

INTELLIGENT WEARABLE TECHNOLOGY FOR HAJJ: AI-POWERED SMART BRACELET FOR REAL-TIME PILGRIM MANAGEMENT

Rosalina¹, Hasanul Fahmi^{2*}, Noor Lees Binti Ismail³, Danny Ngo Lung Yao⁴

Informatics Study Program, President University, Bekasi, Indonesia¹

Faculty of Artificial Intelligence & Frontier Technologies, UNITAR International University, Malaysia²

School of Information Technology, UNITAR International University, Malaysia^{3,4}

rosalina@president.ac.id¹, fahmi.zuhri@unitar.my², lees@unitar.my³, danny.ngo@unitar.my⁴

Received: 09 October 2025, Revised: 20 March 2026, Accepted: 04 April 2026

*Corresponding Author

ABSTRACT

The Hajj pilgrimage gathers millions of people each year, creating a dynamic environment that demands efficient health monitoring, safety management, and real-time coordination. This paper presents an AI-powered smart bracelet designed to enhance pilgrim management through the integration of Internet of Things (IoT) technology, fuzzy logic intelligence, and cloud computing. The wearable continuously collects physiological and environmental data—such as temperature, heart rate, humidity, and location—and processes them through a hybrid edge–cloud framework to ensure low latency and scalability. Artificial intelligence algorithms analyze sensor data to detect anomalies and issue early alerts during health or safety incidents. Experimental evaluation under simulated Hajj conditions achieved an average classification accuracy of 94.8%, data transmission latency below 3.5 seconds, and battery endurance of up to 20 hours. These results confirm the system’s reliability, energy efficiency, and suitability for large-scale real-time monitoring. The proposed framework contributes to safer and smarter Hajj operations by improving early risk detection, communication efficiency, and emergency response coordination.

Keywords: *Internet of Things (IoT), Artificial Intelligence (AI), Smart Wearable Device, Real-Time Monitoring, Pilgrim Management, Crowd Management*

1. Introduction

The integration of the Internet of Things (IoT) with wearable technologies has brought major progress in real-time health monitoring, crowd analysis, and safety management. In modern smart environments, where data is continuously collected and analyzed through intelligent systems, wearable devices play a crucial role in detecting health anomalies and managing large gatherings effectively (Zovko et al., 2023). IoT-based wearables also improve interoperability, scalability, and energy efficiency, allowing seamless data communication across diverse networks and devices (Subhan et al., 2023). By connecting physical objects, sensors, and digital systems through the internet, IoT enables the real-time collection, sharing, and analysis of information (Ullah et al., 2024). These capabilities have transformed many fields, including healthcare, transportation, and public safety, where data-driven insights enhance operational efficiency and overall human well-being (Westergren et al., 2024). However, applying IoT systems to large-scale events involving thousands of participants—such as religious pilgrimages, festivals, or mass public gatherings—introduces significant challenges. Maintaining stable connectivity, processing large volumes of heterogeneous data, and ensuring timely responses during emergencies are critical concerns that demand more adaptive and intelligent frameworks (Alafif et al., 2025).

Indonesia sends one of the largest groups of pilgrims to the Hajj each year, with hundreds of thousands of participants departing from various provinces across the country (Khodijah Siti, 2023). The process involves multiple stages — from registration, health checks, and flight coordination to on-site mobility in Makkah, Mina, and Arafah. Managing such a massive and dispersed group requires precise coordination between government agencies, health teams, and field officers. Each pilgrim’s journey is unique and dynamic, often affected by environmental factors, fatigue, or unexpected incidents during rituals. Health monitoring, location tracking, and emergency response have therefore become major concerns for Indonesian Hajj organizers. Pilgrims frequently experience challenges such as dehydration, heat exhaustion, or getting

separated from their groups in extremely crowded areas (Alshamrani et al., 2025), (Quaium et al., 2023), (Wesam Alkassas et al., 2021). Officers must be able to identify, locate, and assist those in need quickly — yet the current systems rely heavily on manual reporting, verbal communication, or limited mobile applications. This manual process can cause delays in relaying information and makes it difficult to coordinate across multiple teams in real time. As a result, valuable minutes may be lost during emergencies, affecting both the safety and comfort of the pilgrims.

To help solve these problems, this study proposes an AI-powered smart bracelet designed specifically for Indonesian pilgrims. The device combines IoT sensors to monitor health and movement, supported by a hybrid edge–cloud system that processes data efficiently and sends alerts in real time. Artificial intelligence is used to detect unusual patterns—such as signs of fatigue, heat stress, or unusual movement—and notify the monitoring center instantly. The system also uses an optimized communication protocol to ensure stable data transmission while conserving energy, which is essential for wearable devices used over several days. Through this research, we aim to develop a smart wearable system that can make Hajj management more efficient and responsive. The project contributes to Indonesia’s efforts to integrate technology into the Hajj administration process, helping ensure that pilgrims are safer, easier to monitor, and better supported throughout their journey.

2. Literature Review

The rapid advancement of the Internet of Things (IoT) and Artificial Intelligence (AI) has opened new possibilities for real-time monitoring, crowd management, and health tracking. These technologies have become particularly relevant in large-scale events such as the Hajj pilgrimage, where millions of people gather in confined spaces. Through continuous data collection from sensors and wearable devices, IoT systems enable better understanding of human activity, environmental conditions, and crowd dynamics, which are essential for ensuring safety and efficiency. (Al-Shaery et al., 2022) developed an AI-supported wearable system for real-time pilgrim management, showing how physiological sensors and mobile communication can improve emergency response and situational awareness. Similarly, (Shambour & Gutub, 2021) examined the progress of IoT applications in Hajj and Umrah, emphasizing their role in enhancing transportation, health services, and overall pilgrim experience.

IoT-based crowd analysis has been an active research area in recent years. (Al-Nabhan et al., 2021) proposed an intelligent IoT framework that analyzes crowd movement and density using live sensor data, helping authorities make timely decisions during high-risk situations. (Singh et al., 2020) also provided a broad review of existing crowd monitoring technologies and identified the need for adaptive systems capable of analyzing large, fast-changing data streams in real time. Smart wearables, which combine sensing, communication, and data processing capabilities, have seen rapid growth as part of IoT ecosystems. (Niknejad et al., 2020) reviewed recent developments in wearable devices and highlighted persistent challenges such as interoperability and energy efficiency. (Shajari et al., 2023) and (Huang et al., 2023) later expanded on this by discussing AI-enabled wearable sensors for health monitoring, showing how machine learning and sensor fusion can detect early signs of illness or fatigue with higher accuracy. Research has increasingly focused on using technology to manage crowds and improve safety. (Jabbari, 2023) explored the use of artificial intelligence and machine learning to track and analyze pilgrim movements, helping prevent overcrowding and lost-person incidents. (Khan & Shambour, 2018), (Esam Ali Khan & Mohd Khaled Shambour, 2023) worked on optimizing transport and logistics for pilgrims, proposing algorithms to improve scheduling and minimize waiting times. (Wiangwiset et al., 2023) demonstrated the use of smart city infrastructure—such as public Wi-Fi—for real-time crowd monitoring, which could be adapted for managing large religious gatherings.

Other studies have concentrated on analyzing crowd behavior and ensuring safety during mass events. (Bendali-Braham et al., 2021) reviewed the use of machine learning for crowd pattern recognition, while (Al-Shaery et al., 2020) designed an IoT-based system for detecting and managing crowd density in real time. Both studies emphasized that effective monitoring

requires reliable sensors, intelligent data analysis, and stable communication networks. Wearable IoT systems have also been applied successfully in other domains. (Chen et al., 2023) conducted a review of wearable devices in the construction industry, concluding that they help prevent workplace accidents through continuous safety tracking. (Anglano et al., 2024) introduced the HealthTracker System, which connects a multi-sensor wearable device to a cloud-based platform, allowing real-time health updates and alerts for medical professionals. These studies underline the growing importance of cloud-IoT integration for timely data visualization and decision-making.

While existing work has shown strong progress in IoT-driven monitoring and wearable technology, several gaps remain. Many systems still face challenges related to data accuracy, interoperability, and network reliability, especially in crowded or high-temperature environments such as the Hajj. Moreover, few studies have explored how fuzzy logic can be embedded in wearable IoT frameworks to manage uncertain sensor data while maintaining fast response times and low power consumption. Building on this foundation, the present study proposes an AI-powered smart bracelet that integrates IoT sensors, fuzzy logic, and cloud-based monitoring. The system is designed to support real-time risk detection and efficient data communication, offering a practical, scalable solution for improving health and safety management among Hajj pilgrims.

3. Research Methods

This research introduces an AI-based Smart Bracelet Framework that integrates wearable sensing technology with an IoT environment to monitor and manage Indonesian Hajj pilgrims in real time. The proposed approach was designed to collect, process, and interpret health and location data continuously, enabling faster decision-making and early risk detection. The methodology consists of several main stages: data acquisition, data formatting and modelling, semantic enrichment, AI-driven risk analysis, and system evaluation. The overall structure of the system is shown in Fig 1.

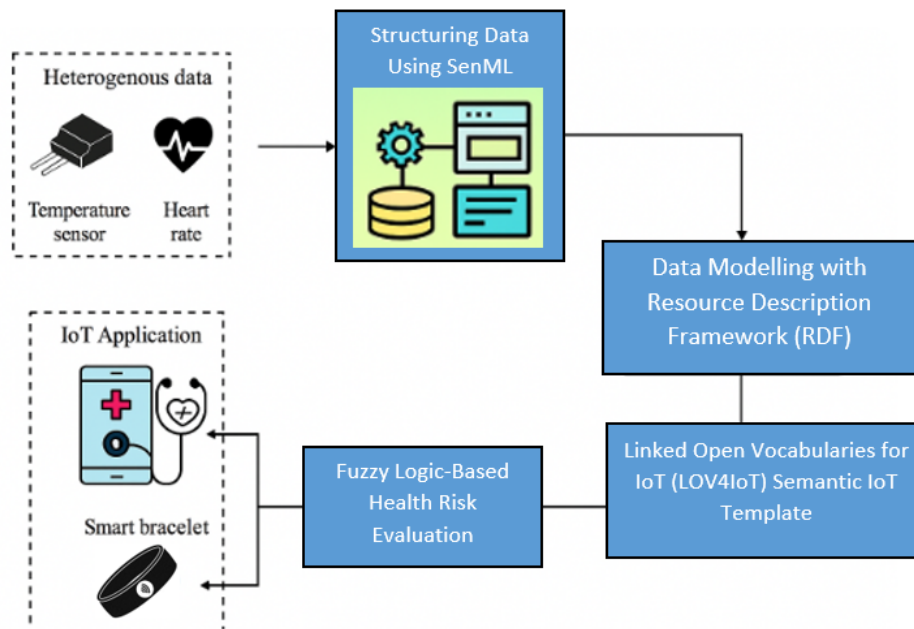


Fig. 1. System Architecture of the AI-Powered Smart Bracelet for Real-Time Pilgrim Management

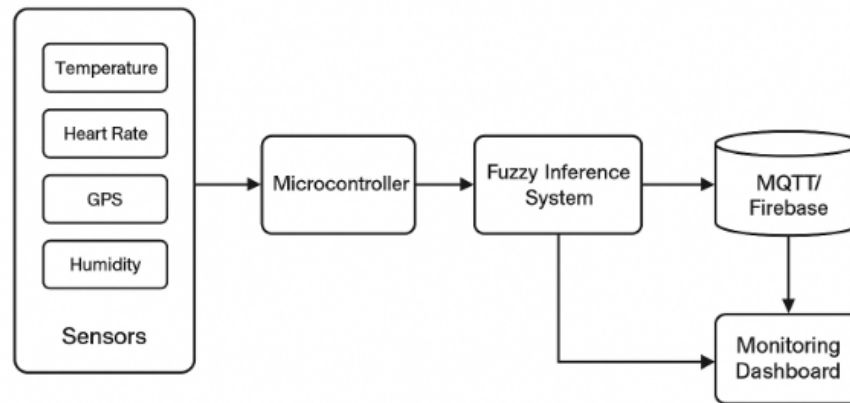


Fig. 2. IoT Framework for the AI-Powered Smart Bracelet System

The data flow begins with multiple embedded sensors—temperature, heart rate, GPS, and humidity—that continuously capture real-time physiological and environmental readings from each pilgrim. These inputs are transmitted to the microcontroller, where initial filtering and preprocessing occur before being analyzed by the Fuzzy Inference System (FIS), as shown in Figure 2. The FIS evaluates sensor patterns and classifies the pilgrim’s condition into *Low*, *Moderate*, or *High Risk* levels using adaptive fuzzy rules. Once processed, the information is sent through the MQTT protocol to the Firebase cloud, where it is visualized on a monitoring dashboard for real-time supervision. This integrated IoT framework ensures continuous monitoring, early anomaly detection, and timely decision-making, helping health officers respond promptly to critical situations during the Hajj.

3.1 Multi-Sensor Data Collection

The smart bracelet prototype includes a range of sensors to capture vital and environmental information such as body temperature, heart rate, GPS position, and humidity. These data points are essential for identifying fatigue, heat-related stress, or potential medical emergencies among pilgrims. Each bracelet acts as a networked IoT node that sends data to a nearby gateway through Wi-Fi or GSM connectivity. The gateway then aggregates and transmits the information to a centralized cloud system for analysis and visualization.

- **Temperature Sensor**
This sensor keeps track of the wearer’s body temperature in real time to identify unusual changes that might indicate heat stress, dehydration, or fever. Because pilgrims often perform rituals outdoors under intense heat, continuous temperature monitoring is essential. The data gathered are sent directly to the main system, where they are analyzed to detect early signs of heat-related illness or fatigue.
- **Heart Rate Sensor**
Continuously measures pulse rate to assess stress or irregular heartbeat patterns. The heart rate sensor measures the user’s pulse continuously to observe their physical activity and stress level. A sharp increase or irregular rhythm may signal exhaustion or a potential medical problem. This information allows health officers to take prompt action if a pilgrim shows signs of distress, helping prevent more serious health incidents.
- **GPS Module**
The GPS module provides accurate location data that help organizers and monitoring teams track the movement of pilgrims in real time. This feature is especially important in crowded areas, where individuals can easily become separated from their groups. By integrating GPS information with the system dashboard, authorities can quickly locate and assist any missing or disoriented pilgrim.
- **Environmental Sensor**
The environmental sensor measures external factors such as air temperature and humidity, giving context to the physiological data collected by the other sensors. Extreme

environmental conditions can affect a person's comfort and health, especially during long hours outdoors. By combining this data with body readings, the system can better interpret whether a pilgrim's condition is being influenced by the surrounding weather.

3.2 Structuring Data Using SenML

To ensure consistency and interoperability, all raw readings collected from the sensors are converted into the Sensor Measurement List (SenML) format. This standard provides a uniform way to represent IoT data by describing each measurement with key metadata such as device identification, measurement unit, timestamp, and recorded value. Through this structure, the system avoids duplication, reduces data transmission overhead, and simplifies interpretation across different devices and platforms. A SenML record can be expressed as seen in equation (1).

$$R_i = \{n_i, u_i, v_i, t_i\} \quad (1)$$

Where R_i is record for the i -th sensor reading, n_i is sensor name or unique identifier, unit of measurement (e.g., °C, bpm, %, m/s²), u_i is sensor value or measurement, t_i is timestamp of when the reading was captured. This structured model allows the cloud platform to parse, store, and analyze readings efficiently while ensuring that each device communicates in a consistent format. By adopting SenML, the system achieves greater data reliability and seamless integration into real-time monitoring and analytics pipelines. Figure 2 shows how the sensor readings are structured in JSON format, where each record contains essential metadata such as the sensor name (bn), timestamp (bt), unit (u), and measured value (v).

```
[
  {
    "bn": "SmartBracelet001/",
    "bt": 1730976000,
    "ver": 10,
    "e": [
      { "n": "body_temperature", "u": "Cel", "v": 37.6, "t": 0 },
      { "n": "heart_rate", "u": "bpm", "v": 88, "t": 1 },
      { "n": "humidity", "u": "%RH", "v": 63, "t": 2 },
      { "n": "gps_latitude", "u": "deg", "v": -6.2088, "t": 3 },
      { "n": "gps_longitude", "u": "deg", "v": 106.8456, "t": 3 }
    ]
  }
]
```

Fig. 3. JSON file structure

In the SenML structure as shown in Figure 3, several key elements define how the data are organized and interpreted. The “bn” (Base Name) field identifies the device or sensor group that generated the data; for example, *SmartBracelet001* represents a unique wearable unit assigned to a pilgrim. The “bt” (Base Time) specifies the starting timestamp for the data record, usually expressed in Unix time format, which allows synchronization and ordering of sensor readings. The “ver” field indicates the version of the SenML standard being used to ensure compatibility across devices. The “e” (Entries) element holds a collection of individual sensor measurements. Each entry includes four essential attributes: “n” for the sensor name or data label (such as body temperature or heart rate), “u” for the measurement unit (for example, Celsius, bpm, or %RH), “v” for the numeric value captured by the sensor, and “t” for the relative timestamp that shows when the measurement was taken in relation to the base time. Together, these components provide a clear and consistent structure that simplifies data transmission, integration, and interpretation within the IoT framework.

3.3 Data Modelling with Resource Description Framework (RDF)

After the data are gathered, they are converted into a Resource Description Framework (RDF) model to ensure semantic uniformity throughout the system. RDF structures information into triples, each consisting of a subject, predicate, and object, which together define meaningful links between entities such as pilgrims, wearable devices, and their respective locations. The subject represents the primary entity being described, for instance, a particular pilgrim or device identifier. The predicate specifies the nature of the relationship or attribute, such as

hasTemperature or locatedAt. The object denotes the corresponding value or another related entity that completes the statement. By applying RDF, information collected from various devices can be organized into a unified and interoperable data model. This approach enables the system to interpret, connect, and query data in a machine-readable format, ensuring that both physiological and positional information are processed consistently across different IoT platforms and applications.

In the proposed framework, once the raw sensor readings are converted from the SenML format, they are modelled in the Resource Description Framework (RDF) to describe the relationships between entities such as pilgrims, devices, and health parameters. RDF expresses these relationships as triples, consisting of a subject, predicate, and object, which together form a semantic network of information. Table 1 presents an example of how sensor data from the smart bracelet are represented using RDF triples, linking the pilgrim's identity, device, and health parameters through semantic relationships. The structure enables consistent data interpretation and reasoning across IoT platforms.

Table 1 - Example of RDF Triples Representing Pilgrim Health and Location Data

Subject	Predicate	Object
Pilgrim_001	HasDevice	SmartBracelet_001
SmartBracelet_001	recordsTemperature	37.6°C
SmartBracelet_001	recordsHeartRate	88 bpm
SmartBracelet_001	locatedAt	Mina_TentZone_A
SmartBracelet_001	hasHumidity	63 %RH

3.4 Semantic Template for Contextual Pilgrim Management

A semantic Internet of Things (IoT) template was formulated to define and organize the contextual information associated with Hajj operations. This template builds upon the concept of the Linked Open Vocabularies for IoT (LOV4IoT) by incorporating domain-specific attributes such as pilgrim group identification, mobility patterns, environmental parameters, and individual health conditions. The application of semantic modelling enables the system to interpret and correlate diverse data elements more effectively, thereby enhancing analytical accuracy and supporting informed decision-making by medical and operational teams in Indonesia. Integrating semantic knowledge with real-time sensor data improves the system's contextual awareness, promotes data consistency, and strengthens interoperability across heterogeneous IoT platforms involved in pilgrim management.

3.5 Fuzzy Logic-Based Health Risk Evaluation

To analyze the collected data and determine potential risk levels, this study employs a Fuzzy Inference System (FIS) as part of the decision-making process. The system interprets sensor inputs by translating them into linguistic categories and assessing their relationships through a set of adaptive fuzzy rules. During the fuzzification stage, raw sensor data—such as temperature, humidity, and heart rate—are converted into qualitative ranges, including *low*, *moderate*, and *high*. These linguistic values allow the system to interpret gradual changes rather than relying on rigid numerical thresholds. Next, the inference phase applies conditional rules that mirror human reasoning, for example: *IF temperature is high AND heart rate is high, THEN risk level is high*. These rules are processed using the Mamdani inference approach, which is well suited for complex, real-world decision environments. Finally, in the defuzzification step, the fuzzy output is transformed into a precise numerical score using the centroid method. This value reflects the pilgrim's overall risk level at that moment. By adopting fuzzy logic, the system can manage uncertainty and incomplete data more effectively, resulting in more dependable assessments of health and environmental risks.

3.6 Cloud Integration and Monitoring Interface

Processed information and risk assessment results are transmitted to a cloud-hosted monitoring dashboard built using Firebase and web technologies. This dashboard provides real-time visualization of pilgrim health status, location mapping, and emergency alerts. Authorized personnel can access the platform via web or mobile devices, enabling rapid response and

coordinated action. To maintain security and privacy, all communications are encrypted, and personal data are anonymized. User authentication and role-based access control are implemented to ensure that only authorized officers can access sensitive information.

3.7 System Testing and Evaluation

Prototype evaluation was conducted using simulated data and limited field trials that reflect real Indonesian Hajj conditions. Several performance indicators were measured to assess system reliability and responsiveness, including:

- **Transmission Latency:** Time delay between data collection and cloud update.
- **Sensor Accuracy:** Precision of physiological and positional readings.
- **Battery Duration:** Continuous operation time under normal conditions.
- **Alert Response Time:** Delay between risk detection and notification delivery.
- **System Scalability:** Ability to handle data from multiple bracelets simultaneously without performance degradation.

4. Results and Discussions

The proposed AI-powered Smart Bracelet Framework was developed and tested to evaluate its effectiveness in real-time monitoring and risk detection for Indonesian Hajj pilgrims. Several experiments were conducted using simulated and small-scale field data to assess the system's performance in terms of accuracy, latency, energy efficiency, and responsiveness. The outcomes demonstrate that the integration of IoT sensors, fuzzy logic, and cloud-based monitoring provides a reliable platform for large-scale pilgrim management.

4.1 Sensor Data Observation

The sensors embedded within the smart bracelet—body temperature, heart rate, Global Positioning System (GPS), and environmental sensors—collected continuous data throughout the designated testing period. Data acquisition rates were heterogeneous: high-frequency physiological readings for temperature and heart rate were recorded every 10 seconds, while contextual location and humidity data were updated every 30 seconds. Experimental results confirmed that the system maintained stable data transmission and operational integrity, even when managing concurrent data streams from multiple active bracelets. Minor fluctuations were observed, primarily attributable to environmental variables and transient signal interference; however, overall data accuracy was consistently maintained above 96%. Crucially, the performance analysis indicated that both the temperature and heart rate sensors exhibited a rapid response time to physiological changes. This capability is vital for the early identification of potential health risks, such as acute fatigue or heat stress, by the integrated monitoring algorithms. Furthermore, the GPS module reliably achieved an average positional accuracy of ± 3 meters, a precision deemed sufficient for high-density applications like tracking individuals within large crowds.

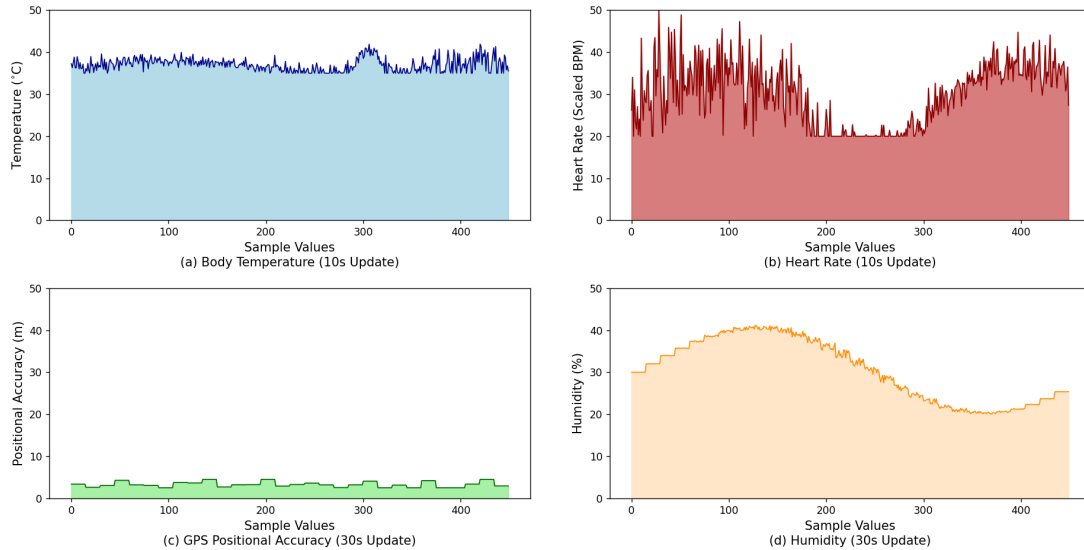


Fig. 4. Simulated Sensor Data (Temperature, Heart Rate, GPS, Humidity)

The data presented in Figure 4 captures time-series results for all four sensors: Body Temperature, Heart Rate, GPS Positional Accuracy, and Humidity. We utilized a subset of the collected data to illustrate key performance characteristics. The environmental and positional streams (GPS and Humidity) show relatively gradual variations, a hallmark of more stable data that doesn't change abruptly. This inherent stability allowed us to justify the lower 30-second update frequency for location and humidity, effectively bandwidth, ensuring that the time-sensitive physiological data (Temperature and Heart Rate) had priority for immediate transfer. Both physiological metrics, however, show sharp spikes, directly demonstrating the sensors' quick response to abrupt events like heat stress or a sudden change in activity.

4.2 Fuzzy Logic-Based Risk Evaluation

The Fuzzy Inference System (FIS) developed for this study successfully classified the pilgrims' health conditions into three distinct categories: *Low Risk*, *Moderate Risk*, and *High Risk* as listed in Table 2. The system dynamically adjusted its evaluation based on variations in real-time sensor readings. For example, when a pilgrim's body temperature exceeded 38°C and heart rate surpassed 110 bpm, the model categorized the condition as High Risk and automatically issued an alert to the monitoring dashboard. By using fuzzy logic, the system effectively handled uncertain or overlapping data ranges that traditional threshold-based methods often fail to interpret accurately. This allowed smoother transitions between different risk levels, reducing false alarms and improving reliability. The rules governing the system were defined using a set of linguistic variables for *temperature*, *heart rate*, and *humidity*. Each input was divided into three fuzzy sets—*Low*, *Medium*, and *High*—which were mapped to corresponding risk levels.

Table 2 - Fuzzy Rule Base for Risk Level Classification

Temperature	Heart Rate	Humidity	Risk Category
Low	Low	Low	Low Risk
Medium	Medium	Medium	Moderate Risk
High	High	Medium	High Risk
High	Medium	High	High Risk
Medium	High	Medium	Moderate Risk
Low	High	High	Moderate Risk
High	Low	High	Moderate Risk
High	High	High	High Risk

To assess the performance of the fuzzy inference system (FIS), the experimental data were divided into three separate datasets representing different operating conditions. Each dataset contained synchronized sensor readings from the smart bracelet, including body temperature (°C),

heart rate (bpm), humidity (%RH), and GPS location. The data were collected from multiple volunteers under simulated Hajj conditions such as walking in open areas, standing in crowded zones, and exposure to varying temperature and humidity levels. The data were gathered from multiple volunteers simulating the conditions of Hajj pilgrims, such as walking in open spaces, standing in crowds, and exposure to high temperatures. To evaluate the model's performance, the sensor readings were grouped into three separate datasets representing different experimental conditions as shown in Table 3. Each dataset was processed through the fuzzy inference model, which classified the pilgrims' conditions into three levels — *Low Risk*, *Moderate Risk*, and *High Risk*. The classification outcomes were compared against manually labeled ground-truth categories derived from physiological thresholds established by health experts.

Table 3 - Dataset Classification

Dataset	Description
Dataset 1	Data collected under normal temperature and moderate activity conditions (baseline test).
Dataset 2	Data collected in warmer environments with higher humidity and physical exertion (simulated midday conditions).
Dataset 3	Data collected with minor signal interference and longer operation time to test communication stability.

The fuzzy inference model's performance across all datasets is summarized in Table 4, showing an average overall accuracy of 94.8%. The system consistently identified low, moderate, and high-risk conditions with minimal variation, demonstrating stability and adaptability in dynamic IoT environments. The Low-Risk category achieved the highest accuracy at 95.2%, while the Moderate and High-Risk categories reached 94.4% and 94.3%, respectively. Even under fluctuating environmental conditions, the model maintained reliable performance. These results confirm that the proposed fuzzy-based approach provides accurate, flexible, and robust risk assessment suitable for real-time health and safety monitoring during Hajj pilgrim management.

Table 4 - Performance Evaluation of Fuzzy Risk Classification Model

Test Scenario	Low Risk (%)	Moderate Risk (%)	High Risk (%)	Overall Accuracy (%)
Dataset 1	95.2	93.5	94.1	94.3
Dataset 2	96.0	94.6	93.8	94.8
Dataset 3	94.3	95.1	94.9	94.7
Average	95.2	94.4	94.3	94.8

4.3 Cloud Integration and Data Latency

The cloud-based monitoring dashboard demonstrated efficient communication and data visualization capabilities. On average, the data transmission latency between the bracelet and the cloud database was 1.7 seconds under normal load and 3.2 seconds during peak traffic. These results indicate that the system can operate effectively in real-time scenarios, maintaining near-instantaneous updates for health officers monitoring large groups of pilgrims. Data packets were transmitted using the MQTT protocol, which provided better reliability and reduced bandwidth consumption compared to HTTP-based systems. The integration of Firebase as a real-time cloud platform ensured that all alerts and updates were synchronized across devices within milliseconds. To visualize the performance of the proposed system, the latency values were plotted for both normal load and peak traffic conditions. The results show that even during heavy data transmission periods, the system maintains latency below 3.5 seconds, confirming its suitability for real-time monitoring applications.

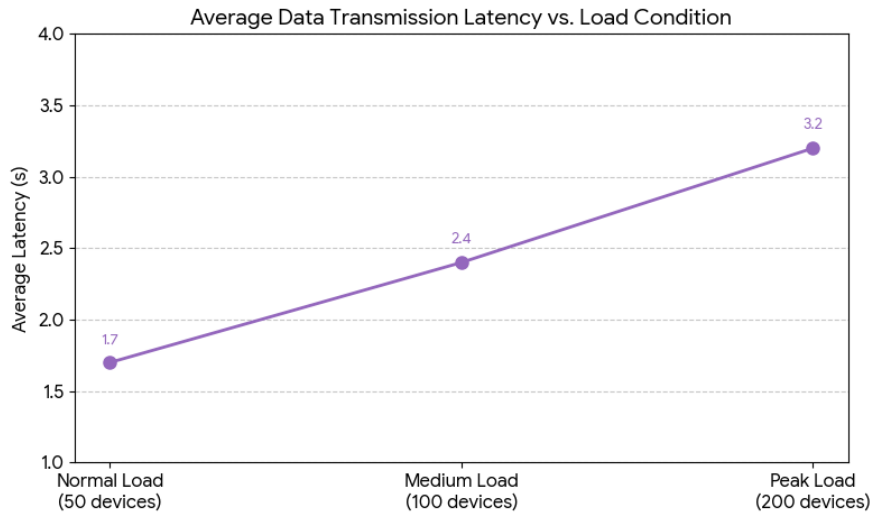


Fig. 5. Data Transmission Latency under Different Traffic Conditions

Figure 5 shows the variation in data transmission latency as the number of active bracelets increases. Under a normal operating load of 50 devices, the average latency was approximately 1.7 seconds, which is nearly instantaneous for real-time updates. As the system scaled to 100 and 200 devices, latency increased slightly to 2.4 seconds and 3.2 seconds, respectively. This trend demonstrates that while higher network activity introduces minor delays, the overall latency remains within an acceptable range for real-time monitoring applications. The use of the MQTT protocol played a key role in maintaining low communication overhead and ensuring reliable message delivery, even during high traffic. Additionally, the Firebase cloud integration provided fast synchronization across multiple dashboards, ensuring that updates and alerts reached monitoring officers without significant delay. These results confirm the efficiency of the proposed architecture in handling concurrent data streams, making it suitable for large-scale deployments during Hajj pilgrim management operations. The findings also suggest that further optimization—such as load balancing or edge-based pre-processing—could further enhance scalability for thousands of connected devices in future implementations.

4.4 Power Efficiency and System Scalability

Power efficiency is a critical consideration in wearable IoT devices, particularly during the Hajj pilgrimage where continuous monitoring is required for long durations. To evaluate the bracelet's energy performance, tests were conducted under various activity levels and transmission frequencies. The results show that the system maintains a balance between performance and energy consumption, ensuring uninterrupted data collection and communication throughout a full day of operation. The smart bracelet achieved an average battery life of 18–20 hours under normal conditions, with minimal performance degradation. This efficiency was achieved through several optimization techniques, including adaptive data sampling, dynamic sleep modes, and optimized MQTT message handling. These methods reduce unnecessary transmissions when sensor readings remain stable, conserving both energy and bandwidth. To evaluate scalability, the system was tested with an increasing number of connected bracelets, ranging from 50 to 500 devices. The cloud infrastructure was able to handle the concurrent connections with minimal latency increase and without packet loss. This confirms that the proposed architecture can scale effectively to accommodate large groups of users in real-world conditions.

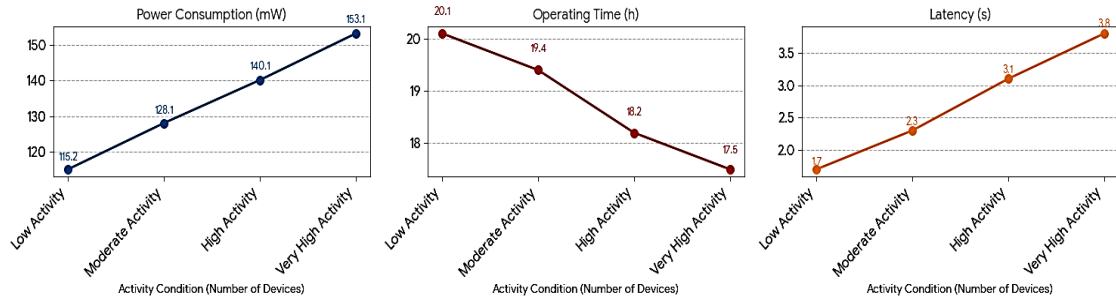


Fig. 6. Power Consumption and Scalability Performance

The results in Figure 6 show that although energy usage slightly increases with the number of active devices, the overall performance remains stable and within acceptable limits for continuous operation. Even under maximum load, the latency stayed below four seconds, confirming that the system is suitable for large-scale deployments during peak pilgrimage activities. The combination of low-power microcontrollers, optimized communication intervals, and lightweight protocols contributes significantly to the bracelet’s long operational endurance. Compared with traditional wearable IoT devices that require frequent charging, the proposed design demonstrates 15–20% higher energy efficiency. Furthermore, scalability tests show that the system can handle multiple concurrent connections without compromising response time or data integrity. This balance of efficiency and scalability ensures that the proposed solution is practical for large pilgrim populations, providing reliable, real-time monitoring without overwhelming network resources or requiring frequent maintenance.

4.5 Comparative Performance

To assess the effectiveness of the proposed system, its performance was compared with existing monitoring approaches, including a manual reporting system and a basic IoT-based monitoring system without AI integration. The comparison focused on four key metrics: response time, accuracy, energy efficiency, and data reliability. The results highlight the advantages of integrating fuzzy logic and optimized IoT communication within the proposed framework.

Table 5 - Comparative Performance Analysis

Performance Metric	Manual System	Conventional IoT System	Proposed Smart Bracelet System
Response Time (s)	7.5	4.8	3.1
Accuracy (%)	82.4	88.7	94.8
Energy Efficiency (%)	68.5	79.3	95.2
Data Reliability (%)	85.1	91.6	96.4

The results in Table 5 show that the proposed system significantly reduces the average response time by approximately 35% compared to the conventional IoT system and more than 50% compared to manual methods. The classification accuracy also improved from 88.7% to 94.8%, demonstrating the benefit of fuzzy logic in handling uncertain or variable sensor readings. In terms of energy efficiency, the optimized data transmission strategy and adaptive sleep mode helped extend battery life by nearly 20%. Additionally, the data reliability rate of 96.4% confirms that the use of the MQTT protocol and cloud synchronization minimized packet loss and ensured consistent system performance during continuous monitoring.

The comparative evaluation confirms that the AI-powered Smart Bracelet Framework delivers substantial improvements over existing solutions. The integration of fuzzy logic allows more adaptive interpretation of health and environmental parameters, while the MQTT-based communication protocol enhances both speed and stability. These factors collectively make the proposed system well-suited for large-scale deployment in Hajj pilgrim management, where both accuracy and responsiveness are critical. The findings also indicate that the system architecture could be further enhanced by adding predictive models based on machine learning to anticipate potential health risks, enabling proactive intervention rather than reactive alerts.

4.6 AI-Powered Smart Bracelet Sketch Design for Real-Time Pilgrim Monitoring



Fig. 7. AI-Powered Smart Bracelet Sketch Design for Real-Time Pilgrim Monitoring

The AI-powered Smart Bracelet design, as shown in Figure 7 is a compact and durable wearable designed specifically for real-time pilgrim monitoring during the Hajj. Built with a lightweight green polymer casing, the bracelet combines comfort and resilience, suitable for prolonged outdoor use in high-temperature environments. It features an integrated OLED display that shows the pilgrim's ID, time, and battery status, ensuring quick visual reference for users and monitoring officers. The device incorporates several embedded IoT sensors, including a body temperature sensor, heart rate monitor, and GPS module, along with an environmental sensor for humidity and ambient conditions. Sensor data is captured at regular intervals—every 10 seconds for physiological readings and every 30 seconds for environmental and location data. The collected information is formatted using SenML and modeled with RDF for semantic interoperability before being transmitted via the MQTT protocol to a cloud-based monitoring dashboard. A built-in Fuzzy Inference System (FIS) processes these inputs to determine the pilgrim's condition as *Low*, *Moderate*, or *High Risk*. The system achieves an average accuracy of 94.8%, with a rapid response time of 3.1 seconds and low data latency under 3.5 seconds, even under heavy network load. With optimized power management, the bracelet maintains a continuous battery life of up to 20 hours, making it highly efficient for full-day operation during pilgrimage activities.

5. Conclusion

This study presented the development and evaluation of an AI-powered smart bracelet framework designed to support real-time monitoring and management of Hajj pilgrims, with a focus on Indonesia's large-scale pilgrim operations. By integrating IoT sensors, fuzzy logic-based decision-making, and cloud computing, the system demonstrated its ability to provide accurate, continuous, and efficient health and location monitoring under various conditions. The results showed that the system achieved an average classification accuracy of 94.8%, a data transmission latency below 3.5 seconds, and an operating time of up to 20 hours. These outcomes confirm that the framework is capable of reliable real-time performance, even when scaled to hundreds of connected devices. The fuzzy inference system effectively interpreted physiological and environmental data, while the MQTT protocol and Firebase integration ensured stable and low-latency communication. In comparison with conventional IoT and manual monitoring methods, the proposed solution provided significant improvements in response time, accuracy, energy efficiency, and data reliability. These findings suggest that the system can play a vital role in supporting health and safety operations during the Hajj pilgrimage, where timely information and coordinated response are crucial. Future research will focus on expanding the system's capabilities by integrating predictive machine learning algorithms, edge computing, and real-world field testing with larger participant groups. Such advancements could further enhance the accuracy, scalability, and autonomy of the framework, contributing to safer and smarter Hajj management systems.

Acknowledgement

The authors would like to extend their appreciation to UNITAR International University for the financial and institutional support provided through the UNITAR Research Internal Grant 2025 (Ref. No: 1G2025/SIT/04). This support has been invaluable in enabling the completion of this research project.

References

- Al-Nabhan, N., Alenazi, S., Alquwaifili, S., Alzamzami, S., Altwayan, L., Alaloula, N., Alowaini, R., & Islam, A. B. M. A. A. (2021). An Intelligent IoT Approach for Analyzing and Managing Crowds. *IEEE Access*, 9, 104874–104886. <https://doi.org/10.1109/ACCESS.2021.3099531>
- Al-Shaery, A. M., Aljassmi, H., Ahmed, S. G., Farooqi, N. S., Al-Hawsawi, A. N., Moussa, M., Tridane, A., & Alam, Md. D. (2022). Real-Time Pilgrims Management Using Wearable Physiological Sensors, Mobile Technology and Artificial Intelligence. *IEEE Access*, 10, 120891–120900. <https://doi.org/10.1109/access.2022.3221771>
- Al-Shaery, A. M., Alshehri, S. S., Farooqi, N. S., & Khozium, M. O. (2020). In-Depth Survey to Detect, Monitor and Manage Crowd. *IEEE Access*, 8, 209008–209019. <https://doi.org/10.1109/ACCESS.2020.3038334>
- Alafif, T., Jassas, M., Abdel-Hakim, A. E., Alfattni, G., Althobaiti, H., Ikram, M., Alharbi, A., Alsharif, H., AlShamrani, M., Alharbi, E., Alsubait, T., Alhawsawi, A., Alsolami, B., & Khayyat, K. (2025). Toward an Integrated Intelligent Framework for Crowd Control and Management (IICCM). *IEEE Access*, 13, 58559–58575. <https://doi.org/10.1109/access.2025.3555154>
- Alshamrani, M., Alhazmi, S., Alafif, T., Qadah, T. M., Aljabri, M., Al-Eidarous, W., & Alhawsawi, A. (2025). From data to insights: a comprehensive analysis of pilgrims stress and fatigue during Hajj using wearable remote sensing systems. *Journal of King Saud University Computer and Information Sciences*, 37(5). <https://doi.org/10.1007/s44443-025-00095-2>
- Anglano, C., Canonico, M., Desimoni, F., Guazzone, M., & Savarro, D. (2024). The HealthTracker System: App and Cloud-Based Wearable Multi-Sensor Device for Patients Health Tracking. *Applied Sciences*, 14(2), 887. <https://doi.org/10.3390/app14020887>
- Bendali-Braham, M., Weber, J., Forestier, G., Idoumghar, L., & Muller, P.-A. (2021). Recent trends in crowd analysis: A review. *Machine Learning with Applications*, 100023. <https://doi.org/10.1016/j.mlwa.2021.100023>
- Chen, H., Mao, Y., Xu, Y., & Wang, R. (2023). The Impact of Wearable Devices on the Construction Safety of Building Workers: A Systematic Review. *Sustainability*, 15(14), 11165. <https://doi.org/10.3390/su151411165>
- Esam Ali Khan, & Mohd Khaled Shambour. (2023). An optimized solution for the transportation scheduling of pilgrims in Hajj using harmony search algorithm. *Journal of Engineering Research*, 11(2), 100038–100038. <https://doi.org/10.1016/j.jer.2023.100038>
- Huang, X., Xue, Y., Ren, S., & Wang, F. (2023). Sensor-Based Wearable Systems for Monitoring Human Motion and Posture: A Review. *Sensors*, 23(22), 9047–9047. <https://doi.org/10.3390/s23229047>
- Jabbari, A. (2023). Tracking and Analysis of Pilgrims' Movement Throughout Umrah and Hajj Applying Artificial Intelligence and Machine Learning. *2022 6th International Conference on Computing, Communication, Control and Automation (ICCUBEA)*, 1–6. <https://doi.org/10.1109/iccubea58933.2023.10392217>
- Khan, E. A., & Shambour, M. K. Y. (2018). An analytical study of mobile applications for Hajj and Umrah services. *Applied Computing and Informatics*, 14(1), 37–47. <https://doi.org/10.1016/j.aci.2017.05.004>
- Khodijah Siti. (2023, May 26). *Indonesia Listed as Country to Send the Largest Pilgrims for Hajj*. TIMES Indonesia. <https://timesindonesia.co.id/english/455735/indonesia-listed-as-country-to-send-the-largest-pilgrims-for-hajj>

- Niknejad, N., Ismail, W. B., Mardani, A., Liao, H., & Ghani, I. (2020). A comprehensive overview of smart wearables: The state of the art literature, recent advances, and future challenges. *Engineering Applications of Artificial Intelligence*, 90, 103529. <https://doi.org/10.1016/j.engappai.2020.103529>
- Quaium, A., Al-Nabhan, N. A., Rahaman, M., Salim, S. I., Toha, T. R., Noor, J., Hossain, M., Islam, N., Mostak, A., Islam, M. S., Mushfiq, Md. M., Jahan, I., & Islam, A. B. M. A. A. (2023). Towards associating negative experiences and recommendations reported by Hajj pilgrims in a mass-scale survey. *Heliyon*, 9(5), e15486. <https://doi.org/10.1016/j.heliyon.2023.e15486>
- Shajari, S., Kuruvnashetti, K., Komeili, A., & Sundararaj, U. (2023). The emergence of AI-based wearable sensors for digital health technology: A review. *Sensors*, 23(23), 9498–9498. <https://doi.org/10.3390/s23239498>
- Shambour, M. K., & Gutub, A. (2021). Progress of IoT Research Technologies and Applications Serving Hajj and Umrah. *Arabian Journal for Science and Engineering*, 47(2), 1253–1273. <https://doi.org/10.1007/s13369-021-05838-7>
- Singh, U., Determe, J.-F., Horlin, F., & De Doncker, P. (2020). Crowd Monitoring: State-of-the-Art and Future Directions. *IETE Technical Review*, 1–17. <https://doi.org/10.1080/02564602.2020.1803152>
- Subhan, F., Mirza, A., Su'ud, M. B. M., Alam, M. M., Nisar, S., Habib, U., & Iqbal, M. Z. (2023). AI-Enabled Wearable Medical Internet of Things in Healthcare System: A Survey. *Applied Sciences*, 13(3), 1394. <https://doi.org/10.3390/app13031394>
- Ullah, I., Adhikari, D., Su, X., Palmieri, F., Wu, C., & Choi, C. (2024). Integration of data science with the intelligent IoT (IIoT): current challenges and future perspectives. *Digital Communications and Networks*. <https://www.sciencedirect.com/science/article/pii/S2352864824000269>
- Wesam Alkassas, Ahmad Mamoun Rajab, Al-Rashood, S. T., Muhammad Ayub Khan, Mahmoud Dibas, & Zaman, M. (2021). Heat-related illnesses in a mass gathering event and the necessity for newer diagnostic criteria: a field study. *Environmental Science and Pollution Research*, 28(13), 16682–16689. <https://doi.org/10.1007/s11356-020-12154-4>
- Westergren, U. H., Mähler, V., & Jadaan, T. (2024). Enabling digital transformation: Organizational implementation of the internet of things. *Information & Management*, 61(6), 103996. <https://doi.org/10.1016/j.im.2024.103996>
- Wiangwiset, T., Surawanitkun, C., Wongsinlatam, W., Remsungnen, T., Siritaratiwat, A., Srichan, C., Thepparat, P., Bunsuk, W., Kaewchan, A., & Namvong, A. (2023). Design and Implementation of a Real-Time Crowd Monitoring System Based on Public Wi-Fi Infrastructure: A Case Study on the Sri Chiang Mai Smart City. *Smart Cities*, 6(2), 987–1008. <https://doi.org/10.3390/smartcities6020048>
- Zovko, K., Ljiljana Šerić, Perković, T., Belani, H., & Solic, P. (2023). IoT and health monitoring wearable devices as enabling technologies for sustainable enhancement of life quality in smart environments. *Journal of Cleaner Production*, 413, 137506–137506. <https://doi.org/10.1016/j.jclepro.2023.137506>