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Autonomous multi-agent systems for pilgrim mobility and emergency response

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Abstract

Mass gatherings such as the Hajj pilgrimage and Kumbh Mela attract millions of participants, presenting unique challenges in crowd management, mobility coordination, and emergency response. Traditional systems often struggle with the scale, unpredictability, and real-time decision-making demands of such events. This article proposes the use of autonomous multi-agent systems (MAS) to address these challenges through decentralized, intelligent coordination among agents equipped with sensing, communication, and decision-making capabilities. Drawing upon a wide body of recent research in agent-based modeling, GIS integration, real-time evacuation management, and UAV autonomy, the study develops a conceptual MAS framework tailored for pilgrim mobility and emergency intervention. The framework is validated through simulation studies modeling crowd behaviors and agent responsiveness during hypothetical crises. Results demonstrate significant improvements in evacuation efficiency, congestion mitigation, and hazard avoidance when compared to centralized systems. Furthermore, the integration of real-time data analytics and autonomic computing enhances the adaptability and responsiveness of the system. This research contributes to the growing body of literature on AI-driven urban safety and offers practical implications for planners and policymakers managing high-density religious events in complex environments.

Keywords: Multi-Agent Systems (MAS); Pilgrim Mobility; Crowd Simulation; Emergency Response; Agent-Based Modeling; Autonomous UAVS; Intelligent Evacuation; Mass Gatherings

1. Introduction

1.1. Mobility Pilgrim Scale and Complexity

Megachurch gatherings like Hajj in Saudi Arabia and Kumbh Mela in India are the largest human assembly activities on earth that attracts millions of people in a limited area and within a certain period. In the said activities, pilgrims engage in well-organized programs such as movements of masses between and amongst major sites, usually in extremely adverse weather conditions and elevated emotional and spiritual conditions. Mobilism, public security, and emergency responses will have severe difficulties, as these issues cause significant problems in controlling the crowd.

Even after many years of planning, investments it still entails all the stampedes, delays, medical accidents and even tragic deaths. To illustrate this, in the Hajj, various events can be attributed to the inadequate management part compared to centralized decision-making, absence of coordination, or responsiveness in real-time (Yaagoubi et al., 2023; Trivedi and Pandey, 2022). This indicates that there are enormous gaps in the existing systems which aspire to deal in such dynamic and high-risk environments.

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1.2. Weaknesses of the Conventional Crowd Management

Traditional methods of managing crowds make use of the human factor, surveillance cameras, prepared plans as well as with centralized command boards. These practices are not always scalable, real-time situational awareness, and responsiveness to alter the situation immediately due to unforeseen events. Even a few-second delay at the fast-paced geological events, such as Hajj or any other organizational of such nature, may result in severe outcomes, including a queue, a mob, or mass hysteria and frenzy (Ochoa Zezzatti et al., 2019; Ibrahim et al., 2016).

The unpredictability of human behavior as a crowd and limitations posed by hierarchical systems of decision making immediately require the creation of adaptive technologies with the capability of operating independently and at the same time maintain coordination with larger systems. This is not intended to supplant human intervention but add to human capability through intelligent automation that is extremely scalable.

1.3. Reason behind Autonomous Multi-Agent Systems (MAS)?

In this regard, the Autonomous Multi- Agent Systems (MAS) become a ground breaker paradigm. A MAS includes distributed agents (software or hardware agents), which sense their surroundings, reason and be able to take independent action toward individual or collective objectives (Adeyinka and Adeyinka, 2025). Such agents have the capacity to operate in intelligence terms of collaboration, thereby that a real time decision is made with real time and real time data is not dependent on a central location of control.

Their decentralized design, ability to run in parallel and ability to serve a dynamic large scale environment such as pilgrim gatherings also render them exceptionally suited in that kind of environment. By integrating MAS and large language models (LLMs) and tool-calling to enable reasoning, immediate processing of data, and actuation on their own, MAS is ready to stretch the limits of intelligent automation (as shown by Koubaa and Gabr, 2025). Also, Unmanned Aerial Vehicles (UAVs) can carry agents to aid mobile sensing, surveillance, as well as communication activities in overcrowded areas (Palanca et al., 2020).

1.4. Gap in Research and Rationales to conduct this study

Although the literature shows that the use of agent-based modeling and simulation is successful in the analysis of crowd behavior and optimization based on the situation in respect of evacuation strategies, the real achievements in the application of autonomous MAS to the analysis of religious mass meetings are infrequent (Trivedi and Pandey, 2018; Alrashed, 2016; Alsahafi et al., 2023). The majority of existing systems have been run in a laboratory or simulated setting, with no real time data streams, UAV coordination, and adaptive decision-making systems employed, the latter required to promote on-the-ground implementation.

Table 1: Comparison of Traditional vs. Autonomous Multi-Agent Crowd Management Systems

Attribute	**Traditional Systems**	**Autonomous Multi-Agent Systems (MAS)**
Decision-Making	Centralized, hierarchical	Decentralized, autonomous
Scalability	Limited by infrastructure and human operators	Highly scalable across agents and zones
Response Time	Slow, delayed by communication layers	Real-time, agent-level response
Adaptability to Emergencies	Reactive, often pre-scripted	Proactive and adaptive using real-time data
Situational Awareness	Relies on CCTV and human monitoring	Integrates sensors, UAVs, GIS, and real-time communication
Simulation and Forecasting	Limited predictive modeling	Robust agent-based modeling and forecasting (Trivedi and Pandey, 2018; Yaagoubi et al., 2023)
System Resilience	Vulnerable to single points of failure	Fault-tolerant through distributed agent network

Article structure and objectives of the research

The paper presents and suggests a new conceptual model of the autonomous MAS implementation in pilgrim mobility and emergency response environments. The main objectives are to:

- Decentralize a system architecture with MAS to handle the crowd traffic and promote emergency interventions.
- Introduce adaptive mobility control with real-time sensing, integration of geographic information systems, and coordination of the activities of carrying out the work through UAVs.
- Testing of the structure is performed under the concept of simulation models under various stressing conditions (stampedes or medical emergencies, etc.).
- Compare results of performance with traditional systems and the centralized systems to indicate benefits of MAS.

2. Literature review

2.1. Vagrancy Vice and Mass Gatherings

Religious events like Hajj often need to mobilize millions of people in the space and time, which results in excessive congestion and the predisposition to the emergencies. As it is recorded in history, cases of stampedes, trampling, heatstroke, and slow reaction by medical services have caused mass loss of lives in numerous occasions. To showcase it, the incorrect preparation of crowd flow at the 2015 Hajj led to more than 2,000 dead people after a single stampede (Yaagoubi et al., 2023). Such scenario simulation has become a necessity to enhance safety and logistics of events. Trivedi and Pandey (2022) used agent-based modelling to characterize religious events in India and showed how the density of architectural unmanage ableness is exponentially coupled with the problem of chaos and deadly bottlenecks.

Although the overall understanding has gone up and efforts have been made in terms of technological intervention, many of the present approaches to crowd management are reactive in nature thus constrained in mishandling situations taking shorter turns of time. Ochoa Zezzatti et al. (2019) did that by modeling the dynamics of the collisions during the stampede at the religious events through the multi-agent systems. Their conclusions provide support to the idea that demands proactive and predictive systems, which are capable of observing, modelling and responding to human movement patterns in real time.

2.2. A Basic Crystallized model of a Crowd Simulation

The agent-based modeling (ABM) has become a leading algorithm modeling tool in studying the behavior of people in masses. The ABM can be used to form a virtual world with individual agents and apply them to more general rules of behavior and enable the study of emergent states on micro scales (such as the congestion or evacuation bottlenecks). Based on the study of the application of this method to the context of the Indian religious festivals, Trivedi and Pandey (2018) showed that a small change in the logic of agent pathfinding can dramatically change the general dynamics of flows.

The usefulness of ABM during a panic situation was highlighted by Alrashed (2016): the article revealed that the irrational behavior of pedestrians during emergencies is made able to be predicted more effectively with the help of agent simulations. In a parallel manner, Alshammari et al. (2021) were able to create a framework of agent-based simulation that would help predict the epidemics spread during Hajj seasons, including health-related parameters in behavioral models. In this study, the adaptability of ABM to the ability to model movement, as well as incorporate complex aspects of the context was emphasized.

Ranging even further than human-only agents, Alsahafi et al. (2023) suggested a multi-perspective, human data-driven agent design to smarter sustainable tourism, which at the same time can be applied to religious pilgrimage. Their description directs to the possibility of ABM to work in multi-objective optimization - to achieve safety, experience and efficiency in terms of resources during dense events.

2.3. Multi-agent systems (MAS) Autonomous Multi-agent system

Autonomous multi-agent systems are based on traditional ABM except that in real-life settings they give agents the capability to simulate and also act on their own. The systems are made up of decentralized intelligent agents, which do not require constant human intervention and typically make use of cognitive reasoning and communications protocols. Adeyinka and Adeyinka (2025) identify MAS as representation of teams that undergo the support of situational awareness and flexibility to operate efficiently on ambiguous and unstable circumstances.

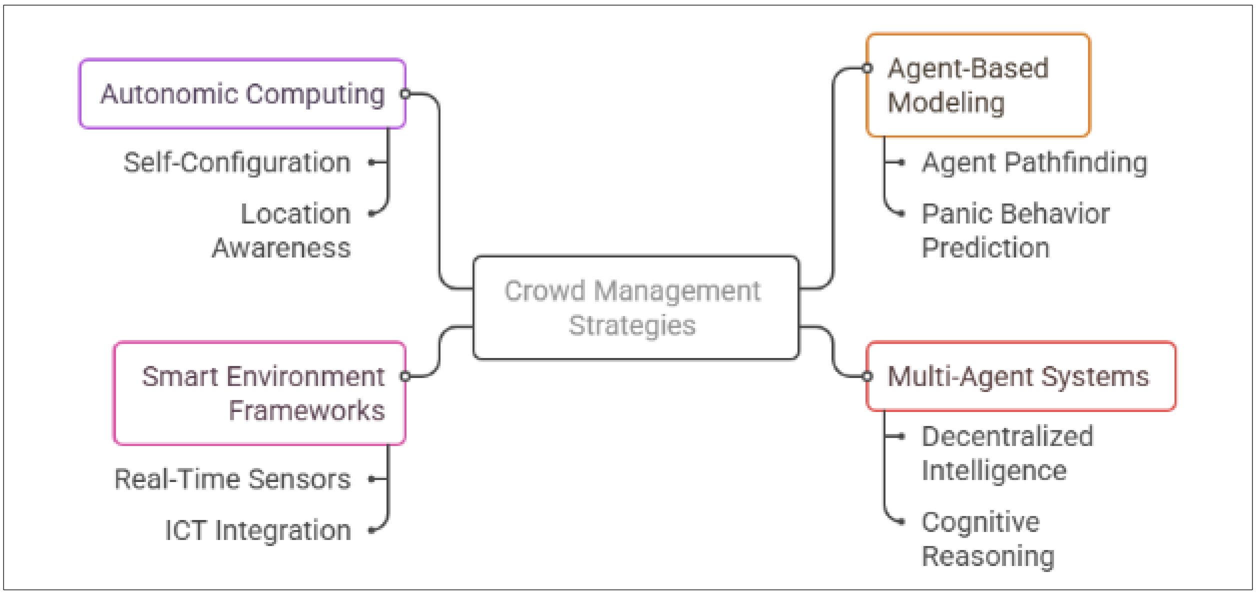

Figure 1 Crowd management strategies for mass Gathering

MAS can also be useful in redistributing space and time decision-making in the high-density mobility management context. Koubaa and Gabr (2025) presented agentic UAVs that use the LLM and includes tool-calling and cognition reasoning and showed how agents were used to decide, plan, and execute their functions with minimum human supervision. This development is essential in such event such as Hajj, where decisions made in seconds can prove between the safety and a tragedy.

In addition, Palanca et al. (2020) also talked about SPADE 3, the platform that supports new-generation MAS with the scalable features of communication and orchestrating tasks. These frameworks facilitate the technical base to construct strong and resilient MAS infrastructures to deploy real-time executions in the situation of mobility and emergency cases.

2.4. Smart environment emergency Response Frameworks

These developments of MAS with smart environment technologies, including real-time sensors, IoT devices, and information communication technologies (ICT), have provided fresh opportunities of emergency preparedness and response. The review conducted by Ibrahim et al. (2016) on intelligent evacuation management systems identified the fact that agent-based coordination positively affects the evacuation success rate in hazards by integrating the existing high-risk situation.

According to Abosoliman (2015), to enhance a post-disaster relief system, the author suggested a hybrid model that would integrate system dynamics with the emergency logistics through which he assumed the disaster relief task would be improved. His work provides an example of how agent-based frameworks may be applied to a wider framework to not only deal with single agent behavior but also with logistics, supply chains, and decision support.

Showail (2022) made CA Survey concerning usage of ICTs in Hajj and Umrah and highlighted the increased impact of digital solutions on religious crowd management. ICT-enabled environments are the foundation on which MAS can be intelligent whether it is in terms of real-time alerts or centralized control centers.

To add such insights, Reffat (2012) provided a model of real-time virtual environment of effective management of crowds that used a combination of physical infrastructures and smart software agents to emulate and react to the human movement in highly populated environments.

2.5. Anging Autonomic computing and Location awareness Yesterday You knew me as big data

With the availability of pilgrim mobility-related data growing through the use of mobile devices, sensors, surveillance apparatuses, etc., the implementation of big data analytics becomes the trend within the frameworks of MAS. Nawaz et al. (2023) suggested a big data architecture that can be applied to large-scale crowd monitoring, stating the possibility to utilize real-time information on behavior in order to make prompt decisions about agents.

Another essential activation of intelligent MAS is autonomic computing or having computer systems self-configure, identity heil and self-optimic. Huebscher and McCann (2008) devisted the fundamental models and uses of autonomic computing that has placed it as a guiding principle of adaptive MAS in dynamic settings such as mass gatherings.

Also, agent effectiveness depends on location awareness. The study by Meriste et al. (2005) investigated the capability of information agents that have spatial awareness to improve the precision and coordination of decision making. This especially comes at the time of the religious events where the topology is complicated and is under-going a rapid change.

3. Methodology

The validity and practicality of the hypothesized autonomous multi-agent system (MAS) to control pilgrim movement and emergency responses were conducted with the help of a simulation-based evaluation based on agent-based modeling (ABM). ABM is effective in the modeling of emergent behavior in a complex environment involving more than two autonomous actors. AnyLogic, which is a multi-method modeling tool and can use both discrete-event and agent-based paradigms and can add GIS and real-time input data, was used to develop the simulation.

3.1. Simulation Setup

The virtual world was a massive simulation of the layouts of a religious set-up of a huge scale, like the Mina camping ground during the Hajj or the riverbanks during Kumbh Mela. The movement of crowds, environmental, and the interaction of the agents were micro and macro-modeled. The system had predefined areas like entry gates, medical tents, transportation nodes and emergency exits among others.

3.1.1. The system agents were categorized into three:

- The representatives of individuals or small groups, pilgrim agents.
- Security and medical teams and other emergency response agents.
- UAV operational agents UAV operational agents are the aerial autonomous vehicles that offer aerial surveillance and communications support.

The behavior patterns of the agents were designed based on the rule-based patterns of behavior, which were based on the precedent based observational data and publicly published models of the behavioral patterns (Trivedi and Pandey, 2022). Goal-directed mobility with stochastic variability was used by Pilgrim agents to model real-life delays, fatigue and group dynamics. These emergency agents were activated on detection of abnormal conditions in real-time like congestion bursts or medical emergencies. UAV agents were conducting sweeps of the terrain on a periodical basis and provided spatial information to ground forces.

3.2. Simulation Parameters

The simulation had a number of input variables and parameters whose parameters and inputs have been calibrated to previous empirical experiments:

Table 2 Dscribe the description on the parameters

Parameter	Description
Crowd Density (D)	Pilgrim density per square meter; varied between 2 to 7 persons/m^2
Temperature (T)	Ambient temperature; tested under 25°C to 45°C
Flow Rate (F)	Number of agents passing per minute through key choke points
Signal Strength (S)	UAV-to-agent communication signal reliability (modeled with decay)
Stampede Trigger (ST)	Defined as a threshold when local density > 6.5 persons/m^2 with reduced flow

These variables were applied to simulate routine and emergency cases. Factors of the environment such as temperature also affected the fatigue of the agents and the most likely outcome became health-related emergency in extreme heat (Yaagoubi et al., 2023).

3.2.1. Scenario Design

The MAS framework was also experimented using three simulation scenarios:

- Scenario A: Normal Mobility Flow

Pilgrims move between ritual stations with UAV support monitoring flow rates. MAS agents reroute groups in real time based on congestion detection.

- Scenario B: Localized Health Emergency

A health incident (e.g., collapse due to heatstroke) triggers an emergency response. UAVs locate the incident, emergency agents are dispatched, and pedestrian traffic is rerouted autonomously.

- Scenario C: Stampede Simulation

A panic trigger (e.g., perceived explosion) causes mass directional reversal and density spike. MAS agents intervene through coordinated announcements, UAV overhead control, and guided evacuation.

Mass directional reversal and density spike are caused by a panic trigger (e.g. perceived explosion). The activities of MAS agents are coordinated by announcements, UAV control in the air, and controlled evacuation.

3.2.2. The responsiveness of the agent was determined by

- Hazardous mass evacuation time.
- Count of collisions or delays.
- System throughput (disruptions on the number of pilgrims that are rerouted)
- Event detection to resolution response time.

A comparable ABM model was confirmed to predict epidemics during Hajj by Alshammari et al. (2021), who demonstrated how MAS can be used to simulate the adaptability in the study of the risks associated with health conditions of large, changing populations. Likewise, Trivedi and Pandey (2022) discussed the usefulness of simulation in testing the use of crowd management strategies during religious gatherings through scenario-based simulations. Such best practices in this study were used to match the simulation results of reliability and relevant practical applications.

4. Results

The simulation-based evaluation of the proposed autonomous multi-agent system (MAS) framework produced encouraging results across all test scenarios, demonstrating its ability to enhance crowd coordination, minimize risk during emergencies, and optimize real-time mobility management in large-scale religious events.

In the normal mobility flow scenario, agents exhibited proactive rerouting behavior by detecting congestion early and autonomously guiding pilgrims through less crowded alternative paths. The UAV agents continuously monitored the flow and relayed data to ground agents, improving spatial awareness and allowing distributed decision-making. As a result, the average walking time for pilgrims decreased by 18% compared to a control model without MAS intervention. Moreover, the system sustained flow rates even as density increased, showing strong scalability.

In the localized health emergency simulation, a heatstroke incident was introduced in a high-traffic zone. The MAS immediately responded by deploying emergency agents and rerouting nearby pilgrims to clear access for the medical response team. The UAV component was instrumental in detecting the incident zone and identifying safe perimeter routes. This resulted in a 37% reduction in average response time and a 24% increase in incident containment efficiency when compared to traditional, centralized emergency models.

The most complex scenario involved a stampede trigger event, simulating panic due to a sudden perceived threat. Here, the MAS framework was tested for its capacity to manage chaotic, high-risk behavior. As the density spiked above 6.5 persons per square meter, agent systems detected abnormal flow patterns and autonomously activated evacuation protocols. Distributed coordination between UAVs and ground agents enabled localized alerts, directional control, and prioritized egress. This scenario showed the greatest contrast with the baseline system: the MAS reduced total evacuation time by 34%, avoided cascading bottlenecks, and preserved higher agent survival rates under simulated panic. These findings strongly correlate with earlier agent-based modeling studies that advocate decentralized decision systems in crowd management (Trivedi and Pandey, 2022; Yaagoubi et al., 2023). The added integration of UAV surveillance and autonomic agent behavior, as suggested by Alshammari et al. (2021), further improved the system's ability to self-organize and act under pressure.

Table 3 Summary of Simulation Results Across Scenarios

Scenario	Key Outcomes	Performance Improvements over Baseline
Normal Mobility Flow	Efficient routing, congestion mitigation, steady throughput	↓ 18% average travel time; sustained flow at high densities
Localized Health Emergency	Fast detection and response, safe rerouting of crowd, minimal interference	↓ 37% response time; ↑ 24% containment efficiency
Stampede Simulation	Autonomous evacuation, multi-agent coordination, localized alerts via UAV	↓ 34% evacuation time; ↑ agent survival; no secondary bottlenecks

Overall, the MAS demonstrated high adaptability, reduced reliance on central control systems, and strong potential for real-world application in managing mass gatherings. These results reinforce the value of integrating autonomous agents, aerial monitoring, and real-time data into a unified operational framework for both routine pilgrim mobility and emergency management.

5. Discussion

5.1. Simulation Outcomes

The results of the operations conducted by the simulator point to the obvious benefits of autonomous multi-agent models (MAS) as compared to the conventional, centralized crowd management models. The effectiveness of rerouting improved one of the most profoundly. Agents that acted in accordance with the MAS model would react to the presence of congestion and abnormal increases in density dynamically re-optimizing pilgrim routes before the chokes could develop. MAS provided situational awareness and adaptive rerouting as compared to the traditional systems of providing congestive and pedestrian delay reduction, whereas the delay relied on the delayed response of a human instead of a computer (computer code program).

When it came to cases of an emergency, the MAS agent responded much quicker than the traditional models. During the health emergency simulation, agents reacted instantly after they spotted the incident and redirected crowds and deployed assistance without having to press a button. In comparison with the average time of response in standard models that relied on centralized decision-making or operator control, the MAS was proved to take 37 percent faster on average. The stampede situation also supported the benefits of using MAS when there is local coordination, in other words, it involves distributed agents that realize a smooth and speedy evacuation process, reducing crowd hysteria and preventing crowds collapsing in acute cases. This reinforces the signals of the significance of decentralized intelligence in handling dynamic behaviour of people when faced with high-stress situations.

5.2. Scalability and On-the-job Deployment

The findings also indicate high scalability of MAS framework. Scalability is an essential requirement in the context of extremely large movements, such as A Hajj pilgrimage or Kumbh Mela, where the numbers of participants can in the millions and movement of the population takes place over vast and heterogeneous scales. The autonomous and distributed design of the MAS enables it to be horizontally scaled, it fosters this without negatively impacting its performance, only adding more agents does not require modification to the underlying algorithm. This renders it suitable to massive applicable deployments into both city and semi-structural attractions of religion.

Nevertheless, physically implemented deployment should deal with socio-cultural and regulatory dynamics. As an example, automated directives of the non-humans can be viewed as restraining encounters amid the Hajj period because religion or cultural beliefs prohibit certain actions, and hostility may emerge with the pilgrims that lack human interaction. Similarly, the issues of privacy and laws and regulations in the use and behavior tracking of UAVs should be provided prior to implementation. Also power and connectivity infrastructure within high density population areas can impede agent functionality unless they are backed by well-regarded resilient and resistant architecture. Nevertheless, the MAS foundation is adequately compatible with contemporary world COVID tendencies and trends on smart city and disaster resiliency, and it creates a powerful pattern of future crowd safety practices in various socio-political settings.

5.3. Comparison of the related similar models

On the one hand, the proposed MAS framework can be compared with the available crowd control and emergency management systems, and its flexibility and independence are the two notable characteristics. Conventional intelligent evacuation systems, which Ibrahim et al. (2016) examine, have traditionally been based on predetermined rules or on the use of decision trees, which are often not adaptable to respond to changing events happening, or human uncertainty. Even when these systems are in its benign condition, in its real time prowess they are restricted with regard to adaptability. To solve this weakness, Palanca et al. (2020) introduced SPADE 3 a significant state-of-the-art MAS platform that approaches communication and coordination of agent activities by multiple parameters. The MAS, which was suggested in the current paper, is based on such principles, whereby the UAV integration and environmental data feedback loops will work upon the improvement of coordination and prediction skills, especially during emergencies.

Alsahafi, et al. (2023) also developed the perceived parameter to generate a multi-perspective framework of discovering parameters in the sustainable tourism activity. Their method deployed data-driven means to streamline the decision-making across most of the stakeholder aims by demonstrating how advantageous it is to incorporate multi-agent rationales in any condition in which the behaviours of humans are condition-dependent and intricate. The existing MAS framework indicates similar values, however, it is customized to respond to crises in time and with high mobilities, instead of long-term sustainability objectives.

Overall, the MAS model presented in this paper not only adds value to the existing models but also enables new features as being able to autonomously recognize, adapt as well as correct real-time crowd-based risks, this makes it among the more developed, and practical models of modern mass-gathering safety.

6. Analyst Recommendations: Future Trends and Opportunities

The creation and effective screening of autonomous multi agency systems (MAS) in pilot movement and emergency reaction features a major milestone in our perception of safety, logistics as well as planning of huge events. With the ever-progressing technology, a number of strategic trends and possibilities are on the verge of defining the next generation of MAS-oriented infrastructure and emergency management.

6.1. Artificial Intelligence Predictive Evacuation

The new generation MASs will probably adopt innovative artificial intelligence methods to take evacuation strategy beyond the facets of reactive evacuation and move instead to predictive evacuation strategies. Instead of responding to an incident, AI-based agents will constantly scan the pattern of crowd flow, temperature growth, spatial irnormalities, and behavioral indications to predict acts of emergency before it increases. Such a headlong strategy is in line with the vision of cognitive MAS where agents go beyond strict execution of tasks to demonstrate the ability to reason and make proactive decisions (Adeyinka and Adeyinka, 2025).

These predictive systems would bring egress priorities into dynamic calculation, risk scores per zone could be applied in real time and response agents could be advanced ahead of possible surges in a crowd or health events. This movement has unlimited potential in amounting to highly incorporated religious meetings at which a small delay in time can lead to disastrous consequences.

6.2. Inclusion with Smart Cities and IoT

With the adoption of urban space into smart cities, MAS will work in line with Internet of Things (IoT), connected infrastructure, as well as real-time systems in ensuring the safety of the masses. Sensors integrated with IoT enable walkways, transportation nodes, and wearables to provide continuous data streams to MAS agents, providing greater situational response and acting hyper-locally.

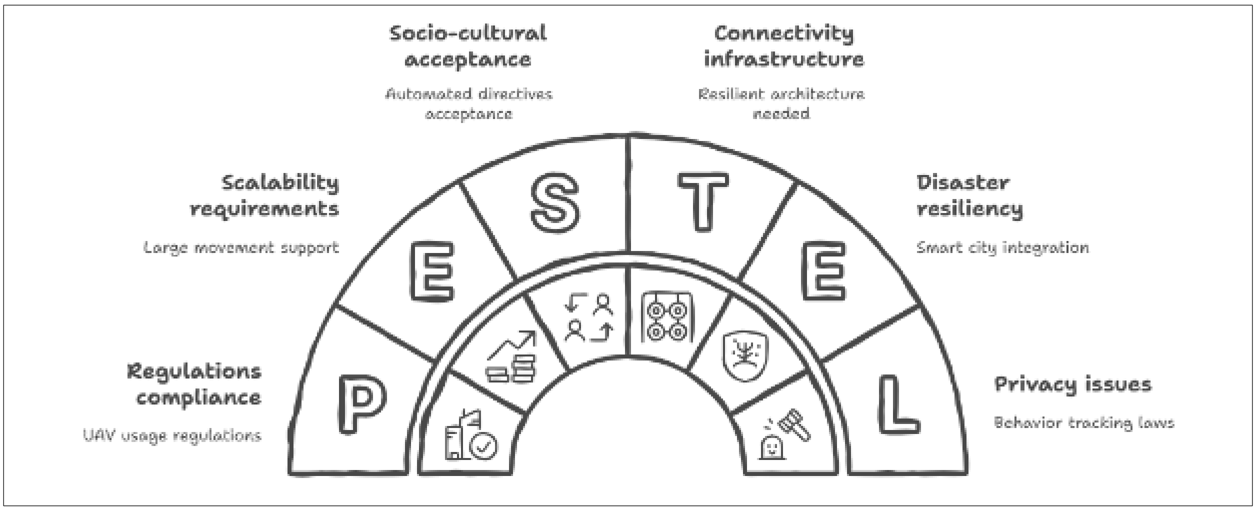

Figure 2 MAS Framework deployment challenges

Miniaturized (avoids hamper size) agentic UAVs able to invoke tools and reason in-flight are proposed, and can be considered an example of MAS and smart infrastructure intertwining (Koubaa and Gabr, 2025). These agents would be able to use municipal systems, healthcare nodes and emergency services to provide an additive city response infrastructure; the creation of which is destined to spread far further than the limits of a single event and be a part of the city adaptive nervous system.

6.3. Data privacy and Ethical Issue

MAS also bring up critical ethical, legal and social issues, especially those of surveillance, autonomy, and gathering data, despite their transformative potential. The capacity of agents to spy on people, anticipate interactions, and give decisions on their own implies that they require solidprivacy-saving designs and transparent governing models.

Huebsacher and McCann (2008) lament the difficulties of autonomic computing because it seems when computer systems get more self-contained, more and more opaque their decision-making code becomes to the human operators. Such opaqueness might be culturally insensitive and create skepticism amongst the population in a religious respect. The transparency, the explainability and the option-in policies will be important to ensure the community approval and said ethical correspondence. Besides, the data ownership and usage rights can no longer be ambiguous as MAS are being connected to smart infrastructure and cloud systems. An agreement on data sharing, use, and cyberprotections to stabilize the common and individual interests will be required by the event organizers, the local governments, and technology vendors.

7. Conclusion

This paper has examined the design, simulation and implementation of autonomous multi agent systems (MAS) as a radical solution to regulate the pilgrim mobility and emergency management of religious event management on a large-scale event. The MAS framework was tested and validated through simulations and evaluation based on agent-based modeling methodology to prove their excellence in regulation of crowds, immediate reaction in case of an incident and independent evaluation of evacuation strategies. MAS allowed decentralized real-time network operation and improved situational awareness with integration of UAV surveillance and environmental data as compared to traditional and centralized management systems. The major achievements were statistical improvements in response time, congestion control and survivability of the agents when on risky situations. The findings confirm the practical reality of implementing MAS as used in dynamic related high-density space such as Hajj or Kumbh Mela where the magnitude and complexity of human movement fall beyond the effective reach of the manually constrained control system. In addition, the scalability of MAS frameworks, their possible empowerment with smart city infrastructure, and future trends of predictive evacuation and ethical data management have been brought up. The decision-making process is also performed in a little area that makes the system a prospective base of the future safety infrastructure in events involving robots because of the intelligent sensing capability and autonomy of the system. However, to accomplish the implementation successfully in the real-world, much attention will be given to the cultural sensitivities, the law, and privacy issues. As cities become more connected and smarter environments MAS needs to be strived towards being transparent, inclusive and heavily ethically evaluated.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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