmatic movement from tectonic activity and thermal conduction of the magma chamber. An increase in earthquake occurrences (more than 1,400/day) can lead to eruptions [4] [7].

Volcanologists strive to make predictions based on the geological history of the volcano in question and monitor daily signs obtained from observations, either visually or instrumentally [4]. Seismicity study with the use of instruments and data, subsurface magma movements can be tracked through observations of seismic activity and small-scale deformation of the volcano, often referred to as deformation [8] [9]. Subsequently, the collected data are analyzed. Before an eruption occurs, there are early indications of changes in physical and chemical parameters, visible both visually and through instrumental measurements, as signs of volcanic activity commonly referred to as "Eruption Precursors" [4]. These data, along with the volcano's

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database, are then used to determine subsequent actions.

One of the key parameters in monitoring volcanic activity is the surface and air temperature around the volcano. A temperature increase often serves as an early indication of magmatic activity beneath the surface. Various technologies have been developed to monitor these temperature changes, including the use of thermal cameras and temperature sensors [10] [11]. However, temperature data analysis often requires adaptive methods capable of handling uncertainty, given the complex and dynamic nature of volcanic systems. Temperature monitoring and thermal anomaly detection in volcanic regions can be conducted in situ using direct contact sensors, such as thermocouples and thermistors, or remotely through thermal infrared radiation (TIR) measurements [12]. Direct contact sensors require protection against acidic gas corrosion, while TIR measurements using infrared cameras enable surface temperature estimation by capturing infrared radiation within specific wavelength ranges. Although in situ measurements are highly accurate, their coverage is limited to small areas, whereas TIR measurements can be hindered by atmospheric conditions such as thick clouds and volcanic ash [13]. Furthermore, while TIR measurements can cover large areas, their spatial resolution tends to be low. The remote and inaccessible nature of volcanic regions adds challenges in communication, power supply, and maintenance of monitoring devices. Therefore, developing portable, energy-efficient, low-cost, and easily replaceable devices is essential to ensure effective real-time geochemical monitoring. This opens opportunities for further innovation in volcanic monitoring technologies. The SHT31D, SHT2x, BME280 and DHT11 sensor are a device designed to measure humidity, temperature, and the heat index of the environment. That sensor can be programmed using Arduino IDE. It offers excellent stability and highly accurate calibration features, utilizing a capacitive humidity sensor and thermistor to measure ambient air, with digital signal output through its data pin [9]. The calibration coefficients are stored in the sensor's OTP program memory, so when the internal sensor detects a condition, the module incorporates these coefficients into its calculations. The The SHT31D, SHT2x, BME280 and DHT11 are regarded as a high-quality sensor due to its fast response, quick data readings, and anti-interference capabilities [14].

In the last decade, the application of wireless sensor networks (WSN) as non-traditional monitoring systems has been widely reported. WSN is a collection of autonomous sensors and actuators with wireless communication capabilities designed to monitor and control physical or environmental conditions at various locations [15] [16]. With its ability to form networks autonomously, WSN offers cost-effective and low-maintenance monitoring solutions. This technology has been applied in various fields, such as medical, environmental, military, precision agriculture, animal tracking, smart spaces, and surveillance, with continuous innovation and expansion of its applications [17]. In the context of volcano monitoring, WSN is considered promising due to its low power consumption and ease of deployment. This technology is often integrated with the Internet of Things (IoT) [18], enabling devices to connect and exchange data over a network. However, most WSN research for volcano monitoring has primarily focused on seismic and deformation signals, while temperature and gas monitoring, which are also critical, remain relatively underexplored.

Fuzzy logic has been recognized as an effective approach to address uncertainty in complex systems. With its ability to process ambiguous or uncertain data, fuzzy logic offers a robust solution for analyzing temperature data from sensors to detect changes in volcanic activity [8]. Several previous studies have shown that fuzzy logic-based systems can provide accurate results in various applications, including environmental monitoring and disaster mitigation. In this research, we developed a volcano early warning system based on temperature sensors integrated with fuzzy logic. This system is designed to monitor the status of volcanic activity in real-time and provide early indications of potential increases in volcanic activity. The study encompasses the development of hardware based on temperature sensors, data processing using fuzzy logic, and system performance testing in both simulated and field environments.

EXPERIMENTAL METHOD

This study proposes a volcano detection method using wireless sensor network (WSN) with an operational workflow as shown in Figure 1. The proposed volcano detection system consists of a reliable, robust, low-cost, low-power, and scalable IoT-based wireless environmental temperature monitoring designed to monitor the environmental temperature in volcanic regions. This wireless network comprises three main elements: sensor nodes, gateways, and stations.

The system operational mechanism can be summarized as follows: The sensor node section includes temperature sensors that function as readers of environmental temperature parameters around the volcano, and a microcontroller that reads the temperature sensor data and commands the LoRa module to send the temperature data to the gateway unit. The gateway, operating dynamically in areas with internet access, manages the network and acts as a transparent bridge that relays messages between the end devices and the central network server. During each sampling period, the gateway communicates with the sensor nodes to initiate the temperature measurement process. Temperature sensor data analysis from the monitoring system is performed using the fuzzy logic method.

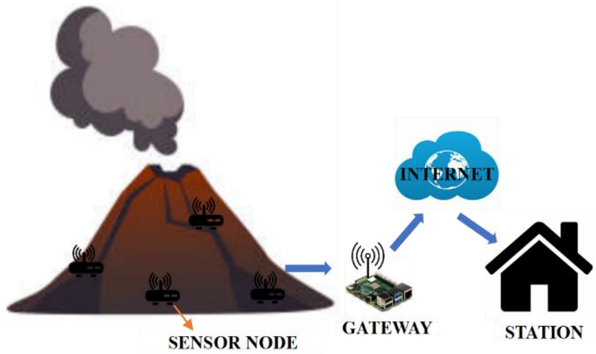

Figure 1. Schematic of the proposed volcano detection system method.

In this study, the temperature sensor system for volcano early detection was tested using a sensor node device, as shown in Figure 2. The sensor node unit consists of five temperature sensors controlled by an Arduino Uno microcontroller. Data communication and control are carried out via LoRa radio frequency, which is connected to one of the IoT platforms (Node-RED) for ease of control as well as final data visualization and volcano status display.

The working mechanism of the sensor node device in the temperature sensor system, including the system's fuzzification process, rule base system, and defuzzification process from the temperature sensor input, is illustrated in the block diagram in Figure 3.

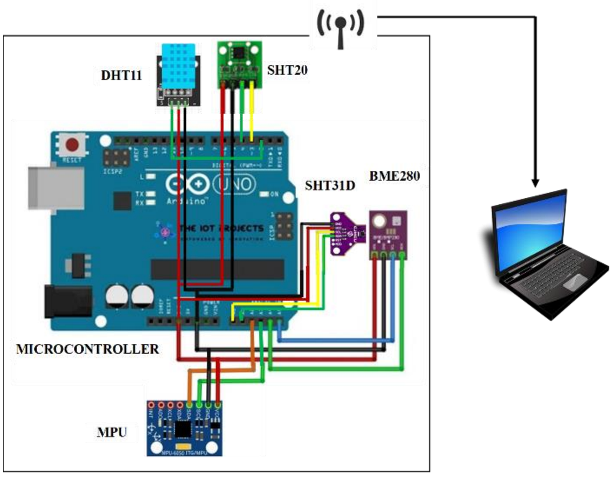

Figure 2. Volcano ambient temperature measurement circuit using IoT device.

The software design is implemented to manage the microcontroller's operation using a fuzzy logic algorithm, as illustrated in the flowchart in Figure 4. The volcano detection system begins with the temperature sensor reading the environmental temperature, the results are then processed by the microcontroller. If the sensor reading shows a temperature within the range of 0–38°C, the temperature data and "Normal" status will be sent to the server, displaying the parameter data and normal status [8]. Moreover, if the sensor reading shows a temperature in the range of 38–40°C, the temperature data and "Caution" status will be sent to the server, displaying the parameter data and alert status [8]. Furthermore, if the sensor reading shows a temperature in the range of 40–42°C, the temperature data and "Siaga" status will be sent to the server, displaying the parameter data and standby status [8]. Addition, if the sensor reading shows a temperature exceeding 42°C, the temperature data and "Awas" status will be sent to the server, displaying the parameter data and warning status. For statuses of "Normal", "Caution", "Warning", and "Evacuate" changes in the volcano's status will occur accordingly. This process is continuous as the system will consistently update, send data to the server, and detect any increases in volcanic activity.

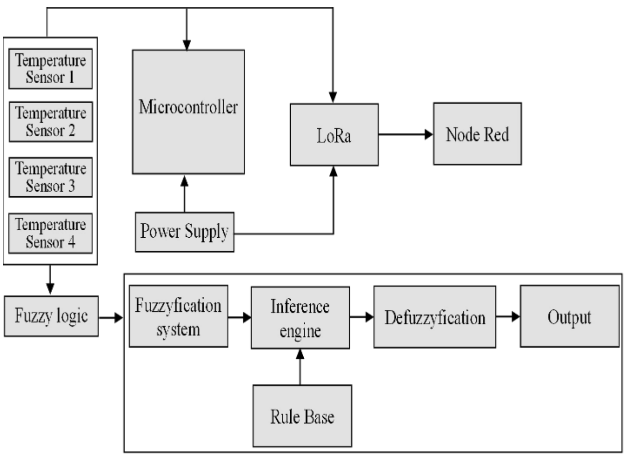

Figure 3. Block diagram of volcano detection system using temperature sensor network.

The fuzzification process involves trapezoidal and triangular membership functions with fuzzy rules. The temperature characteristics are categorized as follows:

Low : $T \leq 38\,^{o}C$
Medium : $38\,^{o}C < T \leq 40\,^{o}C$
High : $40\,^{o}C < T \leq 42\,^{o}C$
Very High : $T > 42\,^{o}C$

The fuzzy rules are expressed in Equation 1. The fuzzy system testing begins with output analysis, where the output design is displayed in the fuzzy system framework. The membership functions for DHT11 sensor, with each membership function defined as Normal1, Caution1, Warning1, and Evacuate1, are assigned to each input variable. The graphical representation of the four memberships is shown in Figure 5.

$$\text{Low: } T\,(^\circ C)\begin{cases} 0 & x < 0 \\ 1 & 0 \le x \le 36 \\ \frac{38-x}{2} & 36 \le x \le 38 \\ 0 & x \ge 38 \end{cases}$$

$$\text{Medium: } T\,(^\circ C)\begin{cases} 0 & x \le 36 \\ 0 \\ 1 & 36 \le x \le 38 \\ \frac{40-x}{2} & 38 \le x \le 40 \\ 0 \\ 0 & x \ge 40 \end{cases} \qquad (1)$$

$$\text{High: } T\,(^\circ C)\begin{cases} 0 & x \le 38 \\ 1 & 38 \le x \le 40 \\ \frac{42-x}{2} & 40 \le x \le 42 \\ 0 & x \ge 42 \end{cases}$$

$$\text{Verry High: } T\,(^\circ C)\begin{cases} 0 \\ 0 & x \le 40 \\ \frac{x-40}{} & 40 \le x \le 42 \\ 1 & x \ge 42 \end{cases}$$

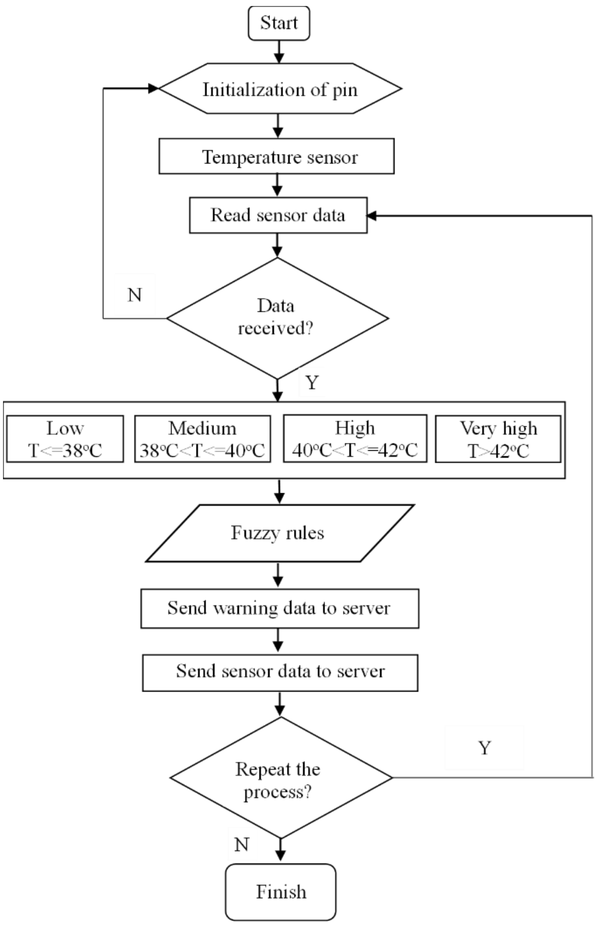

Figure 4. Flowchart of the data processing process on the microcontroller.

In Figure 5, the temperature variable range is defined for each variable, with the range set to [0 45]. The membership functions are as follows:

- **Normal**: Parameters [−16.2 −1.8 36 38] trapezoidal type (trapmf).
- **Caution**: Parameters [36 38 40] triangular type (trimf).
- **Warning**: Parameters [38 40 42] triangular type (trimf).
- **Evacuate**: Parameters [40 42 45 50] trapezoidal type (trapmf).

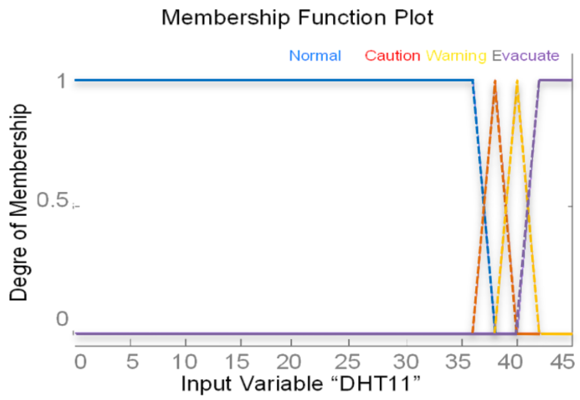

Figure 5. DHT11 Sensor Fuzzy Input

The output membership functions, with each membership function defined as "Normal", "Caution", "Warning", and "Evacuate", are assigned to each output variable. The graphical representation of the four memberships is shown in Figure 6. The warning variable range is defined for each variable, with the range set to [0 45]. The membership functions are as follows:

- **Normal**: Parameters [−16.2 −1.8 36 38] trapezoidal type (trapmf).
- **Caution**: Parameters [36 38 40] triangular type (trimf).
- **Warning**: Parameters [38 40 42] triangular type (trimf).
- **Evacuate**: Parameters [40 42 45 50] trapezoidal type (trapmf).

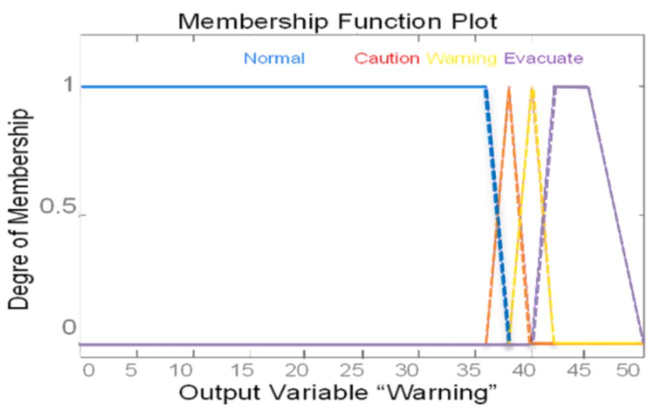

Figure 6. *Output Fuzzy Warning*

Here are the rules for the fuzzy logic used in sensor data management:

a. If the sensor value matches the set point (TS), then the warning is "Normal".
b. If the sensor value differs from the set point by a small negative reasoning value (NK), then the warning is "**Warning**".
c. If the sensor value differs from the set point by a medium negative reasoning value (NS), then the warning is "**Caution**".
d. If the sensor value differs from the set point by a large negative reasoning value (NB), then the warning is "**Evacuate**".

RESULTS AND DISCUSSION

In this study, calibration, laboratory-scale testing, and field testing at an actual volcano were conducted. During the calibration process, the temperature sensor was programmed simply to read and display the temperature in real-time. The sensor was controlled by Arduino, with a 2-wire bidirectional communication path available on Arduino. Data from the DHT11 sensor was observed via the serial monitor on a laptop.

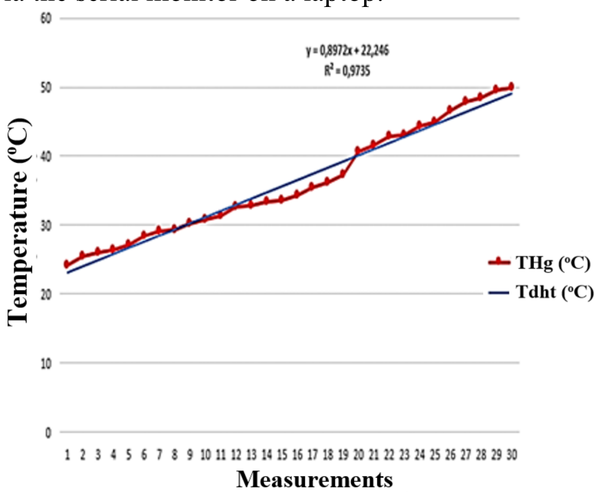

Figure 7. DHT11 temperature sensor calibration

In conducting 30 measurements to calibrate the thermometer and the DHT11 sensor, a difference was observed between the 18-th and 19-th of the measurements. The thermometer recorded temperatures of 30.8°C and 30.2°C, while the DHT11 sensor recorded temperatures of 29.6°C and 29.8°C. This discrepancy is due to the difference in sensitivity between the instruments, as each responds differently to changes in the variable being measured, namely the temperature, between the DHT11 sensor and the thermometer used. Therefore, the 30 mesurements were conducted to demonstrate that the DHT11 sensor functions properly, even though there is a difference in the temperature values obtained by the thermometer.

For the field testing at an actual volcano, the scenario involved testing the system on different volcanoes. This research was conducted on two volcanoes: Mount Guntur (Location 1: PVMBG (Pusat Vulkanologi dan Mitigasi Bencana Geologi/Volcanology and Geological Hazard Mitigation Center) Guntur station; Location 2: Pos Abah; and Location 3: volcanic slope of Figure. 8), and Mount Galunggung (Location 1: PVMBG Galunggung station; Location 2: Tangga Kuning; and Location 3: Atas/summit of Figure. 9). The final step was to compare the temperature DHT 11 sensor test results with the environmental temperature data from each volcano obtained from the PVMBG website.

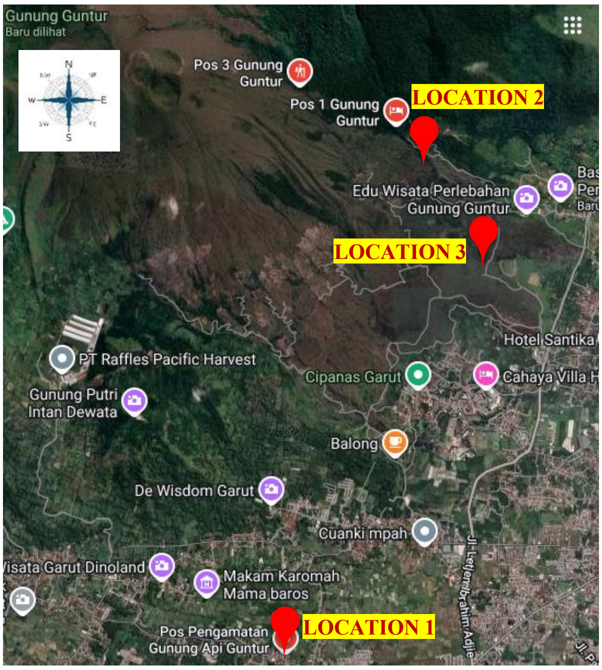

Figure 8. Temperature measurements around Mount Guntur

The data collection for the sensor system testing at Mount Guntur was conducted over three days, from July 26 to July 28, 2024. Figure 10 shows the temperature measurement data collected by the sensors during the afternoon on the first day (July 26, 2024) at location 1 (PVMBG stations). The average temperatures recorded were 35.49°C for the SHT31D sensor, 31.96°C for the SHT2X sensor, 32.20°C for the BME280 sensor, 39.74°C for the DHT11 sensor. The SHT31D sensor has an accuracy of ± 2% humidity and ± 0.3 ° C in temperature, operating temperature range of -40 °C to + 125 °C, response time of 8 seconds. SHT2X sensor has supply voltage range of 2.1V to 3.6V. The BME280 sensor has temperature operation range of -4°C to + 85°C, accuracy tolerance of ±3% relative humidity. These differences in specifications cause the measurement results obtained to differ. Figure 11 presents the temperature measurement data collected by the sensor system during the afternoon in the surroundings of Mount Guntur on the second day (July 27, 2024) at location 2 (Abah Post). The average temperatures recorded were 45.77°C for the SHT31D sensor, 43.61°C for the SHT2x sensor, 41.02°C for the BME280 sensor, and 39.70°C for the DHT11 sensor. Figure 12 displays the temperature measurement data collected by the sensor system during the afternoon in the surroundings of Mount Guntur on the third day (July 28, 2024) at location 3 (Volcanic slope/New Spot). The average temperatures recorded were 44.20°C for the SHT31D sensor, 44.91°C for the SHT2X sensor, 42.74°C for the BME280 sensor, and 40.18°C for the DHT11 sensor. The DHT11 sensor produced a temperature 4.77 °C lower than the average of the other three sensors, exceeding the ±2 °C tolerance, making it unacceptable for precise temperature measurements in environmental monitoring such as volcanic activity. Possible causes of differences include; Low DHT11 resolution (1 °C) so it cannot detect subtle fluctuations. Slow response to rapid temperature changes. Effect of direct solar radiation (if the DHT11 is placed in an open location without protection, the actual temperature may be lower than the ambient air temperature due to radiation). The maximum temperature limit of the DHT11 is 50 °C – when approaching the upper limit, performance and accuracy may deteriorate drastically [19][20].

Data collection for the sensor system testing on Mount Galunggung was conducted over three days, on August 2, 3, and 4, 2024. Figure 13 shows the temperature measurement data from the sensor system during midday in the area around Mount Galunggung on Day 1 (August 2, 2024) at Location 1 (PVMBG Galunggung station). The average temperatures recorded were 28.52 °C for the SHT31D sensor, 28.32 °C for the SHT2x sensor, 28.55 °C for the BME280 sensor, 28.44 °C for the DHT11 sensor.

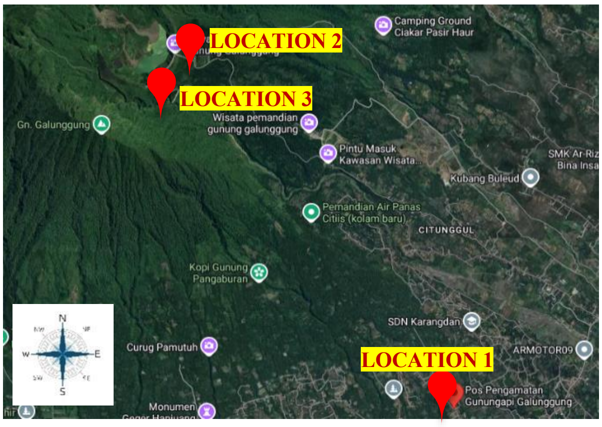

Figure 9. Temperature measurement around Mount Galunggung

Figure 14 shows the temperature measurement data from the sensor system during midday in the area around Mount Galunggung on Day 2 (August 3, 2024) at Location 2 (Tangga Kuning). The average temperatures recorded were 22.55 °C for the SHT31D sensor, 21.96 °C for the SHT2x sensor, 22.20 °C for the BME280 sensor, 23.00 °C for the DHT11 sensor.

Figure 15 shows the temperature measurement data from the sensor system during midday in the area around Mount Galunggung on Day 3 (August 4, 2024) at Location 3 (Atas). The average temperatures recorded were 40.47 °C for the SHT31D sensor, 35.61 °C for the SHT20 sensor, 36.02 °C for the BME280 sensor, and 40.70 °C for the DHT11 sensor. The DHT11 sensor showed a deviation of +3.33 °C from the average reading of the other sensors, exceeding the accuracy limit of ±2 °C. Therefore, the results from the DHT11 cannot be considered accurate in the context of environmental temperature measurements that require high precision, such as for monitoring volcanic activity. Possible causes of differences include Low DHT11 resolution (1 °C) so it cannot detect subtle fluctuations. Slow response to rapid temperature changes. Different sensor location or placement (e.g. direct sunlight) can cause higher readings. Different sensor quality and specifications [19][20].

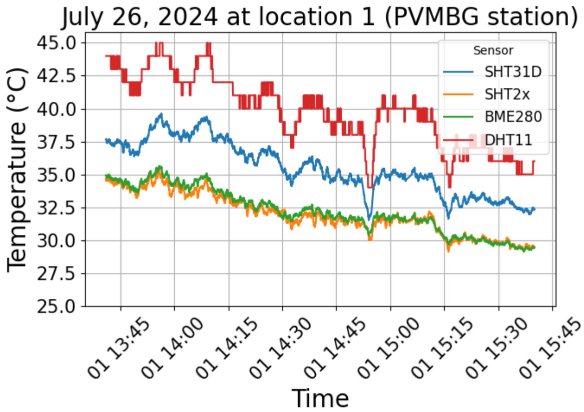

Figure 10. Environmental Temperature Data of Mount Guntur on Day 1 at Location 1

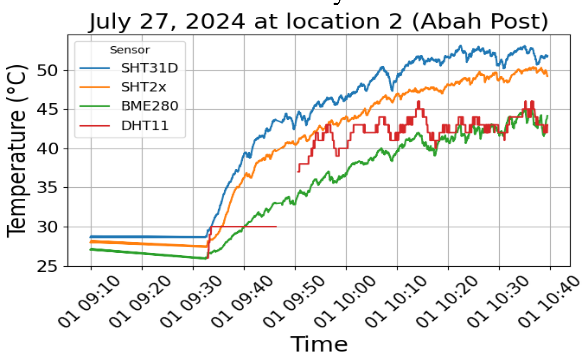

Figure. 11. Environmental Temperature Data of Mount Guntur on Day 2 at Location 2

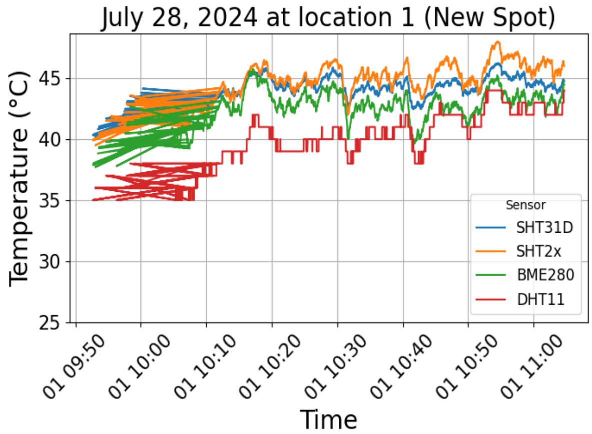

Figure 12. Environmental Temperature Data of Mount Guntur on Day 3 at Location 3

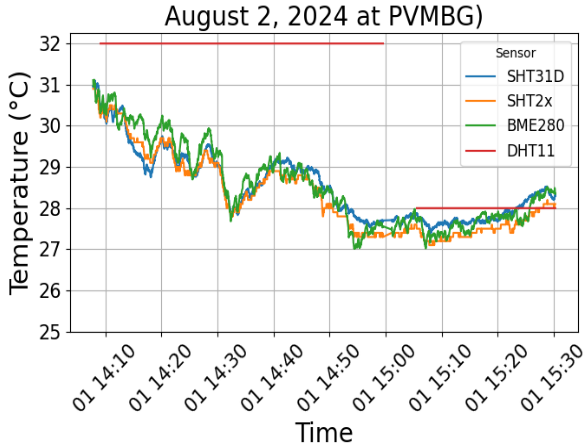

Figure 13. Environmental Temperature Data of Mount Galunggung on Day 1 at Location 1

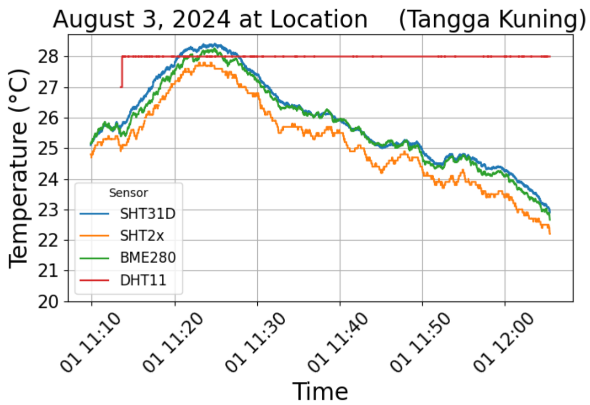

Figure 14. Environmental Temperature Data of Mount Galunggung on Day 2 at Location 2

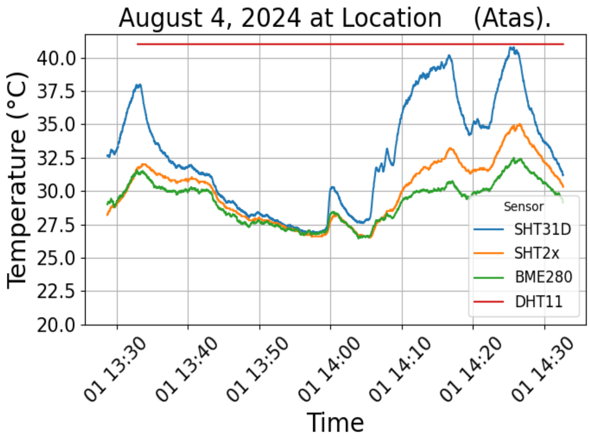

Figure 15. Environmental Temperature Data of Mount Galunggung on Day 3 at Location 3

The results of the detection system test on Mount Guntur on July 26, 2024 obtained input values from the SHT31D sensor = 35.49°C, SHT2X = 31.96°C, BME280 = 32.20°C and DHT11 sensor = 39.74°C. With the fuzzy rule, the membership degree value Z(x) = 1, the alert level is x = 39.74 as shown in Figure 16. So, the alert level is categorized as "Siaga".

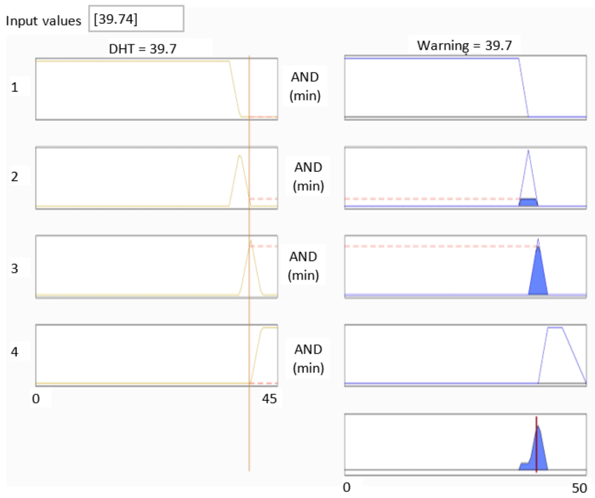

Figure 16. Results of inference of input data from Mount Guntur on July 26, 2024.

The results of the detection system test on Mount Guntur on July 27, 2024 obtained input values from the SHT31D sensor = 45.77°C, SHT2X = 43.61°C BME280 = 41.02°C and DHT11 sensor = 39.70°C. With the fuzzy rule, the membership degree value Z(x) = 1, the alert level is x = 44.6 as shown in Figure 17. Therefore, the alert level is around 44.6% or can be categorized as "Awas".

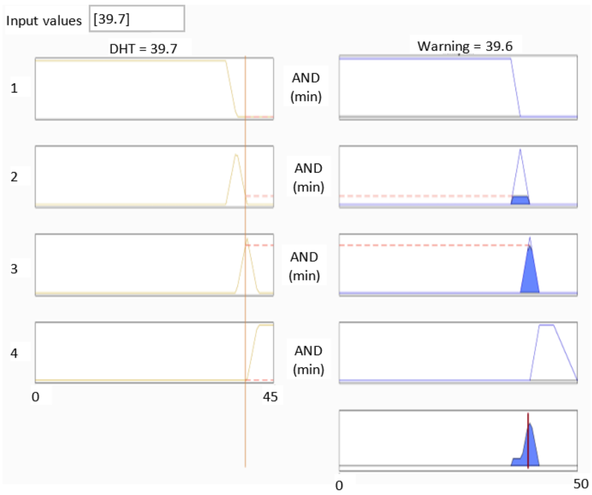

Figure 17. Results of inference of input data from Mount Guntur on July 27, 2024.

The results of the detection system test on Mount Guntur on July 28, 2024 obtained input values from the SHT31D sensor = 44.20°C, SHT2X = 44.91°C BME280 = 42.74°C for the DHT11 = 39.74°C and the DHT11 sensor = 40.18°C. With the fuzzy rule, the membership degree value Z(x) = 1, the alert level is x = 43 as shown in Figure 18. Therefore, the alert level is around 43% or can be categorized as "Awas".

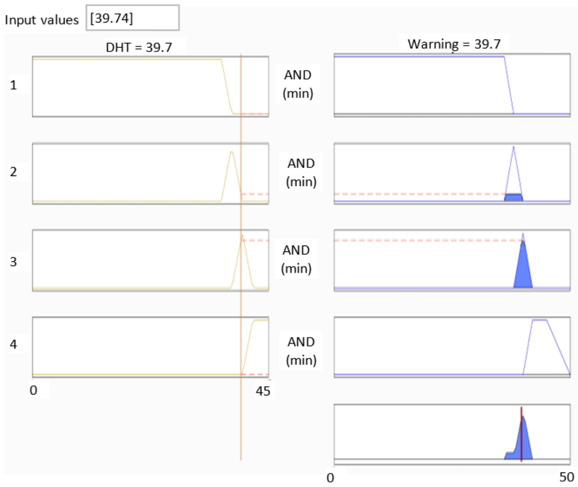

Figure 18. Results of inference of input data from Mount Guntur on July 28, 2024.

The results of the detection system test on Mount Galunggung on August 2, 2024 obtained input values from the SHT31D sensor = 28.52°C, SHT2X = 28.32°C, BME280 = 28.55°C and DHT11 = 28.44°C. With the fuzzy rule, the membership degree value Z (x) = 1, the alert level is x = 18.4 as shown in Figure 19. Therefore, the alert level is around 18.4% or can be categorized as "Waspada".

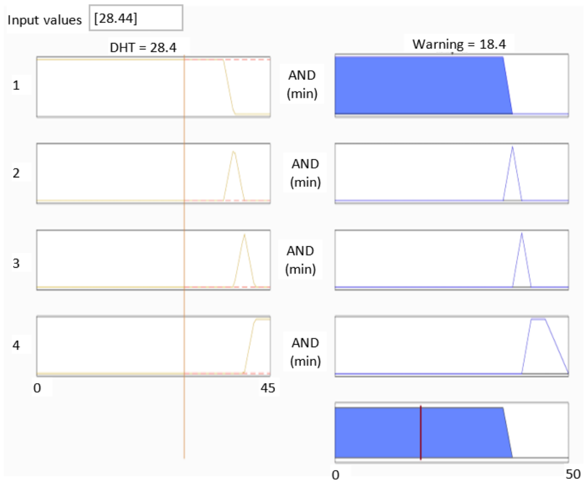

Figure 19. Results of inference of input data from Mount galunggung on August 2, 2024.

The results of the detection system test on Mount Galunggung on August 3, 2024 obtained input values from the SHT31D sensor = 22.55°C, SHT2X = 21.96°C, BME280 = 22.20°C and DHT11 = 23.00°C. With the fuzzy rule, the membership degree value Z (x) = 1, the alert level is x = 18.4 as shown in Figure 20. Therefore, the alert level is around 18.4% or can be categorized as "Waspada".

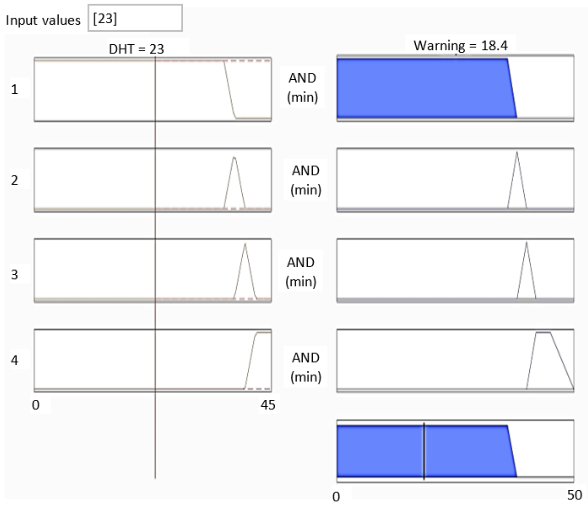

Figure 20. Results of inference of input data from Mount galunggung on August 2, 2024.

The results of the detection system test on Mount Galunggung on August 4, 2024 obtained input values from the SHT31D sensor = 40.47°C, SHT2X = 35.61°C, BME280 = 36.02°C and DHT11 = 40.70°C. With the fuzzy rule, the membership degree value Z (x) = 1, the alert level is x = 43.2 as shown in Figure 21. Therefore, the alert level is around 43.2% or can be categorized as "Awas".

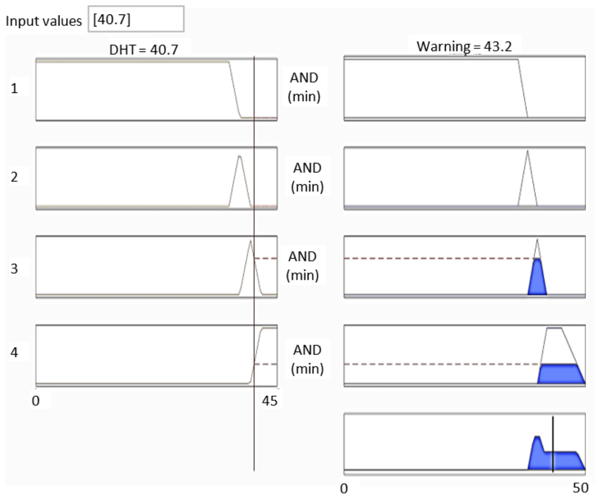

Figure 21. Results of inference of input data from Mount galunggung on August 2, 2024.

Based on the temperature data obtained from the PVMBG website (https://magma.esdm.go.id/), the average temperature around Mount Guntur on 26, 27, and 28 July 2024 was 37.7°C, 35.2°C, and 33.9°C, respectively and volcanic activity at level I (normal). The average temperatures around Mount Galunggung on August 3, 4, and 14, 2024, were 30°C, 33°C, and 26°C, respectively and volcanic activity at level I (normal). These results show that the temperature data is different from the measurement results using the detection system. This may be due to the sensor location that is not exactly the same between this study and PVMBG.

CONCLUSION

This research successfully developed and tested a temperature sensor system for environmental monitoring in volcanic areas. The calibration process shows that the temperature sensor works well, although there is a slight difference in temperature readings compared to a thermometer. Field tests were conducted at two volcanoes (Guntur, and Galunggung) and compared with temperature data from the PVMBG website. The DHT11 sensor produced lower than of the temperature, making it unacceptable for precise temperature measurements in environmental monitoring such as volcanic activity. Possible causes of differences include; low resolution, slow response to rapid temperature changes, effect of direct solar radiation and Different sensor quality and specifications.

The test results show that in general the developed temperature sensor system can measure the ambient temperature with an accuracy close to the temperature data from PVMBG. Fuzzy logic applied to the system is able to classify new temperature sensor data from field measurements. Overall, this temperature sensor system has the potential to be used as a real-time environmental temperature monitoring tool for volcanoes, supporting disaster mitigation and risk management of volcanic activity.

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