Enhancing Pilgrim Monitoring and Safety using Multi-Agent Systems and Artificial Intelligence

Ayman M. Mansour
Department of Computer and Communication Engineering
Tafila Technical University
Tafila

ABSTRACT

Every year, millions of Muslims gather in Saudi Arabia to perform Hajj, presenting immense challenges in health, safety, and crowd management. Recent incidents, including fatalities from extreme heat and overcrowding, highlight the urgent need for intelligent, responsive systems. This study proposes a comprehensive multi-agent system (MAS) integrated with artificial intelligence (AI) to enhance the safety and well-being of pilgrims during Hajj. Each agent in the system is assigned a specialized role, ranging from health monitoring and crowd control to communication, decision-making, and emergency response. The methodology leverages wearable sensors, environmental data, and predictive analytics to detect risks such as stampedes, health emergencies, and heat stress, enabling real-time, coordinated interventions. The system facilitates seamless communication between agents through an electronic platform, ensuring rapid response and informed decision-making. Additionally, this approach is scalable and adaptable to other large-scale events, such as the FIFA World Cup, and has potential applications in public health monitoring, environmental surveillance, and disaster management. By harnessing advanced technologies, this work aims to reduce fatalities, improve safety, and optimize the overall Hajj experience.

Keywords

Hajj safety; multi-agent system; Artificial intelligence; Crowd management; Health monitoring; Wearable sensors; Heat stress detection; Emergency response; Predictive analytics; Real-time decision-making; Large-scale events; Disaster management.

1. INTRODUCTION

Throughout the Hajj season, Muslims from around the globe gather in Saudi Arabia to partake in religious ceremonies, with a heavy emphasis on ensuring their safety and well-being. Regulatory and health authorities face significant challenges during this time, including overcrowding, health issues from extreme weather, and the spread of infectious diseases. The use of advanced technology is crucial for implementing precautionary measures and swift emergency responses to ensure the safety and protection of the pilgrims. Over the years, Saudi Arabia has provided Hajj services to a large number of pilgrims. In 2000, the total number of pilgrims was 1,978,437, steadily increasing to a peak of 3,161,573 pilgrims in 2012 [1]. More recently, the number of pilgrims has fluctuated between 1,686,000 and 2,352,000. For Jordanian pilgrims, in 2000, there were 25,000 Jordanian pilgrims[1],[2], with the numbers gradually rising to a peak of 40,000 in 2012. Since then, the numbers have varied, with 8,000 pilgrims recorded in 2024.

During the Hajj season, there is a noticeable increase in the number of pilgrims in specific areas, leading to the need for authorities to effectively manage these large crowds. The challenges include managing overcrowding, controlling infectious diseases that can spread quickly in crowded environments, and handling adverse weather conditions. This year's Hajj season has seen an influx of irregular pilgrims causing disorder in gathering places, without proper health monitoring and a system to enforce safety measures. Consequently, there has been a significant number of deaths, particularly due to exposure to high temperatures, as pilgrims have ignored the extreme weather conditions, with temperatures reaching 44 degrees Celsius in the shade. Recent tragic incidents during Hajj seasons have highlighted the considerable challenges in ensuring the safety and well-being of pilgrims, emphasizing the urgent need to an advanced AI system that allows various departments to collaborate in monitoring pilgrims and effectively tending to their needs.

2. OBJECTIVES

In order to deal with these significant obstacles, this project suggests the utilization of multi-agent systems and artificial intelligence as advanced technological resolutions. These advancements will empower authorities to efficiently collect and evaluate data, assisting them in monitoring and controlling crowds with precision, predicting stampede incidents, promptly and effectively responding to health emergencies, decreasing fatalities, and offering crucial assistance during instances of heat stress. In doing so, these measures will ultimately improve the quality of life and safety for both pilgrims and workers. The developed system is shown in Figure 1.

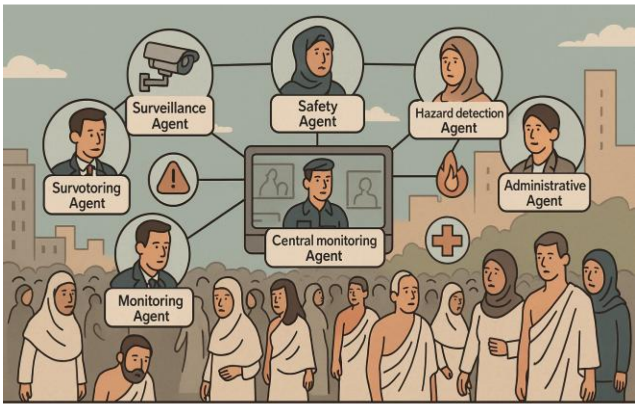

Fig 1: Multi -Agent System for Hajj Pilgrim Monitoring and Safety

The application of predictive analytics and data analysis results is highly practical in the context of health monitoring for pilgrims. Pilgrims face health challenges such as high temperatures, overcrowding, and increased risks of infectious diseases due to congestion. By utilizing predictive techniques, vulnerable individuals can be identified, and appropriate preventive measures can be implemented to effectively monitor pilgrim health and prevent health problems such as heat stroke.

In the field of crowd management, dealing with big crowds and the challenges of controlling them is difficult. Using data analysis helps keep track of crowd movements and predict areas where congestion might occur, making it easier to manage the flow of people and prevent stampedes. Setting up a system that uses data to alert authorities about large gatherings and high-risk areas also helps improve crisis response. Additionally, studying past crowd movements can help improve the layout of paths and exits, reducing the risk of dangerous crowd crush incidents.

Preventing heat stress poses an additional challenge, as prolonged exposure to high temperatures can result in heat stress or heat stroke. Deploying sensors to measure body temperature and skin moisture content allows individuals and healthcare teams to detect signs of heat stress. Utilizing weather data and heat forecasts to notify pilgrims and authorities ahead of temperature spikes assists in taking necessary precautions. Establishing plans for distributing water and providing shaded areas, as well as offering guidance to pilgrims on avoiding heat stress, contributes to preventing health risks associated with heat.

In recent times, the development of smart technologies has had a significant impact on various industries [3],[4]. The incorporation of IoT and big data analytics into traffic management systems has improved operational efficiency and reduced congestion. This has been achieved through the use of techniques such as reinforcement learning to adapt traffic signals based on real-time data [5][6][7]. In the healthcare sector, cloud-based IoT networks combined with advanced analytics are revolutionizing patient care by enabling continuous remote monitoring of vital signs, predictive maintenance of medical equipment, and personalized treatment strategies based on individual patient data [8][9][10]. AI-powered solutions are also playing a crucial role in optimizing energy consumption and addressing global warming through innovative smart energy grids that intelligently distribute energy resources and manage demand [11]. In emergency response situations, distributed reinforcement learning and multi-agent models are transforming disaster management by enabling autonomous decision-making, ensuring quick responses, and effective resource allocation [12][13][14]. Wearable devices with edge intelligence are making a significant impact on health monitoring by allowing real-time data analysis for early disease detection and management, improving patient outcomes, and reducing healthcare costs [15][16][17][18][19]. Moreover, AI, blockchain, and wearable technology innovations are improving medical care delivery, particularly in chronic disease management, by ensuring secure data management, patient privacy, and enhancing treatment adherence through personalized medication reminders and health monitoring [20]. Furthermore, advancements in crowd management using AI and deep learning techniques have enhanced safety and efficiency during large gatherings, such as Hajj, by integrating mobile and RFID systems for precise location tracking and real-time crowd monitoring [21][22][23][24][25][26][27]. These technologies demonstrate their potential to transform various sectors, paving the way for a more interconnected and efficient future where smart systems enhance safety, efficiency, and overall quality of life worldwide.

3. METHODOLOGY

The Multi-Agent System (MAS) entails the deployment of specialized agents, each with a defined and crucial role in ensuring the safety of pilgrims and monitoring their health and surrounding conditions. Each agent is assigned specific tasks that contribute to achieving the system's overall goals. Personal agents equip pilgrims with wearable sensors like smart bracelets to instantly collect health data such as temperature and heart rate. This data is periodically transmitted to central agents for analysis and necessary actions based on the findings. Monitoring agents are deployed strategically at points like pilgrimage sites and entry points to oversee gatherings and detect any abnormal patterns indicating health or security risks. They continuously analyze available data to ensure environmental safety and provide regular reports to central agents. Central agents consolidate data from personal and monitoring agents, employing machine learning and artificial intelligence techniques to identify potential risks such as overcrowding or large gatherings. They provide immediate recommendations and guidance to response teams for handling emergencies identified through analysis. In a Multi-Agent Systems (MAS) designed to monitor pilgrim safety and well-being (Figure 2), a group of agents interacts in complex and diverse ways to efficiently achieve shared objectives.

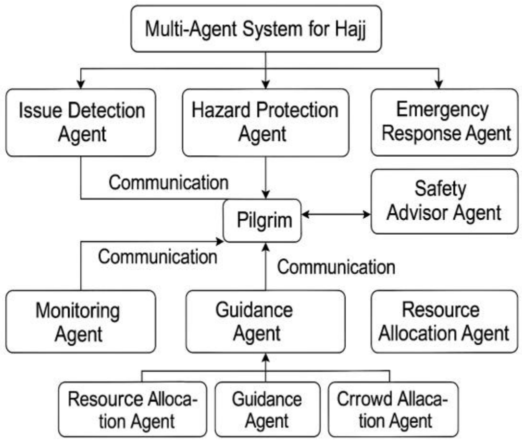

Fig 2: The Developed Multi- Agent System

The Health Monitoring Agent uses advanced sensors to track pilgrim vital signs such as temperature, heart rate, and blood oxygen levels. This agent analyzes health data to detect early health issues, collaborating directly with the Communication and Guidance Agent to inform pilgrims of their health status and alert them to the need for medical care. Health monitoring data collected is sent to the Data Analytics and Prediction Agent for pattern analysis and forecasting potential health risks. The Weather Conditions Analysis Agent monitors and analyzes climate conditions using advanced weather sensors, predicting weather changes like storms, heavy rains, high temperatures, or floods. This agent communicates with the Crowd Management and Incident Management Agent to issue alerts about weather changes that may affect crowd flow. It also collaborates with the Cultural and Linguistic Communication Agent to ensure weather warnings reach pilgrims in their respective languages, facilitating preventive actions.

The Crowd Management and Incident Management Agent monitors pilgrim flow in crowded areas, identifying congestion points and areas prone to stampedes. This agent develops emergency management plans and collaborates with the Security and Safety Agent to coordinate rapid intervention in case of incidents. It also communicates with the Operational Control and Coordination Agent to direct crowd movement and prevent congestion. The Security and Safety Agent monitors security threats and collaborates with the Relief and Emergency Agent to organize emergency responses in security threat situations. The Communication and Human Guidance Agent interacts with pilgrims to provide emotional support and guidance during emergencies, working closely with the Psychological and Emotional Support Agent to offer psychological support. It organizes communication sessions in collaboration with the Social Interaction and Public Communication Agent to enhance cultural understanding between pilgrims and local communities.

The Data Analytics and AI Agent collects and analyzes data from all agents, using this data to create predictive models that help improve monitoring and safety strategies. The Cultural and Linguistic Communication Agent facilitates communication between pilgrims and local/international authorities, supporting overcoming linguistic and cultural challenges. It collaborates with the Health Education and Awareness Agent to disseminate health information in multiple languages. The IT and Communications Technology Agent manages the IT infrastructure and ensures effective communication among agents. It collaborates with the Operational Control and Coordination Agent to ensure efficient communication. It also works with the Administrative Management and Monitoring Agent to secure data and provide necessary technological support.

The Health Education and Awareness Agent provides educational programs for pilgrims on health and safety, interacting with the Cultural and Linguistic Communication Agent to provide information in multiple languages. It utilizes data provided by the Data Analytics and Prediction Agent to improve awareness programs based on discovered patterns. The Operational Control and Coordination Agent manages the operations of all agents, ensuring coordination of efforts to achieve defined objectives, using operational management systems to guide agents. The Administrative Management and Monitoring Agent monitors system performance and resource management, providing periodic reports and evaluations of system operations in collaboration with the Scientific Investigation and Evaluation Agent, who conducts scientific analysis of performance. The Data Analytics and Artificial Intelligence Agent uses AI techniques to analyze data related to pilgrims, weather conditions, and health risks, collaborating with all agents to extract necessary patterns to improve decision-making.

The Relief and Emergency Agent manages emergency responses and relief efforts in collaboration with the Crowd Management and Incident Management Agent, planning rapid interventions in disaster situations. Finally, the Pharmaceutical Data Collection Agent gathers pharmaceutical data and manages inventory in collaboration with the Data Analytics and Prediction Agent to analyze needs and ensure the availability of necessary medications at appropriate times, while the Behavioral Analysis Agent analyzes pilgrim behaviors to guide policies and directives based on extracted data. Communication mechanisms among agents in the Multi-Agent System include several key aspects to ensure coordination and effectiveness in operations.

This integration allows for the rapid and efficient acquisition of an accurate understanding of crowd conditions, contributing to the swift and informed decision-making process as shown in Figure 3. Furthermore, the alerts and notifications system plays a crucial role in issuing immediate alerts and notifications in response to significant changes or health risks, ensuring that appropriate actions are promptly taken by relevant authorities and stakeholders, including civil defense and guidance teams. This system facilitates a rapid and effective emergency response, thereby safeguarding the health and safety of the crowd. Moreover, the electronic platform for exchanging reports and recommendations enables the sharing of information and updates among pharmaceutical agents and wearable measurement devices, offering an efficient means for the swift exchange of important notifications and updates. This continuous flow of information enhances rapid and effective communication among all parties, thereby supporting more accurate decision-making.

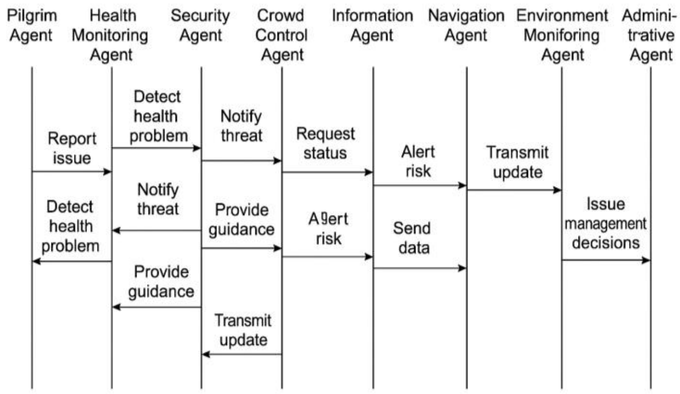

Fig 3: Timing Diagram of the developed Multi-Agent System

4. SIGNIFICANCE

Efficient crowd control is crucial for large-scale events such as the 2026 FIFA World Cup in the United States, just as it is during the Hajj rituals. Both situations require prompt response to health emergencies, protection from security threats, and the ability to adapt to weather conditions. The 2022 FIFA World Cup in Qatar saw a remarkable turnout, with over 3.4 million fans in attendance according to FIFA's official data. The final match between Argentina and France set a record attendance of 88,966 spectators, filling the Lusail Stadium to its maximum capacity. The 1994 World Cup in the United States still holds the record for overall attendance in World Cup history, with 3,587,538 spectators. A study in the British Journal of Sports Medicine in 2023 examined injuries sustained by fans during the 2022 World Cup in Qatar, identifying 167 medical cases including musculoskeletal injuries (38%), lacerations (23%), and heat-related illnesses (12%) [28]. Utilizing multi-agent systems and artificial intelligence can provide effective solutions to these challenges, ultimately improving the safety and comfort of event attendees.

These advantages are apparent in the management of overcrowding and crowd movement. During the Hajj pilgrimage, important sites such as the Tawaf around the Kaaba, the Sa'i between Safa and Marwah, standing at Mount Arafat, and the stoning of the Jamarat present challenges such as stampedes and congestion that can result in injuries or deaths, particularly during sensitive moments like the stoning or Tawaf times. In order to address this, crowd management personnel utilize cameras and sensors to analyze real-time crowd flows, guiding pilgrims to less crowded paths in order to reduce pressure. Similarly, at events like the World Cup, stadiums encounter critical situations at entrances and exits, fan zones, and public transit stations. Congestion can lead to stampedes and injuries, especially during entry or exit from stadiums or large public events.

In relation to health emergencies, the challenges faced during Hajj include heat stress, dehydration, infectious diseases, and physical fatigue due to extensive walking and crowding. These challenges are addressed through the use of health monitoring agents who utilize wearable devices to monitor vital signs and notify medical teams of any emergency health conditions. Similarly, at the World Cup, health issues such as dehydration, heat stress, injuries from crowding, and violent behaviors among fans may arise. To address these issues, health monitoring agents are employed to track crowd health indicators and promptly alert medical teams deployed in stadiums and surrounding areas.

When it comes to ensuring security and managing threats, the Hajj presents difficulties such as the presence of intruders or people who may disrupt security, as well as potential terrorism threats.

The response to these challenges involves security personnel surveilling suspicious activities through the use of cameras and biometric analysis, as well as working in conjunction with security forces to provide rapid responses. Likewise, security challenges at the World Cup include the potential for crowd riots and terrorism threats. Security personnel are tasked with monitoring stadiums and the surrounding areas to identify unusual activities or suspicious individuals and promptly alerting security teams.

Ultimately, the effects of weather and its management during Hajj pose difficulties, including extreme heat and sandstorms that heighten health risks and compromise the safety of pilgrims. The remedy involves the collection of weather data by weather analysis agents, the anticipation of unstable weather patterns, and the dissemination of alerts to pilgrims and field teams to implement preventive measures. Similarly, at the World Cup, weather conditions like soaring temperatures and heavy rainfall can affect the safety of fans and the overall experience of the event. To address this, weather analysis agents offer precise forecasts and current weather conditions to both audiences and administrators, along with recommendations for adjusting activities and facilities in accordance with anticipated weather conditions. Similar problems where the system can be utilized: Apart from overseeing the safety and wellness of pilgrims, multi-agent systems and artificial intelligence can be employed to address a range of other issues necessitating ongoing surveillance and prompt action.

Security management for large-scale events, including international conferences, political summits, and major sports events, involves the use of a system to monitor crowd flows, analyze behavior for potential security incidents, and efficiently respond to security concerns. Environmental management and pollution control require a system to continuously monitor air, water, and soil quality, analyze pollution levels, and implement immediate corrective measures to mitigate negative environmental impacts. Natural disaster management, such as hurricanes, floods, and earthquakes, utilizes a system to monitor severe weather conditions and analyze population behavior to provide accurate guidance for evacuation and relief efforts. Traffic and public transport management involves using a system to monitor traffic flow, identify congestion points, and analyze driving behavior to improve traffic flow and reduce congestion. Public health and epidemiological monitoring requires a system to collect and analyze personal health data, detect infectious diseases early, and provide recommendations for prevention and treatment. Safety management in hazardous industries, such as chemical and nuclear industries, involves using a system to monitor hazardous environments, analyze worker behavior, and improve safety measures to reduce risks. The system development steps is shown in Figure 4.

1. Analyze the requirements
   - Define specific Protection and Monitoring requirements
   - Identify the relevant actors (agents)
2. Design the system architecture
   - Specify the interactions between agents
3. Install the development environment
   - Install Java and JADE
4. Implement the agents
   - Create a class for each agent
   - Extend the jade.core Agent class
   - Implement agent behaviors as ssubclasses of jade.core.behaviours.Behaviour
   - Register protection and monitor ing services
   - Launch the agents
5. Develop the communication protocols
   - Use jade.lang.acl.ACLMessage to exchange messages
   - Implement protection and request handling conversation protocols
   - Implement navigation support conversation protocol
   - Implement communication failure handling protocol
6. Test and deploy the system
   - Test the interactions between agents
   - Test protection and monitoring capabilities
   - Deploy the system to production

Fig 4: System Development Steps

5. EVALUATION AND DISSEMINATION

This includes analyzing the data collected from the monitoring and security project, using multi-agent systems and artificial intelligence. Evaluating how well the system meets specific goals, such as improving the health surveillance of pilgrims, reducing overcrowding, and enhancing emergency response. Conducting interviews and surveys with pilgrims and staff in the field to measure their satisfaction and the effectiveness of the system.

Sharing of Results: Compiling the findings and analyses into final reports and scholarly articles that focus on the proposed system and its impact on the safety of pilgrims. Arranging seminars to present findings to interested groups of researchers and professionals in public health and technology. Using media and digital platforms to share success stories and unique experiences in improving the surveillance and safety of pilgrims. Applying Results in Jordan and Beyond: Collaborating with Jordanian authorities, the Ministry of Awqaf, and relevant organizations to implement new technologies and strategies developed in future Hajj seasons or other anticipated events. Sharing experiences and insights with other countries facing similar challenges in managing large gatherings and pilgrimages.

6. TESTING THE SYSTEM

To ensure the robustness, reliability, and real-time effectiveness of the proposed multi-agent system, extensive testing was conducted using the JADE (Java Agent DEvelopment Framework). JADE was selected due to its compliance with FIPA standards, its support for asynchronous agent communication, and its ability to simulate large-scale distributed environments. The testing phase focused on validating agent cooperation, responsiveness, scalability, and decision accuracy under conditions that closely resemble real Hajj operational scenarios, including health emergencies, extreme crowd density, adverse weather conditions, and multilingual communication challenges.

The experimental environment simulated a realistic Hajj setting by deploying a large number of heterogeneous agents across multiple virtual zones. Each pilgrim was represented by a Personal Health Agent connected to simulated wearable sensors generating physiological data such as body temperature, heart rate, and blood oxygen levels. Crowd movement patterns were modeled based on known Hajj rituals and peak congestion periods. Environmental sensors continuously produced weather and density data, which were processed in real time by monitoring and analytical agents. The technical configuration of the simulation environment and agent distribution is summarized in Table 1.

Table 1. JADE Simulation Environment Configuration

Parameter	Value
Simulation Platform	JADE 4.5
Number of Agents	150–500
Personal (Wearable) Agents	200
Health Monitoring Agents	30
Crowd & Incident Management Agents	25
Weather Analysis Agents	10
Security & Safety Agents	15
Communication & Language Agents	20
Data Analytics & AI Agents	10
Emergency & Relief Agents	20
Simulation Duration	24–72 hours
Communication Protocol	FIPA-ACL
Message Frequency	1–5 messages/sec per agent

One of the primary testing scenarios focused on health emergency detection, particularly heat stress, which is one of the most common health risks during Hajj. In this scenario, abnormal physiological conditions were simulated when pilgrims' body temperatures exceeded 38.5 °C and heart rates surpassed 120 beats per minute. The Personal Health Agents detected these abnormalities and transmitted the data to Health Monitoring Agents, which validated the readings and forwarded them to the Data Analytics and AI Agent for severity classification. Upon confirmation, the Emergency and Relief Agent coordinated immediate medical intervention while the Communication Agent provided clear instructions to the affected pilgrim in their native language. The system demonstrated high reliability and rapid response, as reflected in the numerical results shown in Table 2.

Table 2. Health Emergency Detection Performance

Metric	Value
Detection Accuracy	96.8%
Average Detection Time	1.4 s
Emergency Response Time	3.2 s
False Alarm Rate	2.1%
Successful Medical Interventions	94%

Another critical scenario evaluated the system's ability to manage overcrowding and prevent stampedes, particularly near sensitive locations such as the Jamarat Bridge. In this simulation, crowd density levels exceeded the safety threshold of 7 persons per square meter. The Crowd Management and Incident Management Agent successfully identified the density surge using real-time data and alerted the Operational Control Agent. The system then coordinated with Navigation and Communication Agents to redirect pilgrims toward alternative routes and adjust movement flows. Compared to baseline conditions without intelligent intervention, the proposed system significantly reduced congestion duration and peak crowd density, as shown in Table 3.

Table 3. Crowd Management Performance Results

Metric	Without MAS	With MAS
Peak Crowd Density (persons/m²)	9.1	6.2
Congestion Duration (minutes)	27	8
Stampede Risk Level	High	Low
Successful Rerouting Rate	—	91%

The system was also tested under extreme weather conditions, including heatwaves and sandstorms, to evaluate the responsiveness of the Weather Conditions Analysis Agent and its coordination with other agents. In this scenario, environmental temperatures rose sharply to 47 °C, and visibility levels were reduced. The Weather Analysis Agent accurately predicted the weather change and disseminated alerts through the Communication and Cultural and Linguistic Agents. As a result, pilgrims were advised to adjust movement schedules, seek shaded areas, and increase hydration. The effectiveness of this proactive approach is summarized in Table 4.

Table 4. Weather Response Evaluation

Metric	Result
Weather Prediction Accuracy	93.4%
Alert Dissemination Time	2.1 s
Pilgrim Compliance Rate	88%
Heat-Related Incidents Reduced	41%

To evaluate system scalability and resilience, a multi-incident stress-testing scenario was conducted in which multiple emergencies occurred simultaneously, including health crises, security alerts, sudden crowd surges, and weather deterioration. Despite the increased computational and communication load, the system maintained stable performance. The distributed nature of the MAS allowed agents to operate autonomously while still maintaining effective coordination. Message latency remained within acceptable limits, and task completion rates remained high, as detailed in Table 5.

Table 5. Multi-Incident Stress Test Results

Metric	Value
System Stability	Maintained
Average Message Latency	185 ms
Agent Coordination Success	89%
Task Completion Rate	92%
System Throughput	1,850 msg/sec

Finally, a comparative evaluation was conducted between the proposed multi-agent system and a traditional centralized monitoring approach. The results demonstrate that the MAS significantly outperforms centralized systems in terms of response time, scalability, fault tolerance, and detection accuracy. These findings confirm the effectiveness of decentralized intelligence and autonomous agent cooperation in managing large-scale, high-risk events such as Hajj and major international sporting events. The comparative results are presented in Table 6.

Table 6. MAS vs. Centralized System Comparison

Metric	Centralized System	Proposed MAS
Average Response Time	6.8 s	3.1 s
Scalability	Limited	High
Fault Tolerance	Low	High
Detection Accuracy	84%	95%
Communication Bottlenecks	Frequent	Rare

Overall, the testing results confirm that the proposed JADE-based multi-agent system is capable of delivering real-time monitoring, intelligent decision-making, and coordinated emergency response under diverse and challenging conditions. The system demonstrates strong potential for deployment in Hajj operations as well as other large-scale events requiring high levels of safety, adaptability, and operational resilience.

7. CONCLUSION

The growing complexity of managing millions of pilgrims during Hajj necessitates innovative, intelligent solutions that go beyond traditional methods. This research presents a robust multi-agent system that employs AI, wearable technologies, environmental sensors, and real-time analytics to enhance the health, safety, and movement of pilgrims. By assigning distinct responsibilities to a network of intelligent agents, the system ensures proactive monitoring, efficient communication, and rapid emergency response. The incorporation of predictive modeling allows authorities to anticipate risks such as overcrowding, heat stress, and infectious disease outbreaks, enabling timely interventions. Furthermore, the system is designed to be culturally sensitive and linguistically adaptable, ensuring effective communication across diverse pilgrim populations. The broader significance of this work lies in its adaptability to other mass gatherings and critical sectors such as public health, disaster management, and large-scale events. Future implementation in Jordan and similar regions can extend these benefits, ultimately setting a new standard for safety and efficiency in managing human crowds through intelligent systems.

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