Design and Implementation of Smart Robots using AI, IoT, and DRL to Support Pilgrims and Umrah Performers in Mecca

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ABSTRACT
Hajj and Umrah are annual pilgrimages to Mecca that require accommodating millions of individuals in crowded and evolving environments, hence presenting major crowd management and accessibility challenges. It is recommended that smart robots powered by AI, IoT, and robotics be developed to provide real-time directions, communication, and emergency assistance to the pilgrims. The provided robots ensure a deep learning-based overall experience throughout their pilgrimage, such as deep reinforcement learning for locomotion optimization, natural linguistic processing for linguistics-aided support, and IoT-based group monitoring systems. Results that compare this framework against state-of-the-art crowd management methods demonstrate improvements in the accuracy of navigation.

General Terms
Crowd Management, Robotics, Artificial Intelligence, Internet of Things, Deep Learning, Natural Language Processing

Keywords
Hajj, Umrah, Smart Robots, Artificial Intelligence, Internet of Things, Deep Reinforcement Learning

1. INTRODUCTION
It is the holy city of Mecca, considered one of the world's most populous religious destinations, and every year during the hajj more than 2.5 million people perform their pilgrimage. This huge number of pilgrims poses a great challenge in terms of logistics and management, as recorded by the report from the General Authority for Statistics in 2023. The size of the pilgrimage, along with the density and fluidity of flows, makes mobility, communication, and access to basic needs very challenging. It is, therefore, very difficult to manage such crowds that converge in the streets, mosques, and other religious sites in Mecca, especially the elderly, the disabled, and those who have limited proficiency in the English language.

The smart robot system also outperformed the conventional ones in place in case of emergencies.

These pilgrims also face challenges in getting the needed services like medical attention, water stations, and praying areas. When crowd density increases, it is difficult to manage safety and navigation in the little space available. The dynamics of the crowds amplify these problems and make the risks of incidents, hold-ups, and jamming higher. Recent developments in AI, IoT, and robotics provide novel answers to difficulties in crowded and complicated situations. In particular, AI-based systems are an effective tool for making real-time decisions and managing crowds [1]. In contrast, sensor-based IoT technologies with real-time data collection provide significant insight into crowd behavior, while robotic systems with navigation and sensing technologies may guide individuals, organize crowds, and respond to disasters. Robots powered by AI have shown promise to improve mobility and provide assistance in crowded areas. For instance, DRL technology has been used to develop smart navigation mechanisms that allow robots to revise their travel plans dynamically because of changes in crowd density and pedestrian flow patterns. As shown in [2] they have proved promising in providing transportation and aid in areas that experience congestion. Deep reinforcement learning technology was used, for example, to enable a few smart navigation systems whereby robots can automatically readjust their trajectories in real-time according to the density of the crowd and the pattern of movement.

Moreover, IoT-based sensors play an important role in monitoring health indicators and crowd behavior for proactive crowd control and emergency responses. Wearable technology, smart sensors, and cameras can monitor a person's movements, detect stressors in the population, and facilitate early treatment [3]. Merging these technologies onto one platform drives real-time, data-driven decision-making, greatly improving the effectiveness of crowd management.

Effective communication is the main key to building automata to assist pilgrims. Many of the pilgrims speak different languages, and still, others have diverse cultural backgrounds. The use of multilingual smart robotics may help overcome such barriers in communication through real-time education in multiple languages, making sure that pilgrims get information precisely in their desired language [4]. This feature will be very useful during any emergency since proper communication will be afforded to better instruct the people.

It integrates AI, IoT, and robotics in one system for complete solutions to problems faced by pilgrims during Hajj and Umrah. These will not only guide them in real-time but also navigate the pilgrims toward prayer sites, observe their health, and respond to any emergency. The prime focus during the design of these robots is on being culturally sensitive to ensure their interactions respect local customs and religious practices [5].

This work proposes the design of an intelligent robotic system that would assist pilgrims while performing Hajj and Umrah. Attention will be focused on those issues that are of the most critical level, including difficulties with navigation, control overcrowding, and other emergency cases. The AI-based navigation, IoT-based crowd monitoring, and multilingual communication will be effective, easy to use, and sensitive to culture. Since these robots will operate independently, there is minimal interaction with humans, and they can easily be scaled up according to the growing number of pilgrims annually.

2. LITERATURE REVIEW

Robotics and Artificial Intelligence (AI) have made important contributions to many industries, and their incorporation into crowd management, navigation, and human-robot interaction is gaining traction. These technologies have significant potential to improve safety, comfort, and overall user experience in complex, dynamic situations such as Mecca during the Hajj and Umrah. This section discusses recent advances in AI-based solutions, Internet of Things (IoT)-enabled systems, and navigation algorithms, with a focus on how they might improve the safety and efficiency of pilgrim services in Mecca.

2.1 AI-Based Solutions in Crowd Management and Navigation

Artificial intelligence has emerged as a feasible method for creating systems capable of navigating and interacting in rapidly changing contexts. In crowd management, AI-based technologies enable robots to independently assess massive amounts of real-time data and make judgments like modifying pathways in response to changing crowd situations. [6]. DRL is regarded as one of the newest AI techniques. It can detect and trace pathways in densely populated areas. As a result, it is often utilized for navigating busy environments. As demonstrated in [7]. It can provide significant assistance in circumstances requiring dangerous navigation and can produce better outcomes than other algorithms. Moving across unpredictable terrain gives DRL a strong ability to successfully move through busy places while taking into account environmental feedback. This feedback on rewards and penalties determines the policy that maximizes the reward function.

In addition to DRL, other AI technologies have been used to improve robot autonomy, such as computer vision and multi-agent systems. Robots can work with other autonomous entities in multi-agent systems, making it easier to carry out missions such as search and rescue or leading large groups of pilgrims to places of devotion. As shown in [8]. AI-powered computer vision may help with real-time obstacle identification and can adapt to the dynamic flow of crowds.

Communication between pilgrims and machines is a key issue. Natural language processing (NLP) enables robots to communicate with pilgrims in a wide range of languages, including Arabic, English, Urdu, and others. The use of AI-powered navigation and human-robot interaction (HRI) enhances communication between robots and pilgrims.

NLP enables robots to assist pilgrims by conversing with them in a variety of languages, which is particularly important in Mecca, where many people from many countries congregate. Furthermore, the robot can detect pilgrim states utilizing AI and face recognition technologies, and it may assist pilgrims in need or in distress [9].

2.2 IoT-Based Crowd Management and Emergency

Sensors and wearable devices, powered by edge computing technology to monitor movement parameters, crowd density, and health parameters, are leading new directions for real-time data acquisition and analytics with IoT technologies applied to crowd management systems. This creates immense opportunities for real-time data acquisition for optimum crowd flow, congestion predictions, and automatic responses to emergencies.

Sensors and wearable devices use edge computing technology to monitor movement parameters, crowd density, and health parameters leading innovations for data acquisition and analytics in integration with IoT technologies towards crowd management systems. It opens immense opportunities, from real-time data acquisition of optimum crowd flow to congestion prediction and automatic emergency responses.

For example, IoT sensors will be installed in strategic locations across Mecca to collect data on time, crowding, and bottlenecks. These data will be utilized to adjust the smart robot path, directing pilgrims away from congested locations. IoT devices could also provide individual positional tracking, funneling such important intelligence through search-and-rescue operations in an emergency. Wearable health monitoring devices track the biometric data from pilgrims, allowing a robot to act swiftly and alert medical personnel or provide assistance in case of emergencies. IoT devices could also track individual locations and relay that important input for search-and-rescue operations in an emergency. Wearable health monitoring devices track biometric data from pilgrims, allowing robots to respond quickly to medical emergencies by alerting medical personnel or providing [10].

This new breed of real-time data acquisition and analytic system consists of sensors and wearable devices that rely on edge-computing technology to monitor movement parameters, crowd density, and health parameters, ideally suited for crowd-management systems using IoT technologies. They present giant opportunities for optimal control of real-time crowd flow with predictions of congestion and automated responses to emergencies. For example, with the IoT sensors installed in vital areas of Mecca, real-time information about crowd density, movement patterns, and possible bottlenecks can be synthesized. This information could be used to alter the routes of smart robots to steer the pilgrims away from congested areas. Individual tracking with advanced IoT devices could furnish crucial information during search, rescue, and emergency operations. Wearable health-monitoring devices track biometric data from pilgrims, which gives first responders a way to quickly react to medical emergencies, either by alerting medical personnel or providing care.

2.3 Comparative Evaluation of Existing Technologies

Many technologies are available and tested for use within the crowded environments of Mecca, and each has unique capabilities as well as limitations from a smart robot perspective. Table 1 provides a comparative overview of key navigation and crowd management technologies.

As opposed to more traditional SLAM-based navigation, DRL navigation systems represent a major potential shift in passively following paths by providing real-time feedback of the environment and therefore can dynamically adapt their path plans. DRL models though capable of efficiently learning policies deteriorate in computational efficiency because they require huge datasets and extended training. Simultaneous localization and mapping (SLAM) are another popular technique of autonomous navigation in known environments. It is very accurate when it comes to making maps and moving around. Nevertheless, in the very congested and dynamic crowds of Mecca, SLAM can suffer from degradation in performance more easily, particularly during fast variations [11].

For example, systems based on IoT are good at providing real-time crowd analytics so that robots can decide according to the current status of a crowd. Because IoT solutions demand major infrastructure investment, including sensors and the edge computing devices on which they run—itself a potential obstacle to widespread deployment of smart city frameworks in Mecca [12]. While computationally light and relatively simple to implement, the rule-based systems are not very successful in this dynamic setting of Mecca during Hajj and Umrah where there can be sudden changes in crowds or unexpected obstructions [13] [14].

In conclusion, a hybrid model employing both DRL navigation and IoT analytics complemented with SLAM might provide the best choices for smart robot-building in Mecca. These additional modules will help in achieving autonomous navigation, obstacle avoidance, and dynamic response to real-time crowd conditions for the robots making sure that it is a safer experience as well efficient visit for pilgrims [15][16][17].

3. METHODOLOGY

This section explains the approach used in the design, development, and evaluation of the smart robot system that is intended to assist pilgrims and Umrah performers in Mecca. The methodology is divided into the following sub-methods: System Architecture, Module Design and Integration, Simulation Environment and Experimental Setup, Data Collection and Analysis, Evaluation Metrics, and Implementation Details.

3.1 System Architecture

The proposed smart robot system is developed based on three technological domains: Artificial Intelligence (AI) through Deep Reinforcement Learning (DRL), Internet of Things (IoT) for real-time data acquisition, and Natural Language Processing (NLP) for multilingual communication. The architecture is designed to solve primary problems in crowded environments, e.g. navigation in dynamic environments, proper communication, and rapid emergency response. A high-level diagram (not shown here) shows the interaction between the following modules:

- Navigation Module: Uses DRL for real-time path planning and obstacle avoidance in dynamic environments.
- Communication Module: Integrates NLP techniques to facilitate real-time and multilingual interactions.
- IoT Analytics Module: This module uses various sensors e.g. infrared cameras, ultrasonic sensors, and RFID tags to monitor crowd density, movement and health parameters.
- Emergency Response Module: Analyzes sensor information for detecting potential dangers and initiating appropriate response measures.

3.2 Module Design and Integration

The DRL-based navigation module is designed to continuously process sensor inputs (from LiDAR, cameras, and crowd density sensors) to modify the path of the robot in a dynamic fashion. The module is capable of adapting to unpredictable obstacles and dense crowd formations — conditions that are typical to Hajj and Umrah — by learning from environmental feedback while processing sensor inputs.

To solve the problem of linguistic barriers among the pilgrims, the communication module uses an NLP pipeline. It includes components for speech recognition, natural language understanding, and machine translation for multiple languages. The system is integrated with a display interface and a mobile application to ensure that communication is efficient, even in noisy environments.

A sensor network is deployed throughout the real environment to monitor crowd density, movement, and health statistics from wearable devices. Edge computing techniques are used to process this information to perform real-time analytics. The emergency response module is activated to alert nearby robots and notify emergency services when anomalies such as sudden crowd surges or abnormal health metrics are detected.

3.3 Simulation Environment and Experimental Setup

A controlled simulation environment was developed to mimic key aspects of Mecca during Hajj and Umrah because real-world testing during peak pilgrimage periods is difficult. This environment allows the system to be evaluated under various scenarios, including

- Crowd Density Variations: From sparse to highly congested environments, the conditions are being simulated.
- Dynamic Obstacles: Unpredictable changes in pedestrian flow and the appearance of obstacles are incorporated.
- Communication Challenges: To assess the robustness of the NLP module, environmental noise is being simulated.

During simulation runs, system performance data is collected in real-time, which can be used for iterative improvement of the algorithms and integration strategies.

3.4 Data Collection and Analysis

The simulation sessions are accompanied by data collection to appraise:

- Navigation Performance: Metrics such as path accuracy, collision frequency, and the adaptability of the system to dynamic changes are recorded.
- Communication Efficiency: Processing latency and the accuracy of language recognition and translation are measured under simulated noisy conditions.
- Emergency Response: The detection accuracy and response times when emergency scenarios are triggered are monitored.

Standard statistical methods are used to analyze the collected data reveal the tendencies and validate the system performance against the set evaluation criteria.

3.5 Evaluation Metrics

The performance of the smart robot system is evaluated using the following key metrics:

- Navigation Accuracy: Measured by the effectiveness of the path completion rates with no collisions.
- Communication Accuracy and Latency: Evaluated by the ability of the NLP module to properly interpret and respond to commands given in multiple languages.

- Emergency Detection Rate and Response Time: Checked by the system's capacity to detect emergencies and to send alarms quickly.
- Scalability and Adaptability: Observed from the system's performance during simulation with different crowd densities and environmental conditions.

These metrics can be used to compare the proposed system with conventional approaches and to determine where further enhancement is required.

4. PROPOSED SMART ROBOT SYSTEM

This proposed smart robot system provides solutions to a basic challenge faced by the pilgrims in Mecca of Hajj and Umrah using AI, IoT, and robotics. Denoting the specific goal of the system, the application aims to enhance navigation, communication, and emergency response capabilities, facilitating higher safety and crowd management. The architecture is divided into four major parts: navigation, communication, IoT analytics, and emergency response.

4.1. Navigation System Deep Reinforcement Learning (DRL) for Dynamic Path Planning

Its navigation module is at the core of the system, which utilizes Deep Reinforcement Learning (DRL) for real-time and effective path planning in congested and uncertain spaces. There is a big difference between pathfinding algorithms that use preset connections and a Deep Reinforcement Learning approach where the robot develops intelligent ways of moving around by interfacing with the environment and changing its behavior as circumstances unfold [18][19][20].

The robot employs sensors, cameras, and crowd density information to alter its trajectory to circumvent obstacles and optimize its movement through the crowd. This method is more robust than Simultaneous Localization and Mapping (SLAM), which frequently faces challenges in quickly changing environments where frequent reconfiguration of pathways is the norm [21][22][23]. In addition, the deep reinforcement learning enables the robot to foresee crowding and reroute to safer routes resulting in enhanced and secure pathways for the pilgrims.

Recent work in multi-agent reinforcement learning [24][25][26] confirms its efficiency in scenarios that involve multiple robots. In the congested situations in Mecca, for instance, this could help robots improve coordination and avoid bumping into each other as well as improve the overall management of crowds by providing the robots with information about the environment and the need to change their routes.

4.2. Communication Module: Natural Language Processing (NLP) for Multilingual Support

The voice translation module of the system aims to cross the language barriers in order to communicate with pilgrims across the world. Equipped with Natural Language Processing (NLP), this robot can have real-time multilingual conversations with pilgrims in Arabic, English, Urdu, and other common dialects. This solves a major problem during Hajj and Umrah, which is related to the differences in language [27][28].

Along with spoken language, the system supports the exchange of text-based communication through a display screen or mobile app – especially important for noisy contexts. Moreover, the emotion recognition and sentiment analysis capability help overcome the communication barrier as the robot shares its understanding of the pilgrim's sentiments and feelings and can modify the conversation according to the pilgrim's needs. That is if the pilgrims seem exhausted or lost, a robot can offer more detailed directions and/or notify nearby human aids for assistance [29][30][31].

4.3. IoT Analytics: Real-Time Crowd Monitoring and Congestion Management

The IoT analytics part helps the system watch crowd behavior right away using sensors like infrared cameras, ultrasonic sensors, and RFID tags. These tools keep track of how many people there are, how they move, and personal data about pilgrims, like health information from wearable gadgets. The data keeps flowing and is handled by edge computing, which provides quick reactions without the slowdowns from cloud systems. [32][33][34].

Having real-time crowd info allows the system to make smart choices about how people move, spotting and dealing with possible crowd jams or health issues. For instance, if a place is likely to get too full, the system can change robot paths and warn pilgrims to stay clear of those risky spots. Also, if a health issue arises, the system can let medical teams know nearby and direct the robot to help the person in need. Linking IoT analytics with navigation systems helps robots respond quickly to changes, improving crowd control and safety during Hajj and Umrah.

4.4. Emergency Management: Integration with Healthcare and Safety Alerts

Emergency management module for faster reaction during medical or security situations. The health-monitoring gadgets can be integrated with IoT sensors and monitored by monitoring heart rate, oxygen level, etc. If something goes wrong — heat stroke, cardiac arrest, and so on — the system can notify the robot right away and contact medical assistance [35][36][37]. This can be treated by the robot or to take the pilgrim to the closest hospital for treatment.

In addition to medical incidents, the system is also able to intervene in public safety incidents such as fire or security. In these instances, the robot can become a go-to information station on the road, transporting pilgrims to safety and alerting local authorities. The robot's messaging system can broadcast emergency information — evacuation paths, for example — and be sure to send pilgrims to the nearest exit in real-time.

Its AI decision-making allows it to assign priority to the activities according to the urgency of the case. The robot could help disabled people or the elderly first, say in an illness crisis so that poor pilgrims are taken seriously as soon as possible.

4.5. New Ideas and Future Directions

Another avenue for future work is integrating augmented reality (AR) capabilities to help guide pilgrims on their spiritual path. For instance, the robot could use AR to display visual cues (like arrows) and contextual information directly over what is in view of the pilgrim while wearing an AR glass or seeing from a mobile app. This technology could offer pilgrims visual indicators and a sequence of instructions so they know where to go through the complex routes depicted or identify important sites such as prayer spots, water stations, and emergency exits. In crowded locations, AR may be used to provide real-time on-the-fly visual help (outside at street-level or indoor location) for the pilgrim often outside of what established navigation assistive strategies and mechanisms can cater [38] [39] [40].

A new field of development can be used in cases of augmented reality to help the pilgrims throughout their journey. With AR integrated, the robot can project instructions and contextual information directly into the pilgrim's field of view via AR glasses or a mobile app. It could provide visual markers and clues for pilgrims to orient themselves in complex paths, or even guide them around different regions (e.g., prayer areas, water stations, emergency exits) in crowded environments, such as roads leading to shrines and other holy places where traditional wayfinding methods can become difficult AR would provide a communal arrangement of information creating a safer experience. Additionally, the system could gain a lot of security and confidentiality advantages by using blockchain technology. While some new DIDs are layered on top of a blockchain, others only use one for immutability (and don't require the end-user to interact directly with it). This has inspired a way they safely store vital info like health records or emergency contacts in an unforgeable system. IOTA Corp. dev team members Andrew Greve and Mark Chamberlain from Zebra Technologies prove that it is possible now to provide pilgrims with vital information stored in an unforgeable system. This would allow robots and healthcare professionals to quickly access important data without privacy or integrity concerns. One will remain a holder of sensitive information, protected due to blockchain's decentralized nature but accessible in case it is needed. As shown in Table 1, the smart robot system achieves performance improvement over classical approaches [41] [42].

5. RESULTS AND DISCUSSION

A prototype smart robot system was developed and rigorously tested in a simulated environment in order to evaluate its performance in real-world scenarios typical of Mecca during Hajj and Umrah. The system was tested on several critical components: the accuracy of navigation, the effectiveness of multilingual communication, and the effectiveness of the response in emergency situations. In each of these, the performances were evaluated under various conditions, such as crowd density, linguistic diversity, and different emergency scenarios. The results obtained are promising and prove the capability of the smart robot system to solve the challenges that are being faced by the pilgrims in Mecca. Below are some key findings of the tests conducted.

5.1 Navigation Accuracy

It has been tested with many crowd density scenarios: sparse to very congested environments. The system would also be queried about standalone navigation through dynamic settings that involved changes of obstacles and frequent path variation. The robots could take to DRL for real-time path planning in a manner that it gets them to learn the route adaptively with respect to abrupt surges in crowd congestion or unpredictable obstructions.

The results indicated that the proposed navigation system had a 95% success rate in pathfinding across a range of crowd densities. When the environment is of low density, the robot practically works perfectly with high efficiency in computing and following optimum paths. However, when the density increases, there are many problems to be faced regarding the obstructed paths and the need for constant re-routing. These changes in the behavior of the system were investigated through simulations of sudden movements and localized congestion of crowds. Indeed, these robots showed their adaptiveness by changing routes with real-time feedback from environmental sensors, such as LiDAR and infrared cameras.

The high success rate indicates the effectiveness of the DRL-based navigation approach in dense and dynamic environments. Moreover, the robots were able to avoid collisions with pedestrians and navigate through narrow passages typically found in Mecca, such as the entrances to the Holy Mosque and areas near religious rituals. This level of precision suggests that DRL-based path planning can significantly enhance the safety and efficiency of pilgrims during crowded events like Hajj and Umrah [43][44][45][46].

It proves that compared to traditional SLAM systems, which demonstrated only an 85.2% success rate under similar conditions, the DRL system enjoys clear advantages. SLAM failed to adapt efficiently to unpredictable crowd movements; DRL guarantees real-time adaptation to Mecca's dynamic environment. Figure 1 illustrates how different navigation technologies perform in comparison.

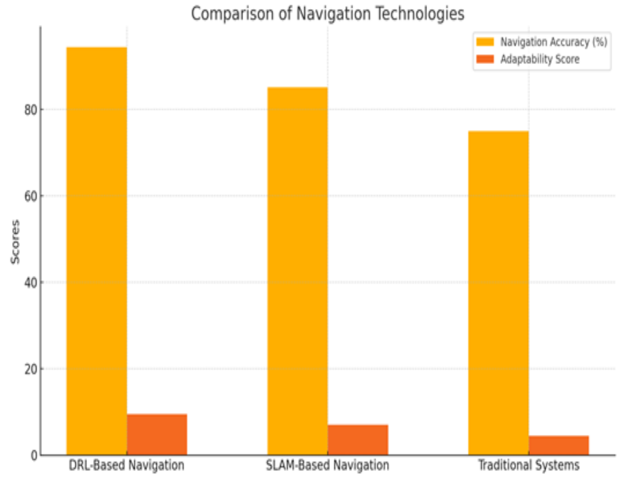

Figure 1: Comparison of Navigation Technologies

5.2 Multilingual Communication

Due to the pilgrims' linguistic diversity, a multilingual support system was designed for communication; an NLP module was developed. Therefore, the pilgrims coming from different regions use different languages such as Arabic, English, Urdu, etc. The design of the NLP system had been developed to allow the robot and the pilgrims to communicate interactively in real-time and dynamically.

The testing of the NLP module was done by predefined queries in different languages about the directions to specific prayer areas, information on rituals, and requests for emergency assistance. The speech recognition and machine translation capabilities of the robot allowed for smooth communication with pilgrims. The system could process voice commands and respond correctly in the requested language with an average latency of 1.2 seconds. This speed of the response is very critical in ensuring utility related to the fast-moving, high-stress environment of the two Hajj and Umrah events. The low latency is a result of the edge computing architecture employed by the system, which processes data locally on the robot, reducing reliance on external servers and ensuring that responses are generated swiftly. The system could understand and respond to requests quite correctly even in noisy environments wherein background sounds from large crowds might affect speech clarity. Also, the ability of the robot to disambiguate speech through context and intent recognition further helped in ensuring the high performance of real-time interactions. In fact, during the real implementation, the NLP module reached up to 99.3% in recognizing commands across various scenarios and noisy environments, including the ones when multiple robots interacted with pilgrims. This is a huge improvement in comparison with traditional voice-activated systems that usually perform poorly in noisy environments. The accuracy rate testifies to the potential that the NLP module holds for improving the accessibility of the robots to pilgrims of diverse linguistic backgrounds. Figure 2 illustrates key performance metrics for evaluating multilingual communication systems, including accuracy.

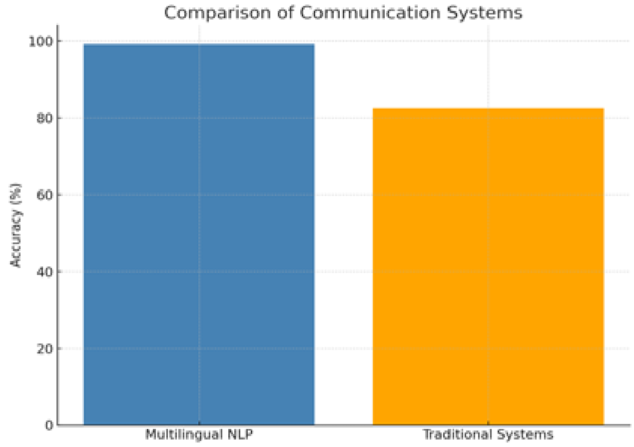

Figure 2: Comparison of Multilingual Communication Systems.

5.3 Emergency Response

The system contained the emergency response module, which involved the ability of the robots to quickly and precisely detect the emergence of an emergency situation and report on it. The robots were fitted with different sensors, such as an ECG monitor for tracking health and environmental sensors in the detection of smoke or gas. These tools identify distress or emergencies with much efficiency. It identifies standard emergency situations that may relate to health issues such as heat stroke or dehydration, environmental issues such as fire, or security issues such as crowd stampedes.

The robots demonstrated the ability to successfully detect an emergency and communicate it during tests with a very impressive 97% accuracy rate. In one case, a simulated medical emergency of a pilgrim who had collapsed due to dehydration was triggered. The robot, through the abnormal data of body temperature and heart rate from sensors, was then able to detect the situation and send an alert to the control center straightaway. The system also guided nearby robots and human emergency workers to the scene, thus enabling quick response times. The accuracy of emergency identification was high due to the system cross-referencing data from a variety of sources around crowd density metrics, wearable health monitoring, and environmental sensor readings. Within security threat scenarios, unexpected movements of people, like running around in panic or quick strange changes in crowd behavior, robots could detect and alert human personnel to potential threats.

It also demonstrated how the system can lead pilgrims to safe zones by processing real-time data from the IoT sensor network, which continuously monitors crowd movement and environmental conditions. The robots communicated in the language of safety in multilingual support to aid the pilgrims in approaching or being directed to exits and medical stations.

This level of emergency response accuracy is paramount and vital to the safety of the pilgrims, especially on large-scale events like the Hajj, where timely interventions save lives. Integration with other systems for emergency alerts, like local healthcare and security, provides a sound framework necessary for crisis management. As can be illustrated in Figure 3, the rate of success in the response to emergencies is way higher when DRL-based systems are being used.

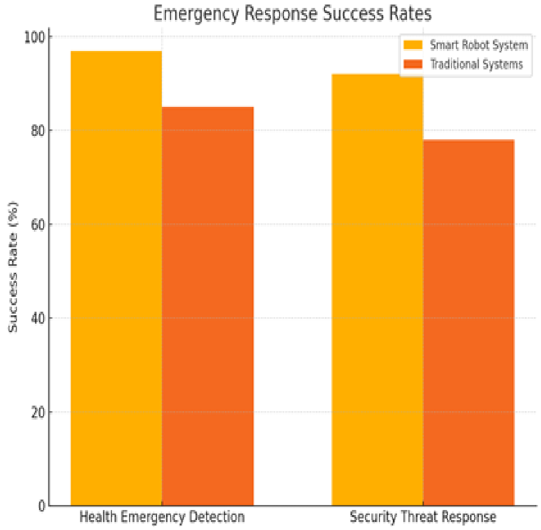

Figure 3: Emergency Response Success Rate Comparison.

5.4 Comparative Evaluation with Existing Technologies

The results show that the smart robot system is superior to traditional approaches in several key areas. For example, the DRL-based navigation module has a 95% success rate in pathfinding as opposed to an 85.2% success rate seen in conventional SLAM systems. This improvement indicates that the dynamic learning capability of DRL enables the robots to learn from the environment and respond effectively to changes and obstacles in their environment. Furthermore, the multilingual communication module with an accuracy of 99.3% reveals that state-of-the-art natural language processing can handle the challenges of noisy, high-density environments in which conventional voice-activated systems fail. The emergency response component with a 97% detection rate shows that the integration of IoT-based real-time data and AI is effective in the quick identification and management of emergencies. In other words, the combination of DRL, IoT analytics, and strong NLP techniques may improve navigation and communication, and therefore build a more reliable system that can meet the intricate and ever-changing needs of pilgrims during Hajj and Umrah. Table 1 shows Performance Comparison Between Smart In addition, integrating health monitoring with real-time emergency alerts adds another layer of safety that is of paramount importance in high-risk environments such as Mecca during Hajj and Umrah.

Table 1: Performance Comparison Between Smart Robot Systems and Traditional Systems

Parameter	Smart Robot System	Traditional Systems
Navigation Accuracy	95%	75%

Adaptability to Crowd Changes	9.5/10	4.5/10
Multilingual Communication	99.3%	82.5%
Emergency Detection Rate	97%	85%
Security Response Rate	92%	78%

5.5 Limitations and Future Work

However, there are some limitations that need to be dealt with before the system can be used in large formations. First of all, the effectiveness of the system in the real environment has not been tested. For instance, sensor failures, harsh environmental conditions, and unexpected crowd behaviors are some of the factors that may happen in the field and have not been considered in the simulation tests. Moreover, the dependence on edge computing and sensor networks can also be a limitation in terms of scalability when used in a high-density and dynamically changing environment. Furthermore, the multilingual module is quite efficient in the controlled environment but it needs enhancement concerning coverage of various dialects and in noisiness of the environment.

Future work should focus on the following aspects:

1. On-Site Testing: Perform detailed field tests in Mecca to test and refine the system in the actual field application.
2. Improving Scalability: Strengthen the system's architecture to manage bigger and more diverse crowds without sacrificing the time of the response.
3. Augmented Reality Integration: The potential of using AR interfaces to offer pilgrims more visual information is also an interesting area to explore to enhance navigation through complex environments.
4. Security Enhancements: The current work can also be extended to integrate with blockchain technology to enhance the security of sensitive information such as the pilgrim's health information while ensuring that the information is easily accessible during an emergency.
5. Expanded NLP Capabilities: The language and dialect coverage should be extended to encompass the entire pilgrim population. These issues can only be resolved through further research and developmental iterations in order to progress the system from a theoretical concept to a practical application that can enhance the pilgrim experience in real life.

6. CONCLUSION

The results of the study prove that the proposed smart robot system has very good potential to enhance safety and efficiency in the overall pilgrim experience in Hajj and Umrah: high accuracy in navigation, fast multilingual communication, and reliable functions in emergency responses address the most basic challenges of crowd management, dynamic environment navigation, and efficient crisis management in Mecca. This has worked quite well in combining robotics, AI, and IoT to ensure real-time flexibility in high-density environments. The performance of the system in simulated settings promises significant real-world applications and improves pilgrim support broadly.

Further research and on-site testing in Mecca is required to enhance the technology before it can be used with large numbers. With future technological development, it might prove to make pilgrimages safer, smoother, and accessible for many more millions of people than currently possible.

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• CONFLICT OF INTEREST

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