Prototyping IoT-Based Safety Telemetry System for Forest Firefighters

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Abstract—Forest fires significantly impact the environment, carbon emissions, and public health. Ensuring the safety of forest firefighters remains a critical challenge, as they operate in high-risk environments with limited communication infrastructure. This study develops an Internet of Things (IoT)-based safety telemetry system utilizing LoRa communication to monitor firefighters' physiological and environmental conditions in real time. The system is built on an ESP32 microcontroller integrated with sensors for body temperature, heart rate, ambient temperature and humidity, CO and CO_2 concentrations, as well as a GPS module for location tracking. Sensor data are transmitted via a LoRa SX1278 module to a Raspberry Pi–based gateway and subsequently forwarded to a cloud server for visualization and monitoring. System performance was evaluated in forested and residential environments over distances of up to 1 km. The results demonstrated an average data transmission success rate of 97% with a latency of 1.47 seconds, indicating reliable LoRa communication in areas with limited cellular network coverage. Furthermore, the sensors achieved measurement errors below 3%, while the system operated continuously for 12.5 hours with a power consumption of only 0.68 W, demonstrating high accuracy, reliability, and energy efficiency. The system also provides an early warning mechanism for hazardous conditions encountered by firefighters. User evaluations revealed an 89% satisfaction rate, particularly regarding the effectiveness of the early warning feature and overall system usability. These findings demonstrate that the proposed LoRa-based IoT telemetry system can effectively enhance firefighter safety through accurate, reliable, and energy-efficient real-time monitoring.

Keywords—Forest Fires; Firefighter Safety; IoT; LoRa; Telemetry

I. Introduction

Forest and land fires are an annual disaster that has serious impacts on the environment, public health, and the safety of firefighters. Global data and figures on forest fires in Indonesia in 2019 show that forest and land fires covered approximately 1.6 million hectares, according to satellite analysis from the Center for International Forestry Research (CIFOR). In many cases, the rugged terrain and extreme weather make extinguishing operations not only difficult but also extremely dangerous for firefighters in the field [1].

In addition to environmental damage and biodiversity loss, forest and land fires also pose a serious threat to the safety of firefighters on the front lines. They work in extreme conditions: high temperatures, exposure to dense smoke, difficult terrain, and the risk of becoming trapped in the flames.

One tragedy that has captured public attention is the death of several firefighters in Kalimantan and Sumatra due to exhaustion, being trapped in the flames, or inhaling thick smoke without adequate protective equipment [2] [3], [4]. To date, the system still relies heavily on manual communication and visual reporting, which is severely limited in terms of speed, accuracy, and reach. Given these conditions, a technological solution is needed that can provide real-time information on the condition of officers and their environment, including body temperature, heart rate, GPS location, air quality, and potential toxic gases.

An Internet of Things (IoT)-based telemetry system is a modern approach with significant potential. IoT enables the integration of sensors and smart devices that can transmit data directly to a command center, enabling a rapid and accurate response to emergencies.

Up to the present, most firefighting operations are still carried out manually and lack support from a technology-based safety monitoring system. The absence of a system capable of detecting and transmitting real-time information regarding officers' conditions (such as location, body temperature, or surrounding air quality) leads to weak safety risk management in the field [5].

IoT is a potential solution to this problem. IoT enables the integration of various sensors, such as GPS, body temperature, heart rate, oxygen, and toxic gases, embedded in wearable devices on officers, which are then sent in real-time to a control center via a wireless network. With this IoT-based telemetry system, field command can directly monitor officers' conditions and provide a rapid response in the event of an emergency.

Several previous studies have discussed the use of IoT for monitoring occupational safety and forest fires. For example, research by Zulkarnain, Dzakwan, and Arrahman WHO developed, a safety monitoring system based on the Internet of Things (IoT), utilizing a LoRa communication network to enhance response to potential accidents [6].

Another study by Zhang et al. showed that sensor-based and IoT monitoring systems are crucial in emergencies because they enable real-time data collection, accelerate detection and response to critical incidents, and improve the efficiency and effectiveness of emergency response management [7].

The IoT offers the opportunity to create automated monitoring systems capable of transmitting health data and personnel location in real-time. However, most IoT systems still rely on GSM/4G networks, which are not always available in forested areas. Therefore, long-range, low-power communication solutions such as LoRa (Long Range) are needed. Demetillo et al. in 2025 developed an IoT-based wearable system capable of monitoring vital signs such as heart rate and body temperature in real time and providing alerts via SMS when abnormal conditions are detected, particularly for worker safety in hazardous mining environments [8]. Similarly, Rafiif et al. in 2025 developed an IoT-based wearable device to monitor heart rate and body temperature in real time, transmit data to the cloud, and display alerts when parameters exceed predetermined thresholds [9].

In addition to workers' monitoring, Raghunatha Rao et al. designed a system to monitor workers' locations in real time using GPS, then sent location information and sensor data via a GSM module (e.g., SMS/GPRS). A similar concept can be applied to monitoring forest patrol officers or workers in the field [10]. This approach is echoed by Rusdi et al. in 2024, who developed an IoT-based worker safety monitoring system that uses sensors and GPS modules to track worker locations and provide real-time alerts via a digital application [11].

Moreover, in 2025, Pourghasem et al. developed a multi-attribute physical layer authentication approach using machine learning and deep learning for spoofing detection in LoRaWAN. Their primary focus was on improving data communication security [12].

However, previous studies of IoT safety systems relying on GSM/4G have not examined LoRa-based telemetry systems that integrate real-time monitoring of officers' physiological and environmental conditions to support forest firefighter safety.the safety of forest firefighters.

Building on these advancements, the current study developed an IoT-based telemetry system with LoRa communication capable of monitoring officers' vital parameters and environmental conditions. The primary focus of this research was to evaluate sensor accuracy, LoRa communication stability up to 1 km, and system power efficiency in a real-world environment.

II. Research Methods

A. Research Stages

The research method used in this study consisted of several stages. The series of stages in the research implementation can be seen in Figure 1, a research flowchart.

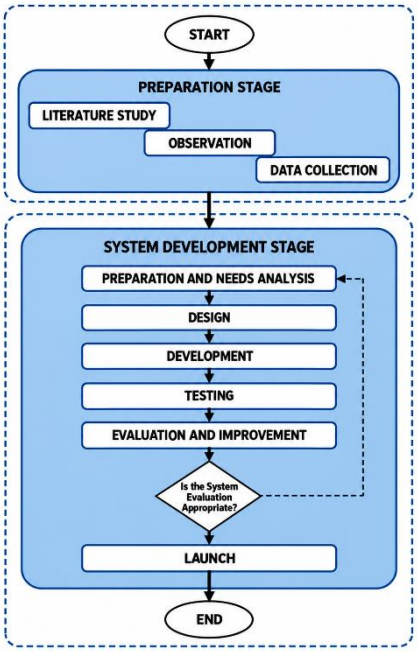


Figure 1. Research Flowchart

Based on the flow diagram, the systematic progression of this study is described as follows:

1. *Preparation Stage*

   The initial stage of the research involved forming a research team and determining a focus area relevant to field needs. Next, a literature review was conducted by searching for scientific articles, books, and strategic issues related to the development of an IoT-based safety telemetry system for monitoring forest firefighters. This literature review played a crucial role in formulating the research problem, objectives, and appropriate research approach [13] [14].

   Furthermore, initial observations were conducted at the research location to identify actual conditions and user needs. Field observation and data collection are crucial stages in applied research to ensure that the developed solutions align with real-world problems [15]. The observations were conducted at the Ketapang Regency Regional Disaster Management Agency office, an agency with direct data and experience related to forest fire management and firefighter safety.

2. *System Development Method*

   System development in this study adopted the Agile Software Development Method using the Scrum model approach [16]. The Agile/Scrum methodology was chosen because it supports iterative system development and is flexible to changing requirements. Through structured sprints, features can be developed and evaluated incrementally, improving system quality, accelerating user feedback, and reducing the risk of development failure. The Scrum model focuses on teams consisting of several members with different roles in

developing the software [17]. The stages carried out in this research are as follows [18]:

a. Backlogs

The backlog development stage involves prioritizing the features to be built into the system. The backlog consists of two parts: the Product Backlog, which contains the entire list of tasks or features to be worked on during system development, and the Sprint Backlog, which contains the list of tasks to be completed within a specific sprint period.

b. Sprints

A sprint is a series of system development activities consisting of several iterations. Each iteration lasts two weeks with a work target specified in the Sprint Backlog.

c. Scrum Meeting

Scrum meetings are held to reflect on the research implementation by discussing the research progress at each iteration.

d. Demos

A demo is conducted at each iteration by simulating the application for user evaluation within a specified timeframe.

Meanwhile, each iteration of development activities consists of a series of analysis and planning, design, development, testing, evaluation, and launch activities, as shown in Figure 2 below [19] [20].

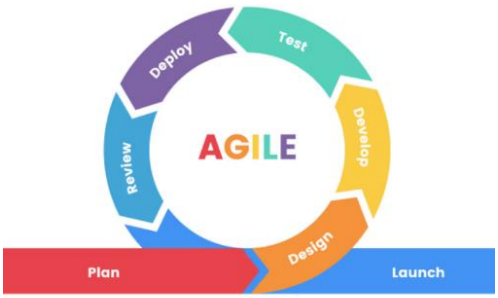


Figure 2. Research Flow using Agile Diagram

This research uses a prototype engineering experimental approach. The system consists of two main components:

1. Sensor Node (End Device): Uses an ESP32 with a LoRa Ra-02 module (433 MHz) as a data transmitter. The sensors used include:
   a. MLX90614 for body temperature,
   b. MAX30102 for heart rate,
   c. MQ-135 for CO and CO_2 gases,
   d. NEO-6M for GPS positioning,
   e. BMP280 for ambient temperature and humidity.
2. Gateway:
   Uses a Raspberry Pi 4 and a LoRa RFM95W module to receive data from the sensor nodes. Data is sent to an MQTT cloud server and visualized through the Grafana dashboard.
3. Test Location and Procedure
   The test was conducted in a forested and residential area around the campus within a radius of 100–1000 meters. Each node transmitted sensor data every 30 seconds. The parameters tested included:
   a. LoRa data transmission success
   b. Signal quality (RSSI, SNR)
   c. Communication latency
   d. Sensor accuracy relative to reference devices
   e. Power consumption and battery life
   f. User response to the system

B. System Design

1. System Architecture Design

The system architecture design shown in the diagram illustrates the workflow and interactions between the components. The following is an explanation of each component and its workflow.

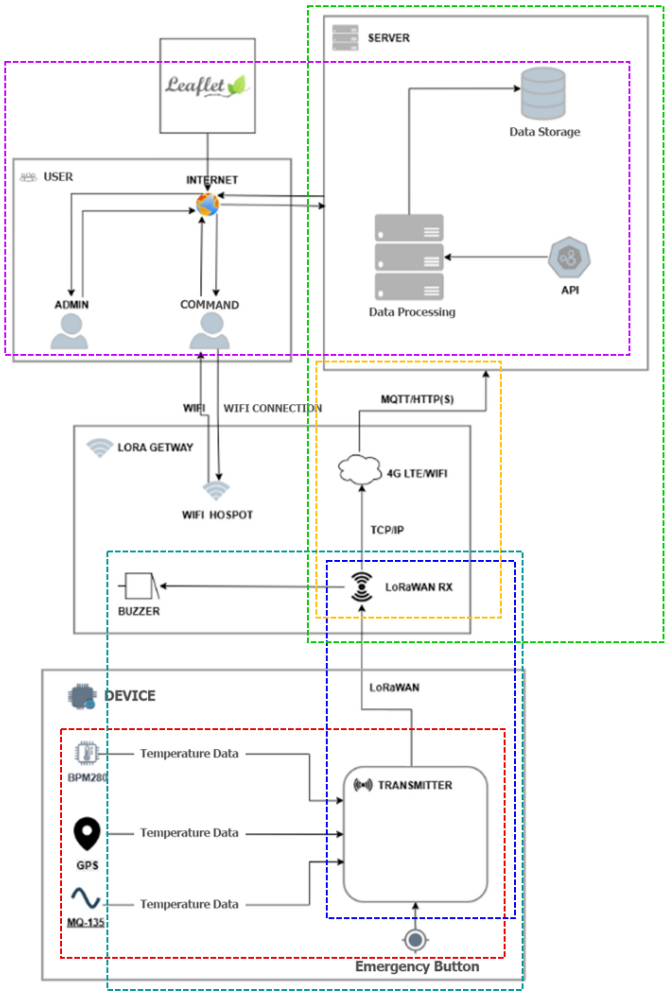


Figure 3. System Architecture

The system architecture design shown in this diagram illustrates the workflow and interactions between the

various key components involved. The following is a detailed explanation of each component and how data and information flow within it.

a. Data Collection in Field Devices (Red Dotted Line)
   1). Sensors such as the BMP280, MQ135, and GPS begin measuring environmental data (pressure, temperature, air quality, and location).
   2). In the event of an emergency, the emergency button can be pressed by the officer.
   3). All this data is collected by the transmitter and transmitted via LoRa communication.

b. Data Transmission from Transmitter to Gateway (Blue Dotted Line)
   1). The transmitter sends data via a LoRaWAN signal.
   2). The LoRa Gateway receives the data via the LoRa RX module.

c. Initial Processing and Internet Connection at the Gateway (Yellow Dotted Line)
   1). The LoRa Gateway has a 4G LTE/WiFi connection and sends data to the server using the TCP/IP communication protocol.
   2). The gateway also provides a WiFi Hotspot, enabling a local connection between the command unit and the buzzer.

d. Local Emergency Notification (Gray Dotted Line)
   If the emergency button is pressed, the signal is forwarded to the buzzer to provide a local audible alert.

e. Data Transmission and Processing on the Server (Green Dotted Line)
   1). Data from the gateway is sent to the central server.
   2). The server processes the data through an internal API, including analysis of temperature, air quality, GPS position, and emergency status.
   3). The results of this processing are stored in a data storage system (database).

f. Data Access by System Users (Purple Dotted Line)
   1). System users (Admin and Command) access data via the internet using a web application.
   2). Data is displayed in real time using an API provided by the server.
   3). The map visualization system uses Leaflet.js to show the geographic location of officers.

g. Management and Decision Making
   1). The admin manages users, devices, and incident reports.
   2). The command monitors field conditions and takes action based on real-time data, either via an internet connection or a direct local connection to the gateway.

2. *Hardware Design*

Hardware design involves two main components: the transmitter and receiver. Both are connected using LoRa wireless communication. The transmitter serves as a data transmitter from the field, while the receiver serves as a notification receiver and displayer at the command center.

a. Transmitter Device

The transmitter is a portable electronic circuit used by field officers to send critical information to the command center. This information includes GPS location, temperature and air pressure, air quality, and emergency signals via a button. Data is sent via 433 MHz LoRa communication, offering a wide range and low power consumption. The entire device runs on a 3.7V Li-ion battery and is equipped with an ON/OFF switch for energy efficiency. The transmitter device is presented in Figure 4.

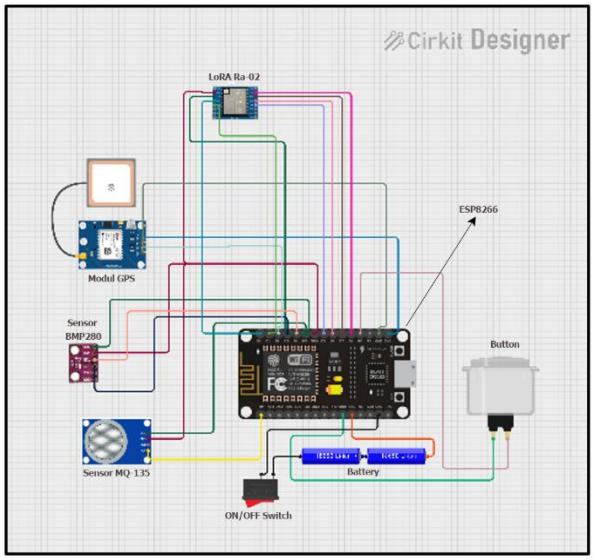


Figure 4. Transmitter Device Design

The components used are as follows:

1). ESP8266 NodeMCU
   Functions as the main microcontroller that reads data from sensors and buttons and then sends it through the LoRa module.
2). LoRa Ra-02 Module
   Used to send data to the receiver using 433 MHz LoRa communication.
3). BMP280 Sensor
   Used to measure the temperature and air pressure in the environment around the officer.
4). MQ-135 Sensor
   An air quality sensor that detects various types of hazardous gases, such as smoke, CO_2, alcohol, and ammonia.

5). GPS Module
Used to capture the officer's location data in real time (latitude and longitude coordinates).

6). Button
When pressed by the officer, it sends an emergency signal to the command center.

7). 3.7V Li-ion Battery
Used as the main power source for the transmitter system so it can be used portably in the field.

8). ON/OFF Switch
A manual switch is used to physically turn the entire system on or off, thus saving energy when not in use.

Table 1. Transmitter Device Serial Pin Connection

No	Components	Module Pins	NodeMCU Pins (ESP8266)
1	LoRa RA-02	VCC	3V3
		GND	GND
		NSS (CS)	D8
		SCK	D5
		MISO	D6
		MOSI	D7
		RST	D0
		DIO0	D1
2	BMP280	VCC	3V3
		GND	GND
		SCL	D4
		SDA	D3
3	GPS Neo-6M	VCC	3V3
		GND	GND
		TX	D2
		RX	(Not Use / NC)
4	MQ-135	VCC	3V3
		GND	GND
		AOUT (Analog Out)	A0
5	Emergency Button	One Leg	RX
		The other leg goes to GND	GND
6	ON/OFF Switch	Between the battery and VIN	- (power line)

b. Receiver Device
The receiver device is designed to receive data from the transmitter sent over the LoRa network. When data is received, this device can provide an alert via a buzzer and can be developed to be forwarded to a monitoring dashboard via a WiFi connection. The receiver device is presented in Figure 5.

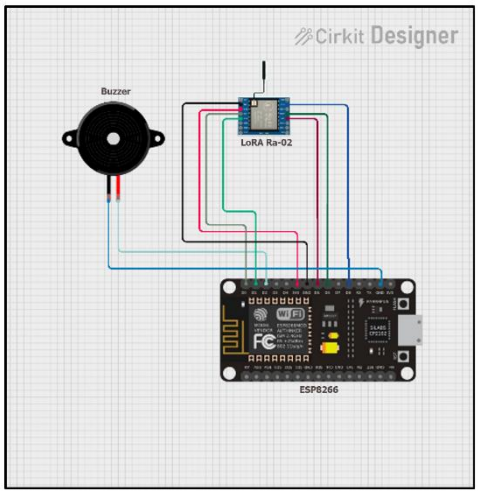


Figure 5. Receiver Device Design

The components used are as follows:

1). ESP8266 NodeMCU
Acts as the main controller, handling the LoRa communication process and buzzer activation.

2). LoRa Ra-02 Module
Receives data from the transmitter. This module uses the SPI protocol to communicate with the ESP8266.

3). Buzzer
Used to provide audible notifications when an emergency message is received or a signal is received.

Table 2. Serial Pin Connection of the Receiver Device

No	Components	Module Pins	NodeMCU Pins (ESP8266)
1	LoRa RA-02	VCC	3V3
		GND	GND
		NSS	8
		SCK	5
		MISO	D6
		MOSI	D7
		RST	D0
		DIO0	D1
2	Buzzer	VCC	D2
		GND	GND

3. Data Flow Design

A use case diagram is part of system modeling that illustrates the interactions between users (actors) and the system based on available functionality. This diagram helps understand system requirements from the user's perspective, as well as the limitations of the system being built.

a. Use Case Diagram for Web Operator and Command
The use case diagram designed for this system has two main actors: the Web Operator and the Command. This use case diagram illustrates the interaction flow between the monitoring system and

the two main actors: the Web Operator and the Command. Its main purpose is to monitor field officers and manage incidents and connected devices within the system.

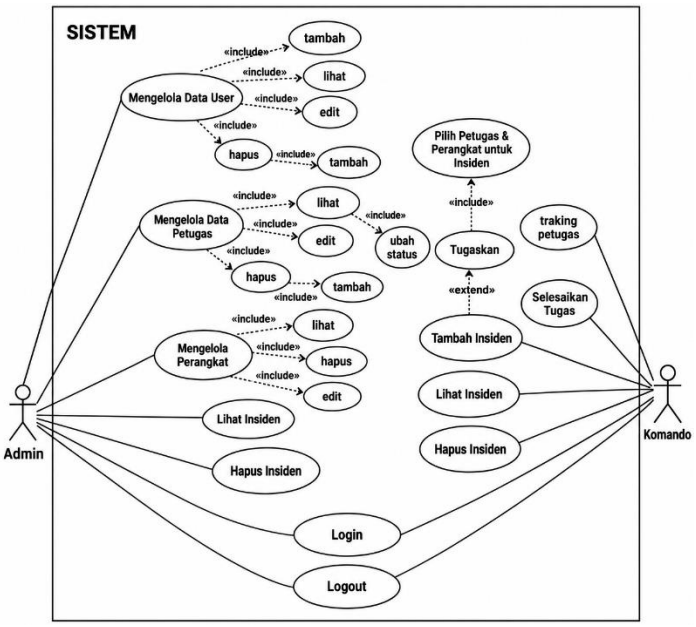


Figure 6. Use Case Diagram of Web Operator and Command

b. Device Use Case Diagram

This use case diagram illustrates the interaction between the officer, transmitter, and receiver in an IoT-based safety monitoring system. The officer can send an emergency signal, which is relayed as an emergency status to the system and triggers a buzzer on the receiver device.

Meanwhile, the transmitter device automatically sends data on the officer's temperature, air quality, and location. The receiver receives this data and forwards it to the server for display on the monitoring system.

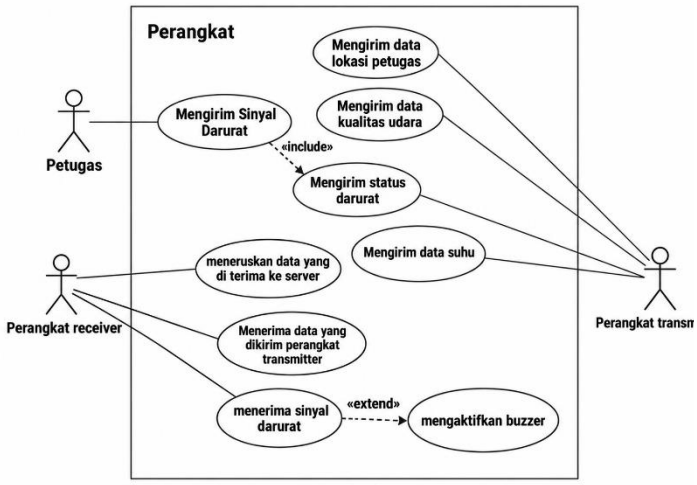


Figure 7. Software Use Case Diagram

4. Database Design

Database design is the process of designing an efficient and organized data storage structure to ensure ease of data management, searching, and retrieval. This stage includes creating a data model that describes the relationships between entities and determining how data will be organized and accessed within the database system to optimally support application requirements.

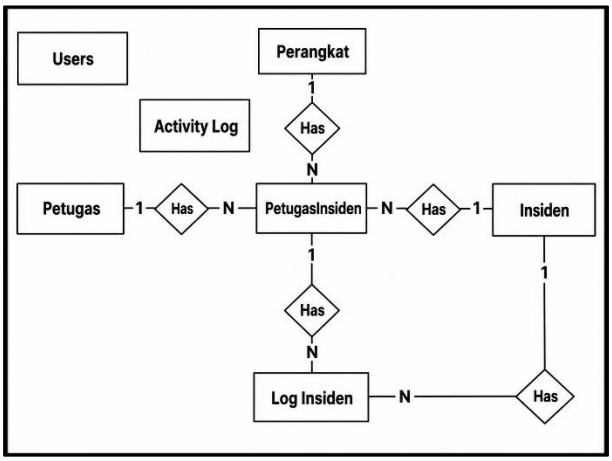


Figure 8. ERD

Figure 8 shows the relationship design between entities in the system, including Users, Officers, Devices, Incidents, Incident Logs, Incident Officers, and Activity Logs. Each entity is connected by relationships that describe how the data relates to each other, such as the relationship between Officers and Incident Officers, which has a cardinality of 1 to N, and the relationships between Incident Officers and Incidents, Devices, and Incident Logs, which show the interconnectedness of data in the incidents handled. This ERD helps to understand the database structure and the flow of information between entities in the system as a whole.

5. Interface Design

The interface design created in this study is designed to support real-time, informative, and easy-to-use monitoring of forest firefighter safety. The interface is structured as a web-based dashboard that displays key data such as body temperature, heart rate, ambient temperature and humidity, CO and CO_2 levels, and the officer's position based on GPS coordinates. The interface designs that have been created in this research are the Login page design, Admin Home Page, Command Home Page, Data Menu Page, Add Data Page, Change Data Page, Delete Data Page, Assignment Page, Officer Detail Page, and Incident Detail Page, which are presented as follows.



Figure 9. Interface Design

III. Result and Discussion

A. System Test Results and Hardware Module Analysis

This research successfully developed an Internet of Things (IoT)-based safety telemetry system that monitors the physiological and environmental conditions of forest firefighters in real time. The system was designed using the LoRa SX1278 communication module as the primary data transmission medium due to its ability to cover a wide area with low power consumption. The sensor node device was equipped with several primary sensors: MLX90614 (body temperature meter), MAX30102 (heart rate), MQ-135 (CO and CO_2 gas levels), BMP280 (environmental temperature and humidity), and a NEO-6M GPS module for position tracking. All sensors were connected to an ESP32 microcontroller, and data was sent periodically every 30 seconds to a Raspberry Pi 4-based LoRa Gateway, which forwarded the data to a cloud MQTT server for visualization via a Grafana dashboard. Testing was conducted within a maximum radius of 1 kilometer in forested areas and surrounding residential areas, involving 10 simulated firefighters. The testing focused on LoRa communication performance, sensor accuracy, transmission latency, system durability, and user response to the system's usability and reliability. From the sensor side, measurement results showed a low error rate—under 3% for body temperature, heart rate, CO gas, and CO_2. This indicates the system's high-precision monitoring capability. The system also automatically provides an early warning when an officer's body temperature exceeds the threshold (38°C) or CO gas levels exceed 25 ppm. Furthermore, the system exhibits good power efficiency, capable of operating for 12.5 hours non-stop with a power consumption of only 0.68 W. A user survey showed an 89% satisfaction rate, particularly with the speed of notifications and the user-friendliness of the interface. After the system development process was completed, the next stage was software testing to ensure that all designed functions function properly and meet user needs. The testing method used in this stage is Black-Box Testing to detect any errors. This testing is conducted by providing input to the system and observing the resulting output using test variables to ensure that each feature and device component responds correctly as expected. In addition, User Acceptance Testing (UAT) is conducted to ensure that the system truly meets the needs and expectations of end users. This UAT testing involves partners. Meanwhile, to ensure that the Firefighter Safety Telemetry and Monitoring System functions as designed, system testing is conducted, the results of which are presented in Table 3 below.

Table 3. Device Test Results

No	Features	Test Variables	Expected Results	Results
1	LoRa Sensor Module	The transmitter sends data and the receiver receives it	The data sent by the transmitter is received correctly by the receiver	Succeed
		The receiver is placed inside the building on the 3rd floor	Data remains receivable within a specified range	Succeed
		The receiver is	Data remains	Succeed

No	Features	Test Variables	Expected Results	Results
		in an open area with an antenna approximately 200 cm high	receivable within a specified range	
		The receiver is in an open area with an antenna below 200 cm (approximately 150 cm)	Data remains receivable within a specified range	Succeed
2	BMP280 Sensor	The temperature and pressure values are read	Temperature and pressure values appear on the serial monitor	Succeed
3	MQ-135 Module	The sensor detects gas	ADC values appear on the serial monitor	Succeed
4	GPS	The latitude and longitude values are read	Coordinates appear	Succeed
5	Button	Pressing the button	The emergency status changes and the buzzer sounds	Succeed

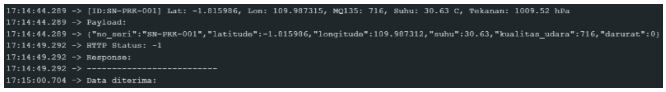


Figure 10. Device Test Results



Figure 11. Button Device Test Results

Based on the test results in Figures 10 and 11, all system components functioned as expected. Testing was conducted on several key features: data transmission via LoRa, temperature and pressure readings from the BMP280 sensor, air quality detection by the MQ-135 sensor, location readings from the GPS module, and emergency status dispatch via the button.

Each feature demonstrated satisfactory results, including successful data transmission and reception, correct sensor readings, and system response to the emergency button.

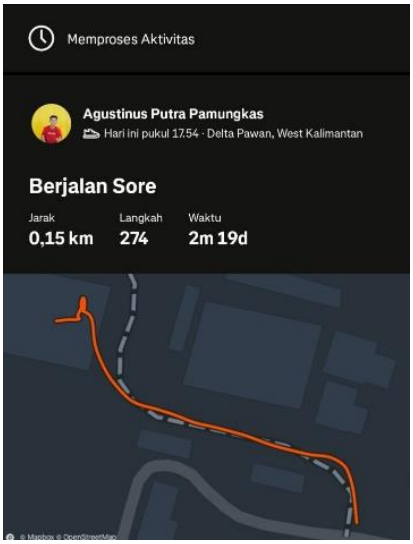


Figure 12. LoRa Distance Test Results

B. LoRa Communication Test Results

LoRa communication testing was conducted to determine the system's ability to transmit sensor data from the node to the gateway stably and efficiently under various terrain conditions. Performance testing was conducted at four locations with varying distances: 100 meters, 300 meters, 600 meters, and 1,000 meters from the gateway. Each sensor node transmitted data every 30 seconds during a one-hour test period at each location.

Observed parameters included the data transmission success rate (% success rate), signal quality (RSSI and SNR), and transmission delay (latency). Testing was conducted in a real-world environment reflecting tropical forest conditions with varying vegetation, ranging from open areas to densely wooded areas. The test results are shown in the following table:

Table 4. LoRa Communication Test Results with a Maximum Distance of 1 KM

No	Distance (m)	Terrain Conditions	Transmission Success Rate (%)	RSSI (dBm)	SNR (dB)	Latency (s)
1	100	Open	100,0	-65	9,8	1,1
2	300	Sparse trees	98,9	-78	8,2	1,3
3	600	Medium trees	96,7	-87	6,4	1,6
4	1000	Dense trees	92,5	-98	4,9	1,9
Average			**97,0**	—	—	**1,47**

Average transmission success rate: 97.0% Average latency: 1.47 seconds. These results demonstrate stable LoRa communication up to 1 km, even in densely vegetated areas. Signal degradation is within tolerance limits, with a minimum RSSI of -98 dBm.

C. Telemetry Sensor Accuracy

Sensor accuracy testing was conducted to ensure that each sensor component in the telemetry system delivers measurement results consistent with actual field conditions. This is crucial because reading errors in physiological and environmental data can lead to erroneous conclusions in monitoring officer safety.

In this study, several types of sensors were used: the MLX90614 for body temperature, the MAX30102 for heart rate, the BMP280 for temperature and humidity, the MQ-135 for carbon monoxide (CO) and carbon dioxide (CO_2) detection, and the NEO-6M GPS for positioning. Each sensor was compared with laboratory-calibrated reference measuring instruments, such as a digital medical thermometer, a heart rate monitor, a portable multi-sensor gas meter, and a standard GPS navigation device.

The testing process involved simultaneously measuring parameters between the sensor and the reference device under the same environmental conditions. Each measurement was taken 10 times, and the average value and error percentage were calculated using the following formula:

$$\text{Error } (\%) = \frac{x\ sensor - x\ refrensi}{x\ referensi} x100\% \quad (1)$$

Table 5. Telemetry Sensor Accuracy Calculation Results

Parameter	Sensor Value	Reference Value	Error (%)	Description
Body temperature (°C)	36,8	37,0	0,5	Accurate
Heart rate (BPM)	79,2	80,0	1,0	Accurate
CO (ppm)	26,0	25,0	4,0	Acceptable
CO_2 (ppm)	392	400	2,0	Stable
GPS (m)	±3,5	—	—	Accurate

Test results showed that all sensors performed with a fairly high level of accuracy. The MLX90614 body temperature sensor produced an average reading of 36.8°C compared to a reference of 37.0°C, with an error of 0.5%. The MAX30102 heart rate sensor produced a reading of 79.2 beats per minute (bpm), compared to a reference of 80 beats per minute (bpm), with an error of 1.0%. This error is within the medical tolerances for field monitoring.

For environmental sensors, the BMP280 had an average deviation of 1.7% for air temperature and 2.3% for humidity. The MQ-135 gas sensor for CO has an average error of 4.0%, while for CO_2 it has an error of 2.0%. All of these error values were below the 5% threshold, which is generally considered acceptable for non-laboratory monitoring systems.

The NEO-6M GPS position sensor demonstrated a horizontal accuracy of ±3.5 meters, which is sufficient for tracking officer locations in open and wooded areas. This location data is then used to display officer movements on a digital map-based dashboard (map overlay).

D. Energy Resilience Testing and User Evaluation

Energy sustainability is a crucial factor in the development of IoT-based telemetry systems, particularly for field applications such as monitoring forest firefighters working long hours and in locations with limited electrical infrastructure. Therefore, this study also evaluated battery life, device power consumption, system efficiency, and user feedback on overall system performance.

Energy sustainability testing was conducted using a 3.7V 10,000mAh Li-ion battery as the power source, which powered a single sensor node consisting of an ESP32, a LoRa SX1278 module, and key sensors (MLX90614, MAX30102, BMP280, and MQ-135). The node was configured to transmit data every 30 seconds during continuous operation. Testing was conducted under representative field conditions with normal transmission and standby cycles.

Table 6. User Power and Response Evaluation

No	Test Aspect	Result	Description
1	Battery life	12,5 jam	Efisien
2	Average power consumption	0,68 W	Rendah
3	Notification effectiveness	91%	Real time
4	User satisfaction	89%	Baik
5	Gateway stability	95%	Andal

Measurement results showed that the system could operate continuously for 12.5 hours before the battery capacity decreased to a safe limit (3.3 V). Average power consumption was recorded at 0.68 watts, demonstrating high energy efficiency for a multi-sensor system. The use of deep sleep mode on the ESP32 and the efficiency of low-power LoRa communication significantly contributed to the increased battery life.

In addition to technical testing, a user evaluation was conducted involving 10 simulation officers as respondents. Each respondent used the telemetry device during simulated monitoring activities in open and forested areas and then provided feedback via a Likert-based questionnaire (1–5). Aspects assessed included ease of use, system reliability, clarity of data display, accuracy of notifications, and overall satisfaction with the system.

E. Discussion

The evaluation results indicate that the developed safety telemetry system meets key implementation requirements, namely long-distance transmission capability, sensor

accuracy, energy efficiency, and user acceptance. The system's ability to monitor officers' physiological and environmental conditions in real time is a key advantage, especially in areas with limited conventional communication networks. This demonstrates the relevance of an IoT-based approach with LoRa communication in monitoring scenarios in forest fire areas.

Communication stability, reaching a distance of 1 km with a 97% transmission success rate and a latency of 1.47 seconds, demonstrates good network performance for field monitoring needs. These values indicate the system's ability to transmit data consistently and responsively. Furthermore, a sensor error rate of less than 5% demonstrates that the resulting data is sufficiently accurate and can be used as a basis for decision-making regarding officer safety.

In terms of energy efficiency, the system's ability to operate for 12.5 hours with an average power consumption of 0.68 watts demonstrates the design's suitability for use in operational areas with limited power sources. Meanwhile, a user satisfaction rating of 89% indicates that the system is easy to use, informative, and capable of providing timely notifications. Overall, the discussion results confirm that IoT and LoRa-based telemetry systems are effective in improving the safety and efficiency of forest firefighters. Future developments through the implementation of multi-gateway LoRaWAN and machine learning integration have the potential to increase monitoring coverage and predictive analysis capabilities for risks in the field.

IV. Conclusion

Based on the results of system testing and hardware module analysis.

1. This research successfully developed an Internet of Things (IoT)-based safety telemetry system capable of monitoring the physiological and environmental conditions of forest firefighters in real time.
2. All hardware components, including sensors, an ESP32 microcontroller, an SX1278 LoRa communication module, and a Raspberry Pi-based gateway, functioned as designed and were stably integrated.
3. The LoRa communication system is capable of transmitting data reliably up to 1 km with an average success rate of 97% and a latency of 1.47 seconds. This performance is supported by the use of Chirp Spread Spectrum (CSS) modulation, which has high reception sensitivity and resistance to interference. Compared to GSM/4G, LoRa offers lower power consumption, lower operational costs, and is independent of cellular operator infrastructure, making it more suitable for telemetry systems in remote areas such as forest fire areas.
4. The sensor accuracy rate showed an error rate below 5%, ensuring reliable data to support safety monitoring in the field.
5. The system was capable of providing automatic early warnings when safety parameters exceeded specified thresholds.
6. In terms of energy efficiency, the device can operate continuously for 12.5 hours with an average power consumption of 0.68 watts, thus supporting use in locations with limited power sources.
7. User evaluation results showed a satisfaction rate of 89%, particularly in aspects of system reliability, notification accuracy, and ease of use of the monitoring dashboard.
8. Early warning systems improve officer safety by detecting hazardous conditions in real-time, allowing for quicker mitigation and reduced accident risk.
9. Overall, the system has met functional, technical, and user requirements and has the potential to be implemented on a real-scale operation with further developments such as multi-gateway networks and predictive analytics integration to increase system coverage and intelligence.

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