IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received October 11, 2020, accepted November 3, 2020, date of publication November 11, 2020, date of current version December 1, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.3037396*

# Digital Revolution for Hajj Crowd Management: A Technology Survey

**EMAD A. FELEMBAN[1], (Senior Member, IEEE), FAIZAN UR REHMAN[2], (Member, IEEE), SARDAR ASAD ALI BIABANI[3], AKHLAQ AHMAD[4], (Member, IEEE), ATIF NASEER[3], ABDUR RAHMAN MUHAMMAD ABDUL MAJID[4], OMAR K. HUSSAIN[4], AHMAD MUAZ QAMAR[2], ROWID FALEMBAN[4], AND FAKHRI ZANJIR[5]**

[1]Computer Engineering Department, College of Computing and Information Systems, Umm Al-Qura University, Makkah 24382, Saudi Arabia
[2]Institute of Consulting Research and Studies, Umm Al-Qura University, Makkah 24382, Saudi Arabia
[3]Science and Technology Unit, Umm Al-Qura University, Makkah 24382, Saudi Arabia
[4]Deanship of Scientific Research, Umm Al-Qura University, Makkah 24382, Saudi Arabia
[5]LIG, University of Grenoble Alpes, 38400 Grenoble, France

Corresponding author: Emad A. Felemban (eafelemban@uqu.edu.sa)

This work was supported in part by the Deputyship for Research & Innovation, Ministry of Education, Saudi Arabia, through project number 0909.

**ABSTRACT** Hajj, the annual pilgrimage to Makkah, is one of the most massive gathering events in the world. It is a mandatory religious activity, once in a lifetime for every sane well-off Muslim. Every year around 3 million Muslims across the globe visit Makkah to perform this spatiotemporally constrained set of religious activities, like circumambulation around the Kaaba and the encampment at Mina, Arafat and Muzdalifah. The key ritual at Rami-al-Jamarat (the stoning-of-the-pillars) is a place seen particularly crowded. The diversified nature of the crowd in terms of race, age, language and culture brings several administrative challenges for local organizers whose responsibility is to ensure the smooth organization of the event. The advent of digital technologies has helped researchers to explore and propose modern methods for better crowd management and devise control strategies to organize such a mass gathering. In this paper, we present a taxonomy that summarizes our survey on the utilization of technology areas for providing needful services and improving crowd management during the Hajj season. These technologies are Wireless, Computer Vision, Spatial Computing, Data Analytics, Mobile Applications, Immersive Technologies, and Crowd Modelling and Simulation. We have also included the current research work and its implementation plan for Hajj 2020. One dimension of the taxonomy is to understand different possible technologies for Crowd management. Another dimension is to understand the impact of technologies to handle such a massive crowd. The discussion section covers a comparison of technologies with multiple aspects that may help researchers to contribute more towards dealing with future mass gathering events.

**INDEX TERMS** Hajj, crowd management, mass gatherings, large events, technology review.

## I. INTRODUCTION

Hajj, the fifth pillar of Islam, is an annual Islamic pilgrimage to the sacred city of Makkah, located in Saudi Arabia. It is performed in the 12$^{th}$ month (Zulhijjah[1]- the month of the pilgrimage) of the Islamic Lunar calendar[2] [1], [2]. It is a mandatory religious activity, to be performed once in life by every sane adult Muslim, who can afford it and is physically fit. Once pilgrims from all over the world reach [2] the vicinity of the holy city of Makkah, they become bounded by certain religious obligations. They are required to perform a series of Hajj rituals which are spatial and temporal in nature. Fig 1 shows the different spatial zones, where pilgrims are required to perform Hajj rituals within the duration of a week. These spatial zones are Masjid Al Haram (the Grand Mosque), Mina, Muzdalifah, Arafat (three plains in and around Makkah where the pilgrims encamp for the whole week or so). Hajj rituals are spatially strict, however, in some cases they may be temporally relaxed, but all rituals must be completed within six days (8$^{th}$ to 13$^{th}$ day of Zulhijjah). Fig 1 shows pilgrims' five days' activities while they perform the Hajj rituals within different spatial zones. On the first day of Hajj, (8$^{th}$ day of Zulhijjah), pilgrims wear special clothes called Ihram and go to Mina where they stay for a day and night. The next day (day 2 – 9$^{th}$ day of Zulhijjah), early in the

The associate editor coordinating the review of this manuscript and approving it for publication was Utku Kose.

[1]https://en.wikipedia.org/wiki/Dhu_al-Hijjah
[2]https://www.islamicfinder.org/islamic-calendar/


**FIGURE 1.** Spatial zones in the holy city of Makkah [2], Five days of Hajj – Pilgrims mobility.

morning, the pilgrims head towards the mountain of Arafat for a day of reflection and repentance. Pilgrims stay within the Arafat area for the entire day and after sunset, they start their journey back to Mina. On the way back to Mina, pilgrims stay overnight in the Muzdalifah area. On the next day, (day 3 – 10$^{th}$ day of Zulhijjah), also known as Yaum Al-Nahr (the day of Sacrifice), the pilgrims go to Jamarat al Aqaba, the first stoning pillar, and pelt it with seven pebbles. The ritual of stoning the Jamarat is called Rami-al-Jamarat.

For the next two days, pilgrims are required to repeat the Rami (stoning) twice (for a total of three-times in 3 days). After the stoning ritual, pilgrims are left with three main activities, namely, going to Masjid Al Haram to perform Tawaf and Sai, sacrificing the animal, shaving or trimming hair. Pilgrims can perform these three rituals during the remaining days of the Hajj. Most of the pilgrims prefer to perform these three rituals on the same day (day 3 – 10$^{th}$ day of Zulhijjah) however due to mobility schedules, many pilgrims complete these rituals on day 4 and day 5 (11$^{th}$ and 12$^{th}$ day of Zulhijjah). Some of the pilgrims complete their rituals in five days while others prefer to stay one extra day (day 6, 13$^{th}$ day of Zulhijjah).

Hajj is an example of a heterogeneous massive crowd where most of the pilgrims are attending the event for the first time in their lives and are hence very eager to comply with the spatiotemporal requirements of the ritual. The Saudi government, through the Ministry of Hajj and Umrah[3] as well as other departments and ministries, plans, implements, and monitors the entire Hajj event. It considers it as its duty to provide pilgrims with the best possible services, from their arrival in Makkah, till they return home. Keeping in mind spatial and temporal constraints, crowd diversity in terms of race-ethnicity, age, language and culture, the organizers have to face several administrative challenges [1]–[3]. Since it is the priority of the Saudi government to plan and execute the Hajj event in a smooth manner, authorities, organizers and researchers continuously investigate innovative ways and means for better crowd management and control strategies. New problems and solutions appear every year which are studied, analysed and improved upon during the next year.

This paper presents a taxonomy that summarizes our survey on the utilization of technology areas for providing required services and improving crowd management during the Hajj season. The taxonomy classifies crowd management technology areas into Wireless Systems, Computer Vision, Spatial Computing, Data Science, Mobile Application, Immersive Technologies, Crowd and Traffic Modelling and Simulation. Later, we present a discussion section that covers a comparison of technologies with multiple aspects, that may help researchers to contribute more to deal with future events.

After the introduction in Section I, crowd statistics and challenges are presented in Section II. Section III discusses in detail the state of advance technologies deployed during Hajj to deal with massive crowds. In Section IV, we summarise the current technologies that were deployed during the Hajj 2020 event. In Section V, we present the technologies proposed or used by researchers during the past Hajj events.

[3]https://www.haj.gov.sa/en

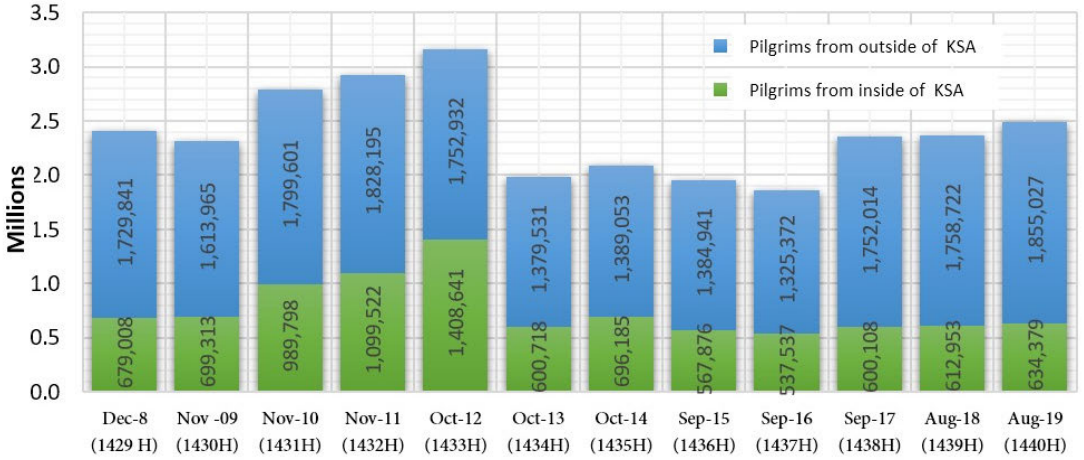



**FIGURE 2.** Pilgrims count over the past decade (2010 (1431-H) to 2019 (1440-H)). Green color is for pilgrims from inside Saudi Arabia and blue color is for international pilgrims.

Section VI is about the discussion that presents some graphical representation of our surveyed papers with the perspective of technologies proposed or used for the Hajj events. Finally, we conclude the survey and discuss future research approach.

## II. HAJJ CROWD STATISTICS AND CHALLENGES

Every year, only around 2 million Muslims out of a total population of 1.8 billion (0.11%) manage to perform Haj, mainly due to cost, physical capacity and time constraints [4]. Over the past 10 years, Saudi Arabia has hosted 23.97 million pilgrims from all over the world [5]. Fig 2 shows the pilgrim count for this period, with the blue part of the bars showing local pilgrims and the green part of the bars showing international pilgrims.

As per the General Authority for Statistics (GASTAT) Kingdom of Saudi Arabia,[4] the largest number of pilgrims were counted in the year 2012, when about 3.16 million performed the Hajj. The lowest recorded count in the last ten years was 1.98 million during the year 2016 [6] when the number of pilgrims were officially controlled due to expansion activities in the area. Table 1 gives an overview of the number of pilgrims during the Hajj 2019 event.

A major area of concern for large gatherings is crowd density, since it has a serious impact on crowd safety [7], [8]. In this context, pilgrims' mobility under spatio-temporal constraints during Hajj introduces different degrees of crowd density. Fig 3 shows a varying degree of pilgrims' crowd seen by the human eye while they perform Hajj rituals. Fig. 3 (a) represents a moderate crowd that can be considered safe. Fig 3 (b) is depicts an overcrowding scenario and requires attention. Fig 3 (c) and Fig 3 (d) show a very dense crowd with a serious threat to public safety [9] that can result in stampedes like the one that happened during the stoning ritual in 2015 [10], or create a human catastrophe in case of fire or proliferation of a pandemic [10]–[13]. Considering all the challenges of the diversified crowd, the authorities connected with Hajj event are constantly working on their respective portfolios to understand, design, implement and provide the necessary services such as pilgrim identification, mobility tracking, navigation to points of interests, and health, to manage the Haj crowd in an efficient manner [1].

[4]https://www.stats.gov.sa/en

**TABLE 1.** Pilgrims count – Hajj 2019.

| Total Pilgrims - 2,489,406 | |
|---|---|
| **Internal Pilgrims** | |
| Male | 406,247 |
| Female | 228,132 |
| Total | 634,379 |
| **Foreign Pilgrims** | |
| Male | 978,987 |
| Female | 876,040 |
| Total | 1,855,027 |

## III. TAXONOMY

Fig 4 summarizes our proposed taxonomy that classifies the various technologies used in Hajj for crowd management. These technologies have been used to design and implement solutions by different researchers to facilitate the Hajj crowd. The taxonomy classifies crowd management technologies areas into Immersive Technologies, Wireless Systems, Computer Vision, Spatial Computing, Big Data Analytics, Mobile Application and Crowd and Traffic Modelling and Simulation.

**Immersive Technologies** emulate the physical world environment into a virtual world using wearable devices. The immersive technologies section is further classified into virtual reality, augmented reality and mixed reality.


**FIGURE 3.** Hajj Crowd, (a) Moderate crowd with no rush, (b) Possibility of overcrowding, the attention required, (c) Crowded, (d) Massive Crowded.

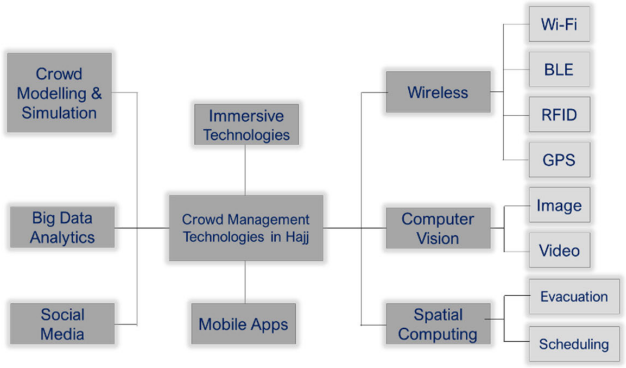



**FIGURE 4.** Taxonomy of Technologies used for Hajj.

**Wireless Systems** provide a ubiquitous platform where we can connect computing devices, and mechanical and digital machines with the ability to transfer data over the network without physical interaction. The Wireless section is categorized into Wireless Fidelity (Wi-Fi), Bluetooth Low Energy (BLE), and Radio Frequency Identification (RFID). The RFID section further discusses application areas such as monitoring, tracking, medical, transportation and location-based services.

The aspects of **Computer Vision** discussed herein are those which are mainly used for crowd management and crowd analytics using Artificial Intelligence based algorithms for image and video processing.

The **Spatial Computing** section discusses different frameworks and approaches for scheduling pilgrims' mobility and techniques for evacuation of large crowds. These are of great importance during Haj, especially in Mina, where around 3 million pilgrims have to stay for 4-5 days in a spatially restricted area.

**Social Media** platforms are in use where pilgrims actively communicate and share their Hajj experiences. Sometimes Hajj organizers utilize these platforms to disseminate useful information about Hajj activities.

The **Mobile Applications** section discusses popular mobile apps used to provide services during Hajj. This section mentions the top 10 downloaded apps in Hajj according to figures shown on Google play store.

The **Big Data Analytics** is used for Big data and multiple types of analytics. This section discusses research work related to it in the Hajj domain.

The **Crowd and Traffic Modelling and Simulation section** describes the process of simulating the movement of a massive crowd of humans or vehicles to understand their behaviour, such as the flow in the network and use it for prediction of future events. This section discusses crowd and traffic modelling and simulation that have been used in Hajj [14].

## IV. CURRENT TECHNOLOGIES

This section provides the list of technologies currently used in Hajj. Based on published research articles, spatial computing, crowd simulation, mobile applications and big data analytics are the areas that appear to be the most active for the last couple of years. The spatial computing and crowd simulation technology areas deal with activities performed mostly before Hajj to prepare the pilgrim movement schedule and to understand crowd dynamics.

### A. SPATIAL COMPUTING

Spatial computing is one of the areas related to managing the Hajj crowd while pilgrims move from one place to another to perform spatio-temporal Hajj rituals. It directly deals with scheduling pilgrims' movement within the holy sites such as Arafat, Mina, Muzdalifah and Jamarat and is done before the actual Hajj event. Organizing authorities try to ensure that that the scheduled plan is followed and may request rescheduling in case of unavoidable situations.

Haase *et al.*, [15] presented an operational research-based decision support system for crowd management. This system provided a scheduling tool and a real-time video tracking system (video-based counting system VBCS), to ensure an uncongested and smooth flow of pilgrims and provide real-time statistics for an early warning system. The system was proved to be effective in stopping the tragic loss of human lives and there was no massive disaster reported from 2007 to 2014.

Felemban *et al.* [16] presented a scheduling process to facilitate pilgrims' movement between holy sites, i.e., Mina, Muzdalifah and Arafat using trains. The optimised scheduling technique considers train movement plans, train capacity, train stations' capacity, roads allowed to/from camps-stations, road capacity, and pilgrims' camp locations

at source and destination sites. The algorithm has been used in Hajj 2019.

During Hajj, sometimes, due to unavoidable conditions or external environmental factors, such as heavy rain, authorities need immediate solutions to reschedule pilgrims' movement. Rehman and Felemban [17] developed an interactive tool that reads the change requests submitted by the authorities and efficiently provides updated schedules by accommodating all the new constraints. The tool allows stakeholders to reschedule the groups based on the pilgrims' temporal preferences to perform the stoning ritual in accordance with the safety parameters. The safety parameters make sure that rescheduling of the group does not violate the capacity of the road and the Jamarat floor. The tool has been used in Hajj 2019 by the Ministry of Hajj and Umrah to reschedule the pilgrims' movement before and during the Hajj event.

### B. CROWD MODELLING AND SIMULATION

Crowd modelling and simulation is done before Haj to understand the human dynamic behaviour from past years' experience using different modelling techniques.

Prof G. Keith was engaged with the Ministry of Hajj and Umrah from 2000 to 2005. He modelled the crowd dynamics on the Jamarat Bridge design [18] and at other large scale public assemblies in complex spaces. This work was carried out in 2003 for new bridge designs and presented an agent-based modelling tool that included extensive analysis of the existing Jamarat Bridge. The new, multi-tiered bridge changed crowd dynamics by providing 5 floor levels with various entry points, using ramps, lifts and escalators. The project was completed in 2004 and there were no accidents reported in the Hajj 2005 event.

### C. MOBILE APPLICATIONS

There are hundreds of applications developed for Hajj pilgrimage in different languages to perform different services such as rituals, navigation, translation, qibla direction, prayer times, weather, currency conversion and places of interest. The ritual service is a step-by-step guide to perform Hajj rituals, the navigation service is to find optimize path or quickest path from one location to another. Translation service helps to convert their native language into the Arabic language to communicate with local shopkeepers or taxi. The Qibla direction helps pilgrims to find the direction of the Kabah to perform their prayers. The prayer times shows the time of daily prayers based on their location. The weather applications show the weather of nearby cities such as Makkah, Madinah and Jeddah. The places of interest service helps pilgrims find nearby places such as restaurants, hotels, barber shops, currency conversion places and more. Below is a review of a few of the Hajj applications with more than 50,000 downloads and 4.5-5 ratings on Google play store (Table 2).

Hajj and Umrah [App1] is one of the most downloaded applications. It is available in English and Urdu language. The application provides Hajj and Umrah ritual service, supplications, prayer times, travel checklist, weather service, places of interest and currency conversion. The Android version of the application was downloaded more than 100,000 times.

Hajj and Umrah Guide Urdu [App2] provides a step-by-step guide to perform Hajj and Umrah rituals, along with the list of permitted and non-permitted tasks during the Hajj journey. The application is in Urdu language only.

Hajj Navigator [App3], Mina Locator [App6] and Almaqsad [App8] provide only navigation services. [App3] provides navigation in Makkah and Mina for different places of interest. [App6] provides navigation inside Mina area to locate camps, hospitals, mosques, etc.

[App3] is in English language only but [App6] supports Urdu and Arabic languages as well. [App8] provides indoor navigation inside Al-Haram mosque, Makkah, using BLE support in Arabic, English, French, Dutch and Urdu.

WeSalam – Hajj and Umrah guide [App4] and Manasikana [App5] are applications with lots of services and support multiple languages. [App4] provides Hajj, Umrah and Tawaf guide, supplications, prayer timings, complete Quran, navigation, places of interest, video tutorial (see Fig 5), and currency conversion services in Arabic, English, French, Urdu, Indonesian, Malay, Turkish, Russia, Hindi, Bengali languages.

Manasikana[5] [App5] is the official application by Ministry of Hajj and Umrah, Saudi Arabia and it provides supplications, prayer timings, qibla direction, weather, navigation, places of interest, contact us, currency conversion, Hajj tweets, Ministry messages services in English, Urdu, Arabic, Bengali, Turkish, Spanish, French, Indonesian, Malay Languages. The application uses highly accurate satellite-based maps of sacred areas to help pilgrims stay at the right place at the right time. The application helps pilgrims locate other fellow pilgrims in case they are lost and find a possible route to reach them.

Al-Haramain [App7] and Al-mutawf [App9] are the official applications launched by authorities in Saudi Arabia. Both the applications show the current crowd status of the Holy Mosques in Makkah and Madinah. Al-Harmain [App7] provides hajj and umrah ritual, supplication, prayer times, navigation, Q&A, live audio and video, contact us and available in Arabic, English and Urdu languages. The applications allow users to request for Itikaf (staying in the Holy Mosque in the last ten days of the holy month of Ramadhan), wheelchair, visiting permission to Kiswa (the cover for the Kaaba made from cloth) factory. The application provides a form to contact the general presidency of the Two Holy Mosque for complaint, suggestion, or any request.

Duas for Hajj and Umrah [App10] provides a list of supplications specific to different places in Mashaer area (spatial context) in Arabic and English. Fig 6 shows the summary of ratings of the above 10 applications based on their reviews on Google play store.

[5]https://www.haj.gov.sa/en/News/Details/12353

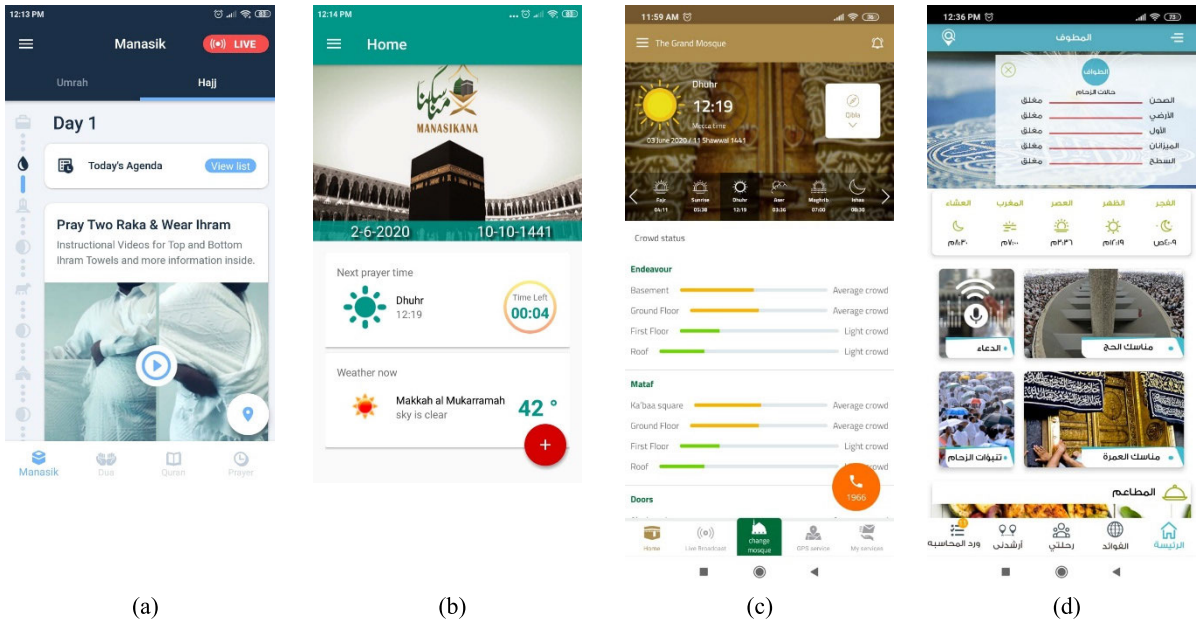



**FIGURE 5.** Screenshots of two applications a) WeSalam [App4] screenshot to perform Hajj rituals step-by-step b) Manasikana [App5] screenshot for prayer time, weather and emergency call along with Hijri and Georgian date, Screenshot of Apps showing crowd status along with prayer times maps live audio and video broadcast, c) Al-Haramain [App7], d) Al-mutawf [App9].

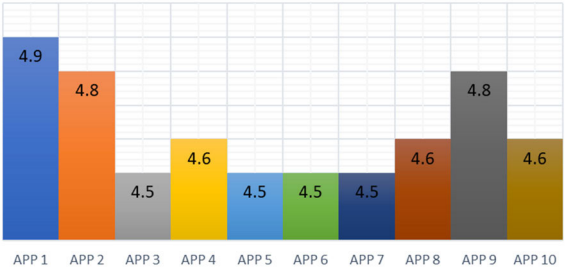



**FIGURE 6.** Ratings of the top 10 downloaded Hajj app in Google play store.

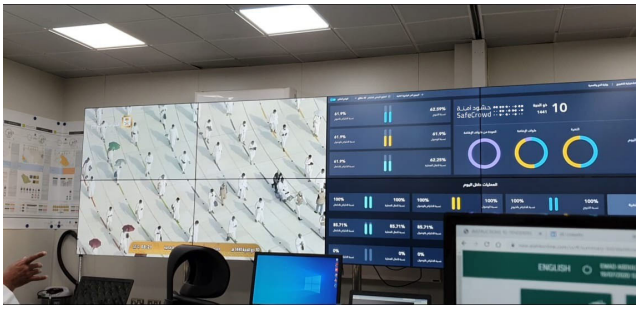


**FIGURE 7.** A Multi-Level Dashboard to Monitor Mobility Progress during Hajj 1441-2020 event [19].

### D. BIG DATA ANALYTICS

The Internet of things (IoT) provides a ubiquitous platform where a tremendous amount of data is generated when pilgrims connect with fellow pilgrims and available services through their smartphones and other communicating devices. A careful analysis of this communication data can help in understanding individual and group behaviour for better crowd management and planning.

Felemban [19] collaborated with the Ministry of Hajj and Umrah, Saudi Arabia and designed and implemented a simple dashboard for monitoring pilgrims' progress while they move through different holy sites during the Hajj 1441 (2020) event (Fig 7).

The deployed system collected data from two main sources, 1) Manually using walkie-talkies and 2) A mobile phone application that was distributed to group leaders. They reported "departure and arrival times" while moving between sites. The interactive dashboard helped in visualizing pilgrims, movement and other statistics during Hajj 2020 event. More than 300 major combinations of pilgrim movement one site to another were counted during the event in both space and time domains [19].

## V. TECHNOLOGIES PROPOSED AND USED IN THE PAST

In this section, we summarize the different crowd management technologies that were proposed and/or deployed during the past Hajj events. Fig 4 gives an overview of our proposed taxonomy for crowd management during the Hajj event, that has been categorized as per services design and proposed solutions.

### A. IMMERSIVE TECHNOLOGIES (IT)

Immersive Technology emulates the physical world inside a virtual environment by leveraging the 360-degree space. It integrates virtual contents with the users' physical environment and engages the users naturally with the blended reality. Being completely isolated from the rest of the world, the users experience virtual elements as a part of physical reality.[6]

[6]https://whatis.techtarget.com/definition/immersive-technology

Some common styles of immersive technology include video games (Virtual Reality-VR), Augmented Reality (AR), and Mixed Reality (MR). In this paper, we also present an overview of the use of immersive technologies contributing to Hajj activities and its benefits in this context.

#### 1) VIRTUAL REALITY TECHNOLOGY

The diversified nature of Hajj crowd in terms of different cultures, languages, literacy rate and ages, makes it difficult for the authorities to deliver information in an efficient manner. To address this, researchers have proposed solutions based on immersive technologies to provide necessary information and virtual training to pilgrims before their arrival for Hajj. The concept of Digital Hajj was presented in terms of virtual games to let users learn how to perform Tawaf and Umrah at the holy mosque of Makkah [20].

Muslim 3D [21] Labbaik [22] and many more applications[7] [23], [24] provide training for pilgrims via immersive virtual reality-powered tools and provide realistic tours of sacred sites and access to books for guidance.

Nassr *et al.* [25] developed a virtual reality-based mobile phone application for Hajj and found that pilgrims reported ease of use and enjoyment with their pilgrimage while they navigated their points of interests.

#### 2) AUGMENTED REALITY AND HAJJ

Augmented reality (AR) is a real-time direct or indirect view of the physical real-world that augments virtual computer-generated information. It can assist Hajj organizers to manage pilgrims' mobility and provide them directions to find the lost pilgrims and places [26], [27]. Devices like head mounted displays, handheld displays, smartphones and PDAs (personal digital assistants) utilize sensors, digital compass, cameras and GPS to guide the pilgrim on demand. Google sky is an application[8] that, on pointing towards a star or planet, lets users know its name. Similar AR techniques can help pilgrims identify their tents and other points of interests during Hajj.

Taileb *et al.* [28] presented a mobile phone application that uses GPS, compass and accelerometer to provide pilgrims with live views and description about places of their interest.

Hajj AR[9] is a mobile phone app, which uses augmented reality and provides pilgrims with a unique and diverse experience for identification and directions of the holy sites and can guide the pilgrims stepwise to perform Hajj related rituals accurately, utilizing 3D maps.

Al Jazeera satellite TV channel provided a guidance segment to explain the complexities of Hajj. It uses augmented reality technology and provides pilgrims with names of places in virtual lettering ''floating'' in the air, once they point their devices towards the holy sites [29].

#### 3) MIXED REALITY TECHNOLOGY

Mixed reality is a continuum of both AR and VR [30], [31]. Mixed reality (MR) integrates real and virtual worlds and produces an environment with both physical and digital objects to exist side by side and visualizes them in such a way that users feel that they are interacting with them in a real environment [32], [33]. MR also known as hybrid reality, generates computer generated virtual constructs which are either real or possible. MR allows experiencing new objects and scenarios which have not even been created yet [34]. All AR and VR Hajj related potential applications proposed by researchers discussed in virtual and augmented reality provide sound footing to innovate mixed reality applications for helping Hajj organizers serve pilgrims in a better way.

### *B. WIRELESS TECHNOLOGY*

The Internet of things (IoT) provides a ubiquitous platform where we can connect computing devices and mechanical and digital machines with the ability to transfer data over the network without physical (human-to-human or human-to-computer) interaction [14]. During Hajj, millions of wireless devices are used. Pilgrims, organizers and authorities interact with several services through different peer to peer and client server-based networks, thereby creating an IoT based environment.

Mohamed *et al.* [35] proposed an IoT based framework that is smart and efficient in terms of crowd time management. It allows users to interact through mobile devices. The interface layer of the proposed framework captures users' sensory data from their mobile devices, followed by a management layer, which extracts the information from the collected data and serves users with vital information about open roads and passages, locating non-crowded areas and finding their groups and friends. An expert crowd monitoring and management IoT-based framework was presented by Nasser *et al.* [36] which is designed to predict possible problems by monitoring the paths leading to the location of the rituals.

Islam *et al.* [37] presented an IoT-based Crowd congestion and stampede avoidance approach that uses a combination of different sensors and machine learning-based WEMOS D1. E-writs belts were proposed to collect data from pilgrims in real-time and predict the possible risk of a stampede.

Yamin *et al.* [38] presented a framework designed for crowd control and management system aiming to manage and prevent stampedes and catastrophes. The proposed framework presents an algorithm for stampede prediction with proof and deployment simulation. There are several IoT companies which have launched many innovative products and solutions using LTE-M (Long Term Evolution (4G), category M1) or NB-IoT(Narrowband Internet of Things)[10] connectivity that enables them to easily deploy numerous devices in crowded areas without impacting their performance [39]. The scalability factor of LTE-M or NB-IoT technologies allow

[7] shorturl.at/luDW6

[8] https://www.google.com/sky/

[9] http://ipay.mobily.com.sa/store/web/portalone/Hajj+AR?mid=8861820519

[10] shorturl.at/advNR

millions of users to use products simultaneously with better connectivity.

The different types of wireless technologies deployed in Hajj to facilitate pilgrims are as follows.

#### 1) Wi-Fi

Jassem *et al.* [40] proposed an offline group locating and tracking system based on Wi-Fi direct (ad-hoc) to enhance the service in monitoring and tracking a large group of pilgrims during Hajj. The system helps in connecting the pilgrim's group members to track fellow pilgrims by providing a map which links to the nearest co-group members and by broadcasting their MAC address and location from their mobiles.

The ubiquity of Wi-Fi enabled devices helped Anas [41] deployed a solar-powered beagle-bone based standalone system for non-invasive massive Hajj crowd analysis. This system continuously sniffs and extracts the MAC address of users' devices in a very large crowd. Eight sniffers were deployed covering about 185,000 people during the Hajj event which analysed their arrival and departure behaviour and extracted the transition pattern from one sub-location to another.

Anis and Saeed [42] presented a multilingual speech translation and local positioning system for Hajj operations. This system uses wireless network architecture and at the front-end, an RF transceiver. The network is a combination of a base transceiver station (BTS), fixed transceiver (FT) nodes and ear connected transceiver (ECT) nodes available for pilgrims. The real-time instructions, sermons, and announcements from administrative authorities are transmitted to the BTS unit, where the translators provide instant translation in multiple languages. The multilingual translated information from BTS node is transmitted to the FT nodes and thereby to pilgrims.

Mohandes [43]–[45] presented Wireless Sensor Networks (WSN) for pilgrim tracking that was interfaced to the Internet through gateway(s) via an Internet service provider (ISP). Pilgrims carried a mobile sensor embedded with a GPS chip, microcontroller, and an antenna. Each mobile unit shared its user identification (UID), latitude, longitude, and a timestamp with fixed data receiving units. This data was integrated with a central server that maps the latitude and longitude information on a geographical information system (GIS).

Mohandes [46] used NFC (Near Field Communication) technology for socio-religious events and applied it to Hajj crowd as a case study. The developed system utilises an NFC-enabled Samsung smartphone that runs on Google Android OS. NetBeans IDE with the Android plug-in was used for developing the application. A Microsoft SQL server was used to store the pilgrims' database and a Microsoft ASP.net web service was created to provide web access to the database. The application incorporated the pilgrim's profile (name, nationality, languages, address, group number, health condition, etc.) and those without NFC mobile phones were given NFC wristbands with all information stored in it. This system helped pilgrims in medical emergencies, Hajj permit verification, pilgrims' identification at any stage, data and information exchange whenever required and more specifically helping lost pilgrims.

Nasser *et al.* [36] utilized RFID and WLAN technologies and proposed an expert crowd management framework that integrated crowd density information with available mobility paths to facilitate the efficient movement of traffic within Mashaer.[11] Furthermore, the framework was proactive in predicting potential problems related to ritual location paths, followed by a concept to substitute the current human force system of crowd control and management.

#### 2) BLE

Bluetooth Low Energy (BLE) is remarkably analogous to Wi-Fi. BLE is used to exchange data over short distances (about 30 meters) however Wi-Fi goes further beyond. BLE prices are low and operate at relatively much less power. Leveraging the low-cost BLE technology, Jamil *et al.* [47] deployed a BLE setup and mobile-phone application during Hajj 2014. BLE tags carried by pilgrims in small groups were easily detected by a smartphone application which was connected to a server-based network. Their main objective was to understand pilgrims' individual and collective behaviour in both indoor and outdoor environments.

Anas [48] proposed relatively cheap off-the-shelf BLE proximity tagging architecture as an alternative method to RFID tagging which needs deployment of expensive RFID readers. BLE was utilized for navigation that provided turn-by-turn bearingsand identified important locations. Furthermore, it suggested pilgrims the appropriate routes at airport terminals, railway stations, tents in Mina and pathways inside the Holy Mosque. The deployed BLE tagging method worked well and Hajj authorities were proposed to make use of the multiple advantages of location-based services and tracking individual pilgrims and groups across different regions (Aziziyah, Mina, Arafat and a night at Muzdalifah) within the holy city of Makkah.

To sense and track group mobility with time constraint, Jabbari *et al.* [49] proposed a passive BLE device for each group of pilgrims which can be detected by scanners deployed on towers on the roadside. This was to detect suspicious group movement (asynchronous speed among the crowd or an opposite direction flow) within the coverage range and accordingly alert the organizing body for needed action.

#### 3) RFID

Radio Frequency Identification (RFID) is a wireless communication technology that uses a radiofrequency portion of the electromagnetic spectrum to identify an object, animal or a person. It has been utilized successively to track individuals and groups in a large gathering.

[11] Mashaer: Holy sites in Makkah including Mina, Arafat and Muzdalifah

Yamin and Ades [50] provide a management framework for large and dense crowds that offers cost-effective solutions to deal with large crowd events.

Hashedi *et al.* [51] proposed a Strategic Information System Planning (SISP) model for the implementation of an RFID system for Hajj management by defining its processes, data classes, information architecture and its priorities in an RFID environment.

Naser *et al.* [52] proposed a lightweight protocol for RFID technology for monitoring and tracking system to be embedded in Hajj.

Based on WSN and RFID, an optimal monitoring and evacuation methodology for pilgrims in Arafat area was proposed by Sonia and Muhammad [53]. The proposed mechanism was evaluated using simulation to solve many of the underlying challenges of Hajj crowd management.

Mohandes [54], [55] conducted a pilot study for pilgrims' identification and tracking during the Hajj event. A prototype using passive RFID technology was tested on a group of 1000 pilgrims from Ivory coast to examine the effectiveness of the system. The details of the pilgrims stored in the RFID tag included personal information (name, address, nationality, age, blood type, medical history, etc.). Information was retrieved by scanning the RFID tag using an RFID reader. The experimental results were promising and convinced Hajj authorities to deploy RFID technology in monitoring, tracking pilgrims and providing them health, transport and location-based services.

Binsalleeh *et al.* [56] proposed an RFID based system to improve pilgrimage management. RFID tags with unique identities were provided to pilgrims which were used to track their location in emergency cases.

Hidayat *et al.* [57] utilized a 2-node MCU communications concept and proposed a system for anticipating the disappearance of pilgrims by detecting their current location through the pilgrim's RFID tag.

Alsubhy *et al.* [58] proposed an automated integrated management model for tracking pilgrims and their property during the Hajj event. The proposed model was based on web and IoT technology that uses RFID tags and readers to monitor and track pilgrims. Pilgrims were provided maps and location services through a mobile phone application.

Mitchell *et al.* [59] introduced a solution to track a pilgrim's mobility in different zones of the Hajj areas via Integrated Mobile and RFID Systems. To enhance the accuracy and tracking time, pilgrims without mobile were distributed RFID tags. RFID reader was installed at multiple points, so once the pilgrims passed by them, their movement was detected and shared with the central control and command centre which could visualise it on a web-based application.

Khan [60] developed an RFID-based system for pilgrim management and was deployed at King Abdul Aziz International Airport, one of the busiest entry points for pilgrims coming from outside Saudi Arabia. Each pilgrim was given an RFID card to track them at different stages of the arrival process. The proposed system helped pilgrims finding their ways to the designated waiting areas for their nationalities and helped officials update their pilgrims' record accordingly.

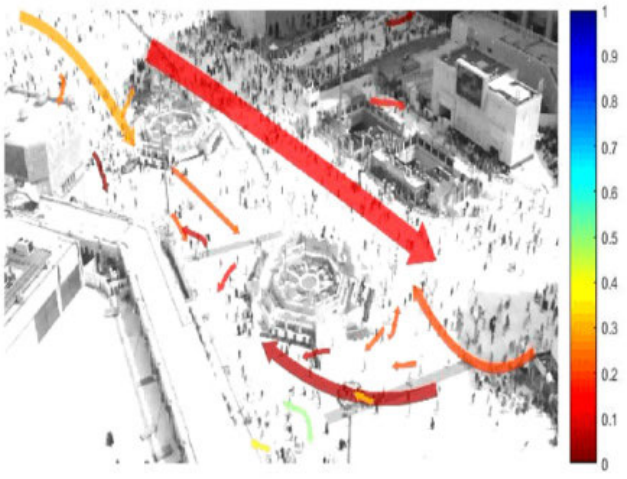



**FIGURE 8.** The arrows on the image represent the dominant flows where more thickness of arrow represents the high density, the arrowhead the direction of flow and the red color, the low speed. [63].

Koshak and Nour [61] presented an automatic RFID based tracking system and GIS framework to monitor and provide information about the pilgrim's mobility in real-time during Hajj 2012. RFID provided information about the pilgrims riding a bus, as well as names of those who have not done so yet. This technique allows Hajj organizers to track the pilgrims, find out who is missing, and take up suitable measures to counter the situation.

Table 3, summarizes the wireless technologies and related applications proposed by different researchers during Hajj.

### C. COMPUTER VISION

Another active area of research in the Haj domain is computer vision (CV). Vital information regarding the Haj crowd has been obtained through the application of computer vision algorithms. Some of the most important areas where these algorithms have provided encouraging results are crowd management and crowd analytics. Many researchers have used computer vision techniques to count the number of pilgrims in different spatio-temporal zones like Mataaf (the round courtyard of the Grand Mosque in Makkah where the Tawaf ritual is performed through circumambulation of the Kaaba) using snapshots. Video recordings of the crowd have been used to process crowd behaviour to detect and avoid possible congestion scenarios in advance [62].

Saqib *et al.* [63], developed a framework that took multiple snapshots from videos of the moving Haram crowd and extracted crowd density and directional flow information by applying an unsupervised hierarchical clustering algorithm, (see Fig 8).

The framework generated trajectories from the snapshots and clustered them based on their spatial and temporal characteristics to produce long-distance paths. Eventually, the

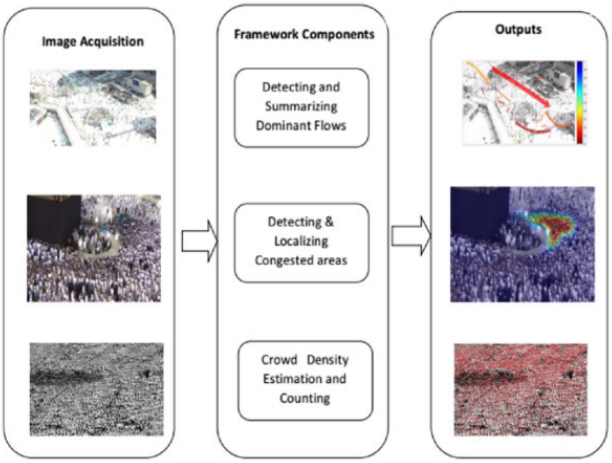



**FIGURE 9.** Crowd Analytic Framework For Crowd Management in Majid-al-Haram [67].

video was converted into multiple small segments to calculate the long-distance trajectories for each segment.

To solve the problem of counting people performing Tawaf at any time, Arif and Daud [64] proposed a computer vision-based framework. After performing background removal, blobs of moving pilgrims were obtained which were then used to estimate headcount according to proportional blob size. Testing was done on 100 frames of video and 95% accuracy was claimed.

Another problem faced by the Haj authorities is the allocation of limited space in Mina for pilgrim tents. Alharthy *et al.* [4], extracted the tent template from three digitized aerial photos of Arafat and passed them over the tested image to compute the matching function for each pixel using cross-correlation matching [65]. The outputs were the 2D coloured map of matching function and a 3D representation. The tent count was calculated by passing maximum filter [66] over the matching function that is exactly equal to the size of the tent template. The results obtained helped in planning the tenting activity in future as well as in estimating the total number of pilgrims present in the area of interest.

Sultan *et al.* [67] proposed a computer vision-based analytical framework to compute crowd density estimation, congestion detection, and dominant pattern identification using videos from IP cameras installed in Masjid al-Haram (see Fig 9).

Dominant flows and scene summaries were calculated initially. Summaries of all the short views were calculated next. Based on the above, crowd density and congested areas were calculated and detected, and security management was informed.

Hussain *et al.* [68] proposed an Artificial Intelligence-based crowd density estimation system (CDES) for Masjid al-Haram. First, foreground features were extracted using edge detection and background removal techniques. Pixel size normalization for perspective distortion correctness was applied to the extracted features. This data was then fed to a backpropagation (BP) neural network to correlate the normalized pixels and number of people.

In Sultan [69], computer vision has also been used to detect congestion in Masjid al-Haram. The system divides crowd video clips into multiple overlapping temporal segments of equal duration. Using the particle advection approach, the trajectories are extracted from each of those segments. Critical congestion locations are identified by calculating oscillation maps from these trajectories. The author has proved the detection accuracy qualitatively and quantitatively.

Stampede during Haj has resulted in many deaths in the past. Musa *et al.* [70] devised a method to count pilgrims to avoid congestion and stampede. An input image of the crowd is converted into a grayscale image. A threshold is applied to segment the head from the body. Heads are detected using erosion techniques to filter the segmented image against the template. Area of the marked region is calculated by inverting and selecting high-intensity pixels and recursively traversing the eight connected neighbours. Area of the marked region calculated in this manner is counted as head if the value is closer to the predefined head region value, otherwise, a noise.

Farooq *et al.* [71] proposed a system that uses block matching and optical flow techniques to help maintain the smooth flow of pilgrims. The system pre-processes input images to segregate the moving shadows and the pilgrims and nullify the false motion due to moving shadows. The implementation results were promising with an accuracy of 90.58% for the congestion classification of pilgrims.

Another technique for counting pilgrims in a crowded environment was proposed by Sajid *et al.* [72]. A slit window is used to mark the area to count people and adaptive thresholding is used to filter and count the relevant blobs to estimate the number of pilgrims.

Dridi in [73] presented a tracking method for an individual pilgrim from a high-density crowd. The objective was to estimate the pedestrian velocity. At the first stage, the crowd density was estimated manually by loading an existing footage to a 3D program. After that, the virtual camera was placed in position so that the rotation and focal length matched with the original camera. This helped construct a grid of Mataaf area in Masjid Al Haram to count the people manually using video editing software. The automatic process was used to estimate the density of expected crowded areas. The density of the crowd was measured using texture mapping. The texture of the low-density area was rough while the high-density area had a fine texture which lead to estimating the number of people. (Fig 10). Shows the manual and automatic estimation of several people in Masjid Al Haram.

Adnan *et al.* [74] used thermal cameras to capture still images and live videos to record and calibrate the temperatures of the pilgrims. The pixel ratio of calculated video frames was mapped to the temperature ruler colour to determine the crowd-density in real-time. Table 3 summarizes the Computer Vision Technologies related research work proposed by different researchers during the Hajj events.

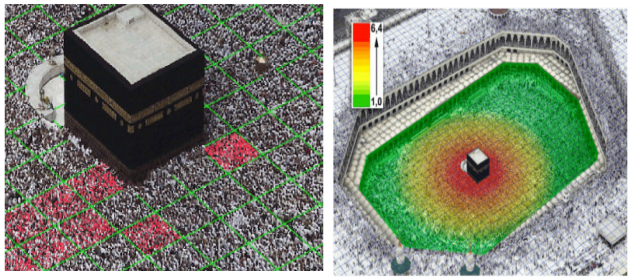


**FIGURE 10.** Manual and Automatic estimation of a number of people in Masjid-al-Haram [73].

Al-Khaffaf *et al.* [75] used background modelling and active contours method to analyse the motion of pedestrians that leads to extracting the speed and density of the pedestrians. The proposed method uses videos from the main gates of Masjid Al Haram to extract these parameters. Initially, the median-based approach is used to remove the background from the dataset. People are detected using the active contour method. The next step is to track people. This is achieved by silhouette tracking, followed by human detection from Fig-Ground segmentation. The pixel-to-pixel subtraction between frames results in finding the movement between images. This movement helps to find the pedestrian speed in the videos.

Khozium *et al.* [76] develop a decision support system to monitor crowd movement. The proposed approach analyses the crowd flow and density in real-time. The system is divided into two main components, i.e., Information management and decision support. The data is acquired using thermal cameras and fed to an analyser to calculate crowd density. The decision support system has two sub-modules named operations research and expert system. The operations research module calculates the pilgrims' mass per unit for each road, while the expert system estimates the road closure, road priorities, and pilgrims' organization.

Al-Sheary and Almagbile [77] presented a crowd monitoring system to calculate the density of the crowd with an accuracy of 80%. High-resolution images were collected using Unmanned Aerial Vehicle (UAV) along with the location of the crowd. The L*a*b colour space was used to segment the image. The crowd density was calculated by converting the segmented image into a binary image. Georeferencing was used to identify the particular area concerning the crowd density level.

Eldursi *et al.* [78] developed a crowd density estimation system, ''Al-Haram Crowd Guide System'', which uses texture-based feature extraction methods for crowd management within Masjid Al-Haram. The application helps users visualize the crowded areas in the form of a heat map.

Alharbi *et al.* [79] presented a crowd counting system for Mas'a within Masjid Al-Haram. The proposed system uses a Viola-Jones detection algorithm to detect faces in frames. The algorithm counts the number of people based on the detected faces. Their experimental results showed that the accuracy directly depends on crowd density. The managing authorities were able to visualize the crowd flow patterns through histograms to take necessary measures in case of overcrowding or an emergency.

Liew *et al.* [80] presented a crowd monitoring framework which uses two crowd density estimation approaches to detect potentially dangerous situations at Masjid Al-Haram. The first approach is a combination of background removal and edge detection while the second one uses the Grey Level Co-Occurrence Matrix (GLCM) to extract texture features. The framework detects the overcrowding and stationary congestion at Tawaf, Sai'e and entrances of the holy mosque and generates alerts for necessary action.

Summary of research contributions that use computer vision technologies can be found in Table 3.

### D. SPATIAL COMPUTING

Spatial computing related problems such as scheduling, evacuation and rescheduling appear when a large number of people stay in a limited area or move from one place to another. During Hajj, around 3 million pilgrims move from one place to another at the same time to perform spatio-temporally restricted rituals and stay 3-4 days in encampment areas such as Mina, and Arafat. A number of scheduling and rescheduling mechanisms have been devised to tackle this problem. Moreover, to be in the state of preparedness, the researcher also devised different evacuation techniques to make an evacuation strategy to handle any emergency conditions.

The different types of spatial computing methods deployed in Hajj to facilitate pilgrims are as follows.

#### 1) SCHEDULING

To minimize the congestion during the Hajj event, a scheduling model was presented that discusses multiple constraints including religious, spatial and temporal ones [81]. This model considered real-time roads congestion and overcrowded areas and effectively provided quantitative background for a general policy decision on Hajj transportation. Considering the congestion during Tawaf around the Kababh, Koshak and Fouda [82] developed a web-based GIS system to provide relevant and crucial spatial information, where important layers were stacked over each other to provide crucial information to authorities to ease the decision-making process. This system used GPS devices and GIS to analyse pedestrian movement for performing the Tawaf ritual. The authors used GPS devices to collect tracking points at different time intervals. The movement coordinates were then visualized using specific GIS tools. Unique patterns of pedestrian movement emerged when the collected data was plotted. This helped the authors identify service level and flow rate of different regions of the Mataaf area.

Khan and McLeod [83] developed a Tawaf agent-based simulation called ''TawafSIM'' to explore the crowd characteristics during movement in the Mataaf area. The goal of authors was to explore throughput, satisfaction, safety and health aspects concerning facility layout and management preferences of Tawaf. The simulator is based on micro-level

behaviour which explores the movement of an individual pilgrim in crowded areas.

Shuaibu *et al.* [84] simulated complex scenarios involving multiple agents interacting with each other and avoiding collision within a defined path. The agents were set at defined velocities on spiral paths during Tawaf ritual, moving counter clockwise with multiple scenarios concerning radii of the seven lapses of Tawaf. Based on flow rate, average velocity, Tawaf duration and pilgrims' density, they found that a spiral movement (4in_3out) presents better Tawaf performance with a duration of about 38 minutes and average density of 4.2 persons per square meter.

Alnabulsi and Drury [7] hypothesized that social identification helps in moderating the effect of crowd density on crowd safety. To validate, they surveyed 1194 pilgrims during Hajj 2012 and found the negative effect of crowd density on crowd safety, which can be moderated by social identification. This offers a novel perspective on crowd safety management.

Mahmood *et al.* [85] proposed an Agent-based Crowd Simulation & Analysis framework that incorporates the use of Anylogic Pedestrian library and integrates Anylogic Simulation environment with external modules for optimization and analysis. The framework can model large crowd in a spatially explicit environment at real scale.

Ahmed *et al.* [86] proposed Hajj Management System which helps pilgrims in an emergency. In case a pilgrim is missing or there is an emergency, pilgrims interact through HajiPilot, a mobile phone app. The framework develops an emergency strategy were HajiPilot auto-responds and shares the location with family members or friends through an SMS containing the user's location.

#### 2) EVACUATION

Hajj, the diversified massive crowd is always at a high risk of natural or human-induced disasters. A couple of past events were a gas cylinder explosion in 1975 and then in 1997 when 550 pilgrims were reported dead and the latest was the Mina Stampede in 2015 that caused massive causalities.[12]

Mahmood *et al.* [85] modeled and analysed the Tawaf ritual using an agent-based crowd simulation and analysis framework. Incorporating Anylogic Pedestrian library, this framework provided a runtime environment for analysing complex situations like emergency evacuation plans. However, the authors noted that the effectiveness of these plans may vary with the increase in the complexity of the crowd simulation scenarios due to additional physical and behavioural details.

Felemban *et al.* [87] presented a Capacity Aware Multimodal Transportation platform that was designed to evacuate either pilgrims' crowd and/or public or private buses transporting them from Mashaer area in case of any disaster. During the Hajj 2018 event, the movement of 20,000 buses was tracked using trackers installed in buses. The proposed platform can extract knowledge from captured GPS data from 20,000 buses (operating under the control of the Ministry of Hajj and Umrah) and combine it with the available transportation plan to provide innovative decision analysis to Hajj organizers for pre-planning exercises.

Bilal *et al.* [88] presented Spatio-Temporal Service Model (STSM), a theoretical model, that can detect and predict anomalies within a large crowd. This model correlates captured crowds' real-time mobility information with past user's Spatio-temporal data and their traffic mobility and generates alerts for an optimized path to shelter points and safe exits in case of any possible disaster. As a use case, data captured by tracking devices installed in 2970 buses during Hajj 2016 was analysed and summarized to develop a basic model for future.

Yang *et al.* [89] proposed a novel approach-Crowd-separated Allocation of Routes, Exits and Shelters (CARES), which will reduce the chances of conflict due to movement in the opposite direction during evacuation. CARES assigns path and destination shelters to specific groups to be evacuated and attempts to minimize evacuation time under the constraint of spatial dis-jointness of evacuee groups assigned across different shelters. CARES deployment over the Hajj crowd showed that it provided faster evacuation plan when compared with a current practice based on the Nearest Exit or Shelter (NES) paradigm. Moreover, CARES showed much less evacuee movement conflict risk concerning current computational approach, known as capacity-constrained route planning (CCRP) scheme.

### E. SOCIAL MEDIA

Different Social media platforms are in use that allow pilgrims to actively communicate and share their Hajj experiences. Sometimes Hajj organizers utilize these platforms to disseminate useful information about Hajj activities. This has made social media a very important real-time source of information.

Akhlaq [12] presented Hajj Geo-Social Network (HGSN) to efficiently diffuse important information in multilingual Hajj crowd. HGSN (see Fig 11) utilizes the social data captured by pilgrims' social network while they were using communication services to help them perform their spatiotemporal religious activities. Pilgrims with many acquaintances or those who had higher language degree were tracked and a second layer of network MLH (multilingual hub) was constructed to bridge the linguistically diverse subnets of HGSN.

The theoretical results showed that by considering pilgrims with language degree 6 or higher, the entire network can be utilized for quick diffusion of information.

Ahmad *et al.* [90] presented a data collection architecture that validates the quality of sensory data captured through a mobile phone application for multiple services during Hajj, integrates it with pilgrims' personal information and social media content generated through their Facebook, LinkedIn and Twitter as well as the Hajj messenger account. The Hajj messenger was an application provided to pilgrims for blogging, discussing and reflecting their opinions, memories and

[12]https://www.bbc.com/news/world-middle-east-34346449

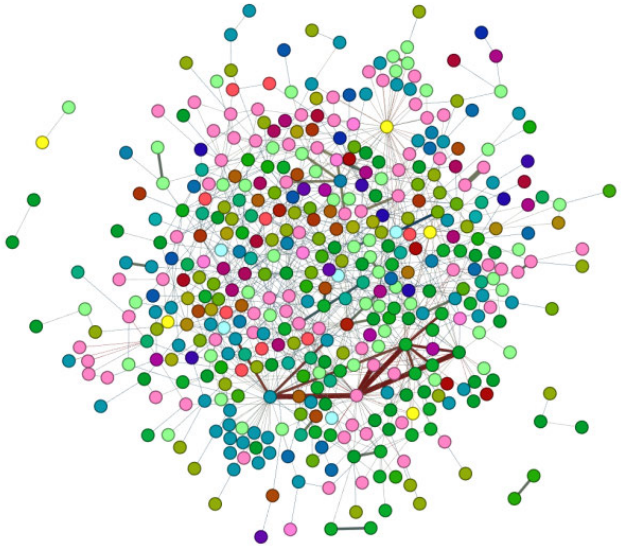


**FIGURE 11.** HGSN – (Hajj Geosocial Network). A multilingual social network of 48 different nationalities (each nationality has a different color) during Hajj 2014 event.

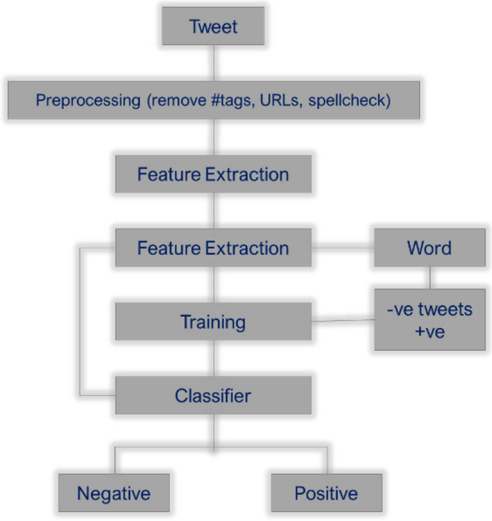



**FIGURE 12.** Sentiment analysis methodology of Twitter – System Architecture [91].

experience about Hajj. The architecture fine-tunes the users' contexts and provides them with a set of adapted services.

Elgamal [91] presented sentiment analysis methodology that uses Hajj related tweets to get rapid and accurate views and impressions of pilgrims about some quality of service. The proposed system architecture is shown in Fig 12 below.

Ghassan [92] uses Spring XD, Hadoop, Hive and MS Excel to collect, refine and visualize pilgrims' tweets. The author uses Big Data tools effectively to make better decisions and enhance provided services during the Hajj event.

Qurashi and Sharpley [93] discussed the impact of using social media during the Hajj event. Albeit th existence of several benefits of social media interaction, the author criticized the use of social media while pilgrims perform Hajj rituals which impacts their spiritual experience.

Bilal *et al.* [94] present an ad-hoc social network platform that connects Community of Common Interest (CoCI). The application allows users to group for shared intra-city transportation with the aid of multimedia content. The pilot project was presented to connect pilgrims during the Hajj 2015 event to address their transportation needs.

Yamin *et al.* [95] proposed a mobile phone application that integrates social media and provides pilgrims with information about disasters related to Hajj crowd so that they can adopt safety measures.

### *F. MOBILE APPLICATIONS*

Mobile phones embedded with varieties of sensors help researchers design applications that can capture users' data, analyse it and provide them with services of their interests. One of the most significant uses of these technologies is to develop applications to provide solutions to several challenges faced by diversified communities of common interest. In this context, many applications have been developed, deployed and tested which were purposefully designed to cope with Hajj crowd challenges. In this section, we summarise a few popular applications that were provided to pilgrims to facilitate them in performing Hajj rituals.

Many mobile phone applications have been proposed by researchers to help pilgrims by providing them multiple services such as rituals guide, navigation, translation, qibla direction, prayer times, weather, currency conversion and places of interest [96]–[100].

Ahmad *et al.* [101] presented a spatiotemporal GPS based diary that serves pilgrims with multimedia content shared by past years' pilgrims. The multimedia content associated with different Hajj areas helps pilgrims get educated about the holy place they are in which in turn helps in crowd management related to the area.

Faizan *et al.* [102] presented a cloud-based multimedia routing application that tracks pilgrims through their GPS information and helps pilgrims in their mobility with multimedia content when they navigate to their point of interests.

Ahmad *et al.* [1], [2] designed and deployed a mobile phone application "Perform Hajj and Umrah", that reads the pilgrims' context and offers them multiple location-based services, such as locating points of interests, providing guidance and set of supplications associated with the spatial zone they are in, lost and found service, a Hajj messenger service with audio-video facility and many more.[13] Addressing the spatiotemporal nature of the Hajj rituals, out of boundary service was provided to pilgrims that showed the them if they were inside or outside the Haram, Mina, Muzdalifah and Arafat boundary.

Faizan *et al.* [103] presented a data collection framework that helps pilgrims find optimized routes while they perform spatio-temporal Hajj rituals. Users were provided with a mobile phone application where they can upload multimedia

[13]https://iitwares.com/perform-hajj-umrah/

information about accidents, congestion and traffic flow along with spatial and temporal coordinates. The framework was able to recommend users with an optimized path by integrating these constraints and users' preferences.

Koshak and Fouda [82] utilized Global Positioning System (GPS) and Geographic Information System (GIS) and analysed pilgrim movement during the Tawaf ritual during Hajj 2004. The deployed system captured users' temporal data to be integrated with past data to understand flow rates at different hours of the day and added their recommendations to remove obstacles and facilitate pilgrims' mobility during the Tawaf ritual.

Parveen and Aldhlan [104] proposed a system to report missing pilgrims and track their location simultaneously. The suggested framework will have a mechanism to identify and track the pilgrim through periodic updates.

Mantoro *et al.* [105] presented Hajj Locator framework for tracking pilgrims using GPS sensory data. The framework has two parts, a mobile device and a tracking system that uses a database server. The pilgrims carry GPS enabled mobile phone devices to share data with the Subscriber Identity Module (SIM) card number as their identities along with other information such as their position coordinates. In case of no connectivity, the system switched to an automatic mode where an SMS is sent as an alternative option. This feature made Hajj locator a better option as compared to other tracking frameworks where internet connectivity was compulsory.

Koshak *et al.* [61], [82] deployed an RFID and GIS technology-based framework to monitor and provide real-time information about pilgrim mobility. Vehicles carrying RFID tags were detected when they passed by the readers installed at key locations and communicated wirelessly to a workstation to get back interactive maps through a GIS application.

### G. BIG DATA ANALYTICS

Nowadays, multi-sensory data can be easily collected continuously from social sensors, vehicle sensors, physical sensors, human sensors, etc., through mobile phones, radar, IP-cameras, OBD within vehicles, and many other IoT devices. These data are huge, fast in generation and processing, and composed of a variety of data types, e.g., number, text, photo, video, etc. Due to the nature of big data, the tools for management of traditional data have failed to provide efficient services even in simple queries., Intelligent methods have thus been adopted for data collection and storage, data analysis and computation, and data collaboration and sharing. Big data solutions outperform traditional data approaches in exploration, availability and utilization.

Big data content is usually hosted on a cloud computing infrastructure [106]. In an occasion like Hajj, where crowds are huge and vehicular traffic and social networks are relatively dense, the availability of multi-sensory technology with an internet connection and big data analytics (i.e., cloud computing) makes it possible to continuously collect a variety of information, including spatial and temporal data from different sources (e.g., smartphones, digital devices, OBD4 equipped vehicles, etc.), process and store them and retrieve them from the server as needed. These big data platforms are designed to be elastically scalable by splitting massive clustered data into chunks to allow parallel processing.

Big data technology has served various applications in Hajj, supporting parties such as ministries, private and government agencies, health care officials, and individual pilgrims. For smart tutorial and guiding services of pilgrims in Hajj; Snoussi *et al.* [107], [108] used the big data concept to store printed and handwritten documents, video clips, sound recordings and cards that contain information about Hajj rules, prayers, Duaa of Hajj and Umrah, etc., then process these data to provide spatiotemporal advice to pilgrims and answer users' questions through a mobile application.

For multimedia diary and routing services, [109], [102], [110] utilized Amazon EC2 server for big data computation with Amazon S3 as permanent storage for huge geo-tagged multimedia data containing images, audios and videos collected from smartphones, social, and vehicle sensors, and PostgreSQL with PostGIS as spatio-temporal and relational databases, as well as DynamoDB for NoSQL data. DynamoDB stores expired sessions of a person's diary information and users' mobile-application-based historical information.

For routing service, Semantic Multimedia Routing Algorithm (SMRA) was proposed in [102] to handle real-time spatiotemporal route fetching queries on big data. For private-community services as in [94], Amazon EC2 server was adopted with the Hadoop Distributed File System (HDFS) as NoSQL database along with relational and in-memory databases to store massive multimedia and sensory data collected from smartphones and vehicles. Spatial Hadoop, Postgres and Apache Geode were used as NoSQL, relational, and in-memory database management systems to handle the request of a user for shared community transportation in Hajj and for finding members of interest in a large crowd.

For context-aware services, Ahmad *et al.* [2], [90] proposed a cloud-based server that uses Amazon EC2 server for computation of pilgrims' smartphone sensory data, Amazon S3 for the storage of analysed big data, PostgreSQL database for storage of users' own or nearby points of interest spatial data, and DynamoDB, which is a NoSQL database, for the storage and retrieval of any amount of data using the Map-Reduce approach. The data stored in S3 were used for online analytical and transactional queries related to Hajj and Umrah services.

For pilgrim monitoring, analysis, and visualization services, Saeed *et al.* [111] proposed the iCrowd framework that collects, reads, stores, analyses, and retrieves spatial and health data of pilgrims in Hajj obtained from the built-in sensors in their smart wearable devices. For data storage, NoSQL Cassandra and HDFS were utilized. For data management, Apache Kafka was used to ingest and map data, Spark Streaming to filter and enrich data, Map-Reduce techniques to analyse data, and QGIS to visualize the crowd.

Another attempt that supports geo-clustering visualization solutions for an online map of pilgrims' crowd was proposed by Atta *et al.* [112]. The authors in that study adopted RabbitMQ Server for storage and retrieval of data streams from the built-in sensors in the pilgrims' smart wearable devices. Elasticsear was used for in-memory data storage and indexing, MongoDB for historical data storage, and HDFS for archiving both historical and recent records.

For evacuation planning services using Multimodal transportation, bus monitoring, analysis, and visualization services in Hajj, Felemban *et al.* [87] migrated bus GPS data to a NoSQL database management system- Cassandra cluster- to increase efficiency and scalability, and used Presto to run effectively distributed SQL analytical queries on HDFS for big data aggregation services. For personal health and diseases educating and monitoring services,

Nafea in [106], [113] proposed the Hajj Health Control (HHC) system that collects data from smartphone and magic card, then combines cloud computing Amazon Web Services (AWS) and big data Amazon S3 storage services to provide services relevant to pilgrims' health and disease prevention as well as control during Hajj.

### *H. CROWD SIMULATION AND MODELLING*

Abdelghany *et al.* [114] presented a microsimulation model for the multidirectional movement of the crowd. The authors adopted a cellular automata discrete system for the microsimulation model, which allows them to represent each agent in detail. It also assists in representing walkways and movement area in the Mataaf area.

Koshak [115] proposed ways to help curb the problem of overcrowding by designing a more robust urban environment for the purpose of spatio-temporal visualization of the movement of pilgrims to the Jamarat area according to a schedule developed by the Ministry of Hajj. The approach utilizes GIS (Geographic Information Systems) to simulate the movement of groups of pilgrims from their tent camps to Jamarat and back to their camp.

Sabban *et al.* [116] describe the shuttle bus transportation system that existed in the 2002 Hajj season. A simulation model was designed for this system and translated into a simulation program using the Arena simulation system.

Sarmady *et al.* [117] show that simulation of the movement and behaviour of crowd can be useful in crowd management. This paper uses a multi-agent-based method to simulate the crowd in the Tawaf area. They present the architecture of the software platform, which implements their proposed model and briefly reports their early experience in using Repast J, which is an agent-based simulation toolkit to model the crowd at the area.

Narain *et al.* [118] introduce a novel scalable-interactive model that simulates a large crowd of pedestrians. They describe the mathematical models underlying the proposed simulation for dense crowds, including agent-level planning and agents motion. They test the model with different scenarios and crowd sizes and Compare scenarios, results, and performances.

Zainuddin *et al.* [119] suggest various mitigation measures to alleviate the problems associated with the circumambulation of the Kaaba. The entries into the Tawaf area are directed and limited, and simulations are done using SimWalk to compare the differences of the time taken to complete the seven rounds. The basic algorithm to design the pedestrian walking path in this software is the shortest-path algorithm where the pedestrian finds the shortest route to reach his/her destination after avoiding all the obstacles. The study of circumambulation of the Kaaba is taken as an illustrative example, where performing Tawaf is one of the rituals when performing Hajj. The process of Tawaf involves circumambulation of the Kaaba seven times in a counterclockwise direction. The pilgrims face two main problems in this situation. The first is the overflowing of the pilgrims during the Hajj season. Many pedestrians will cause crowd congestion and may cause disasters as pedestrians push into each other. Elderly pilgrims and women face difficulties in completing the seven rounds. Secondly, entry into the Tawaf area is unlimited, which causes pilgrims to flow in from various directions at the same time.

Mulyana and Gunawan [120] developed an ''intelligent agent'' that can recognize and adapt with the environment to do the right action. It can also be used for other crowd simulations because of the existence of reusable components or objects. System output showed that Hajj crowd simulation could demonstrate more realistic pilgrims' behaviour for Tawaf, Sa'yee (the ritual of movement in a straight line between the hills of Safa and Marwa), and Jamarat. The design of an intelligent agent can help in figuring out the right behaviour and activities based on current location or environmental conditions (for each specific location and specific ritual).

Zainuddin *et al.* [121] discuss the problem regarding the ritual of circumambulation of the Ka'aba (Tawaf), where the entrances to this area are usually congested, which worsens during the Hajj season. They have used a computer simulation using SimWalk, which is based on the Social Force Model, to simulate the movement of pilgrims in the Tawaf area.

Sarmady *et al.* [122] devised a method to utilize a cellular automata model for the simulation of the pilgrims' circular Tawaf movement. The authors utilized a discrete-event model to simulate the actions and behaviour of the pilgrims. The proposed models were used in a software platform to simulate the actions and movements of pilgrims in the area. A sample application was also presented based on the model that can help in predicting whether specific changes to the architecture could increase the throughput of the Mataaf area.

To ensure safe, secure, and efficient movement of pilgrims after understanding their spatiotemporal constraints, Tunasar [123] used queuing theory to simulate pilgrim's mobility and traffic flow, which explains the macro movements across the Hajj areas. This led the author to test the simulation models for mechanized movement solutions for the elderly and the handicapped.

Curtis *et al.* [124] developed a system that can model agents with varying age, gender, and behaviour, supporting the heterogeneity observed in the performance of the Tawaf, even at high densities. Tawaf was used as a case study by the authors. They used a finite state machine to specify the behaviour of the agents at each time step in conjunction with a geometric, agent-based algorithm to specify how an agent interacts with its local neighbours to generate collision-free trajectories.

Curtis *et al.* [125] present asymmetric interactions between agents rather than symmetric relationships with a large group of crowds. The authors formulate, a novel model called Right of Way that provides asymmetric interactions between the crowd, which leads to a realistic and desirable simulation. This principle can be applied to different crowd models. Tawaf scenario was used as a case study where such a dynamic relationship is prevalent.

Manenti *et al.* [126] depicted cultural heterogeneity in crowd and groups of individuals to represent the interaction of such groups in a crowded scene. The model presented by the authors is based on agent proxemics, where the personal space of agents influences the movement patterns. The simulation is based on a multi-agent system, where the agents are instilled with different cultural proxemics.

Reffat [127] proposed a framework for developing an intelligent real-time virtual environment model for facilitating efficient and timely vehicle traffic movement during Hajj, utilizing various movement scenarios, simulation, and optimization methods. The model utilizes intelligent agents within a real-time 3D virtual environment that represents the departure from Arafat to Muzdalifah, also known as Nafrah. The proposed framework has three primary phases, each of which has specific components. Initially, a spatial analysis of current pedestrians and vehicle access in the Nafrah location coverage from Arafat to Muzdalifah is conducted. Furthermore, evaluation of the movement efficiency of current scenarios of the Nafrah using computational simulation is performed. Finally, the development of a multi-agent system within a real-time 3D virtual environment for improving the movement efficiency of vehicle traffic in the Nafrah.

Haghighati *et al.* [128] evaluate the impact of density, service rate, and service time on the throughput of the central court of Masjid Al-Haram and develop a simulation model for Tawaf area with safe and flow reduced crowd. The authors described the conceptual model for Mataaf operation and the proposed a queue system used in ARENA simulation. Furthermore, they investigated the factors affecting the Mataaf flow and validated their model by increasing the average service time in the queue system. Different strategic scenario models for Mataaf operation were also tested.

Crociani *et al.* [129] develop, calibrate, validate, and evaluate a dynamic pedestrian and crowd simulator, named MAKKASim that takes into consideration mainly the coherence of agents as groups in the environment. The system architecture for developing MAKKASim simulation was introduced and tested for different strategies of crowd

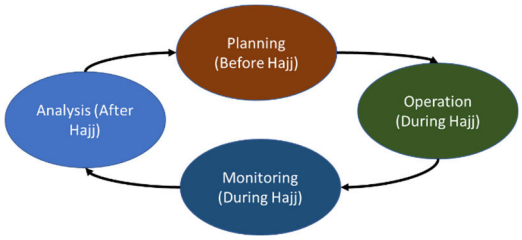



**FIGURE 13.** Four phases of Hajj events.

management in a real-world application. The agent-based computational model used in the developed pedestrian simulation has also been discussed. MAKKASim simulation was calibrated and validated.

Alonso *et al.* [130] proposed to develop a dynamic crowd simulation model discussing the study of pedestrian panic using the discrete element model (DEM). The computer simulation is based on complex shapes of particles to simulate pedestrian dynamics.

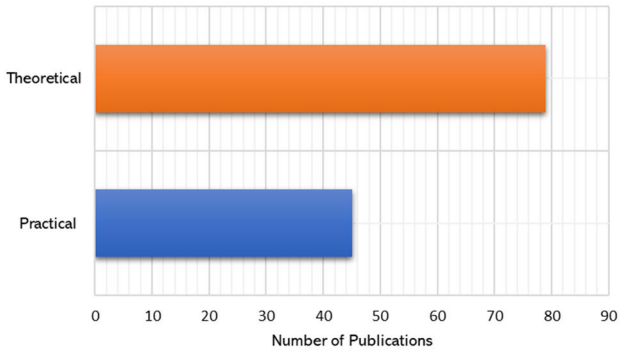
Curtis *et al.* [131] simulated the movement of individual agents in large-scale crowds performing the Tawaf. The authors used a velocity-space-based pedestrian model, which exhibits consistent results even under extreme density called reciprocal velocity obstacles (RVO). Furthermore, the authors extended RVO to include priority and right of way in which the agents respond to potential collisions asymmetrically depending on context; one agent may yield, to varying degrees, to another. The developed simulation uses an RVO in conjunction with a finite state-machine to demonstrate collision-free trajectories for the agents.

Sakellariou *et al.* [132] utilized a multifaceted approach to identify, simulate, and analyse crowd behaviour. Original video recording of the high-density crowd has been used to extract data and patterns of behaviour of crowd movement, that are used in a general modelling framework to simulate crowd movement.

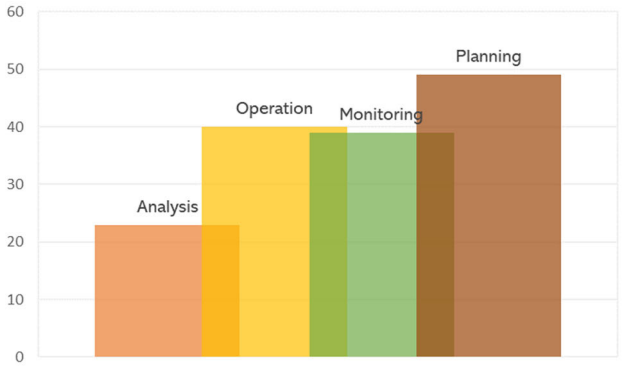
Shuaibu *et al.* [133] reduce the collision problem that is affecting the flow of pedestrians in a dense environment such as the Tawaf ritual. The authors proposed a spiral model that simulates the movement of 1000 agents towards a unified direction while ensuring minimal collision among pedestrians during Tawaf.

Tayan *et al.* [134], [135] presented an approach for effectively incorporating efficient transport systems in a primary candidate application domain, such as the Hajj pilgrimage traffic scenario. The paper initially reviews all the technologies used for traffic modelling during hajj and proposes and hybrid model suitable to ease the congestion at saturated intersections. The developed model was also used to estimate and predict traffic flow, which enhances precision.

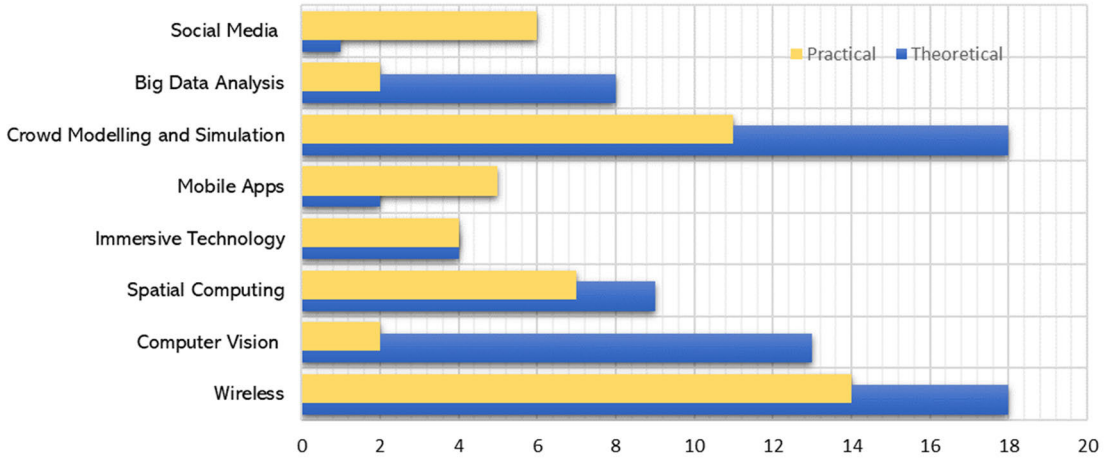
Rahman *et al.* [136] presented an agent-based crowd simulation using CUDA over a Graphic Processing Unit (GPU) to correctly navigate an agent through the environment while avoiding obstacles. Due to the limited computational power of CPUs to display this increasing number of pilgrims, the execution time for a single simulation step increases, which in



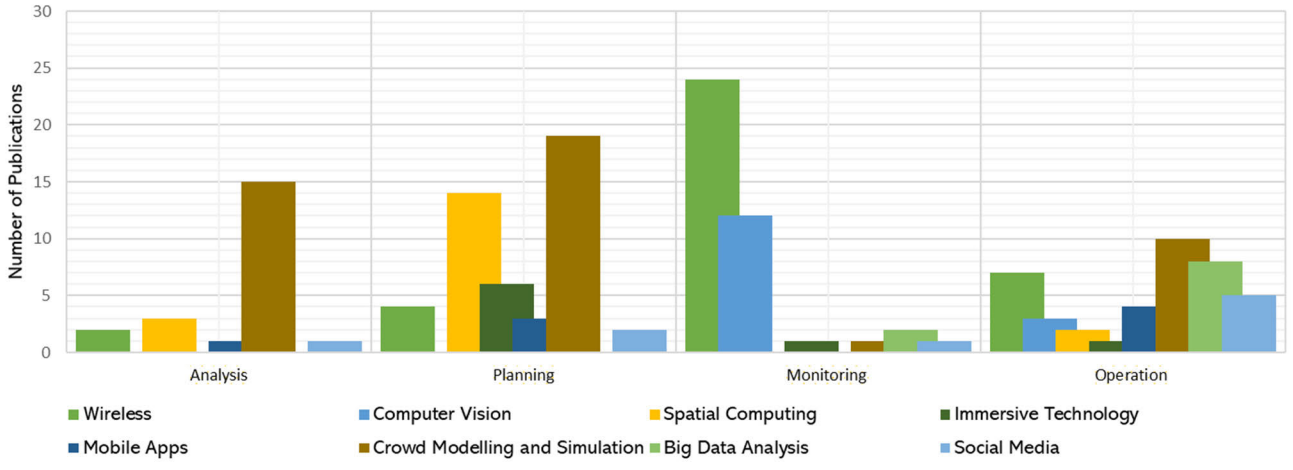

(a)




(b)




(c)




(d)

**FIGURE 14.** Number of publications (a) Describing theoretical and practical contributions, (b) Related to Four phases of Hajj, (c) Showing technologies proposed or implemented during the Hajj events, (d) Showing technologies used for four phases of Hajj.

**TABLE 2.** List of popular android-based Hajj applications.

| S. No | Apps Name | Application Link | Downloads | Date | Version | Service code | Languages |
|---|---|---|---|---|---|---|---|
| App1 | Hajj and Umrah | https://play.google.com/store/apps/details?id=com.hasshub.hajjoumrah | 100,000+ | Aug 2019 | 3.5 | Hajj and Umrah ritual, supplication, prayer timings, travel checklist, weather information, places of interest, video tutorial, and currency conversion | Urdu, English |
| App2 | Hajj & Umrah Guide Urdu | https://play.google.com/store/apps/details?id=com.suave.urduhajjguide | 50,000+ | June 2019 | 1.2.7 | Hajj and Umrah Rituals and List of Do's and Don'ts during the Hajj Journey | Urdu |
| App3 | Hajj Navigator | https://play.google.com/store/apps/details?id=sa.iff.minatentlocator | 50,000+ | Aug 2018 | 6.4.2 | Navigation | English |
| App4 | WeSalam-Hajj & umrah guide | https://play.google.com/store/apps/details?id=com.hajjnet.salam | 100,000+ | Jam, 2020 | 4.1.3 | Hajj, Tawaf and Umrah rituals, supplications, prayer timings, Complete Quran, Navigation, Places of Interest, video tutorial, and currency conversion | Arabic, English, French, Urdu, Indonesian, Malay, Turkish, Russia, Hindi, Bengali |
| App5 | Manasikana | https://play.google.com/store/apps/details?id=com.hajj.manasikana | 50,000+ | Sep 2018 | 1.0.12 | Supplications, Prayer timings, Qibla direction, Weather, Navigation, Places of Interest, Contact Us, Currency Conversion, Hajj tweets, Ministry Messages | English, Urdu, Arabic, Bengali, Turkish, Spanish, French, Indonesian, Malay |
| App6 | Mina locator | https://play.google.com/store/apps/details?id=com.MinaLocator.AndroidApp | 50,000+ | Aug 2019 | 1.0.29 | Navigation | Arabic, English, Urdu |
| App7 | Al-Haramain | https://play.google.com/store/apps/details?id=com.rize.alharamain | 50,000+ | May 2020 | 1.1.1.59 | Umrah Ritual, Supplication, Prayer times, Navigation, Q/A, Live Audio and Video, Contact Us | Arabic, English, Urdu |
| App8 | Al-maqsad | https://play.google.com/store/apps/details?id=app.navibees.alharam | 50,000+ | Jan 2019 | 1 | Navigation | Arabic, English, French, Dutch, Urdu |
| App9 | Al-mutawf | https://play.google.com/store/apps/details?id=com.madar | 500,000+ | Feb 2020 | 13.5.0 | Hajj Ritual, Umrah Ritual, Supplications, Navigation, Q/A, Currency Conversion, Graphical Representation of Mashaer Area | Arabic |
| App10 | Duas for Hajj and Umrah | https://play.google.com/store/apps/details?id=com.ilib.hajjumrahdua | 50,000+ | Feb 2018 | 1.2 | Supplications | Arabic, English |

turns decreases the frames generated per second. The authors show that utilising GPUs to simulate a crowd of pilgrims performing different rites in Makkah, a far higher number of pilgrims can be simulated than by using OpenSteer, an existing single-threaded open-source CPU based 3D visualization library running on Open Graphics Library (OpenGL) API.

Kurdi *et al.* [137] The authors surveyed recent attempts to model the critical Hajj rituals of tawaf and Sa'yee and highlighted ways in which some of the limitations of these studies may be overcome in future work.

Dridi *et al.* [138] discuss existing extensive approaches to simulate huge crowds and model their behaviour in overcrowding environments. The social and physical forces affected the pedestrian behaviours in PedFlow simulation. The structure of the data needed in PedFlow was also demonstrated. Mataaf area was tested using the developed simulation model to determine its average capacity.

Kim *et al.* [139] presented an interactive algorithm to model physics-based interactions in dense crowds. The authors combined a velocity-based collision-avoidance algorithm with external physical forces. The overall model produces various effects of forces acting on agents and crowds, including balance recovery motion and force propagation through the crowd. The authors further extended the method to model more complex behaviours involving social and cultural rules. Finite-state machines are also used to specify a series of behaviours and demonstrate our approach to many complex scenarios.

Nasir and Sunar [140] address the recent incident that occurred in Mina, Saudi Arabia, when two large pilgrim groups converged on the same street, causing a crowd crush. Since many of the crowd simulation techniques introduced tend to focus more on individual behaviours while ignoring group behaviours, less attention was given on the grouping aspects of the crowd even though it is a common phenomenon and a key element affecting crowd behaviour. This paper intends to create a simulation of the multi-group crowd under reasonable conditions based on the Social Force model. Tawaf is used as a case study due to its heterogeneous nature.

Majid *et al.* [141] provide a parallel simulation model that will improve the performance of pilgrims performing the vital ritual of Tawaf in large numbers. An optimized parallel model is proposed. The model utilized is based on the agent-based architecture, which comprises agents having a reactive design that responds to a fixed set of stimuli.

## VI. DISCUSSION

Integrating past Hajj events and the research work related to Hajj crowd management and planning presented in this paper helped us to further classify the Hajj event into four phases. This classification is based on proposed and implemented technologies before, during and after the Hajj event (Fig 13).

The planning phase is completed before Hajj, Operation and Monitoring phases are carried out during Hajj, whereas the Evaluation or Analysis is done after the completion of the

**TABLE 3. Summary of research article with the description of Hajj phases and technologies proposed and/or implemented by different researchers for the Hajj event.**

| Author | Taxonomy | Technology Proposed/Used | Application | Implementation | Phase |
|---|---|---|---|---|---|
| Schlosser [20] | Immersive Technology | Virtual Reality | Game to learn about Hajj | Theoretical | Operation |
| Muslim 3D [21] | Immersive Technology | Virtual Reality | Virtual Guide | Theoretical | Monitoring |
| Labbaik [22] | Immersive Technology | Virtual Reality | Virtual Guide | Theoretical | Planning |
| Nassr et al. [25] | Immersive Technology | Virtual Reality | Virtual Navigation | Practical | Planning |
| Obaida et al. [26][27] | Immersive Technology | Augmented Reality | OnDemand Guidance | Practical | Planning |
| Taileb et al [28] | Immersive Technology | Augmented Reality, GPS, Accelerometer | Location-based services | Practical | Planning |
| News Cast Studio [29] | Immersive Technology | Augmented Reality | Augmented Guide | Theoretical | Planning |
| Mohamed et al. [35] | Wireless | RFID-Tags | Pilgrims Tracking | Theoretical | Monitoring |
| Nasser et al. [36] | Wireless | WSN & Sensor Units | Crowd Monitoring Framework | Theoretical | Monitoring |
| Islam et al. [37] | Wireless | Sensors, Wemos D1(Wi-Fi-based board) | Crowd controlling system using E-wrist belt to predict possible stampede risk | Theoretical | Monitoring |
| Jassem et al. [40] | Wireless | GPS, Ad-hoc network | Pilgrims Tracking and Monitoring Large groups | Theoretical | Monitoring |
| Anas Basalamah [41][48] | Wireless | BLE | Crowd Sensing | Practical | Operation / Monitoring |
| Anis et al. [42] | Wireless | RF | Multilingual Speech Translation System | Theoretical | Operation |
| Mohandes [43][44][45][46] | Wireless | RFID | Pilgrims Identification and Tagging | Practical | Monitoring |
| Jamil et al., [47] | Wireless | BLE | Hybrid Crowd Sensing for Group Dynamics | Practical | Operation |
| Yamin et al. [50] | Wireless | GPS and RFID-Tags | Management Framework for Large and Dense Crowds | Theoretical | Planning |
| Hashedi et al., [51] | Wireless | RFID | Implementation of RFID System - Pilgrims Identification and Tagging | Theoretical | Planning |
| Naser et al. [52] | Wireless | RFID | Pilgrims Tracking & Monitoring System | Theoretical | Monitoring |
| Mantoro et al., [105] | Wireless | GPS | Pilgrims Tracking and Monitoring System | Practical | Monitoring |
| Binsalleeh et al. [56] | Wireless | RFID | Pilgrims Tracking and Tagging | Theoretical | Monitoring |
| Hidayat et al. [57] | Wireless | GPS, RFID | Pilgrims Tracking | Theoretical | Monitoring |
| Alsubhy et al. [58] | Wireless | RFID | Pilgrims Tracking and Monitoring | Theoretical | Monitoring |
| Mitchell et al., [59] | Wireless | RFID | Pilgrims Tracking | Theoretical | Monitoring |
| Khan [60] | Wireless | GPS, RFID | Pilgrims Tracking and Monitoring | Practical | Monitoring |
| Yamin et al., [38] | Wireless | RFID, GPS, WSNs, | Crowd Control and Management System | Theoretical | Analysis |
| Haase et al. [15] | Wireless | RFID | Tracking and Monitoring pilgrims, transportation | Practical | Operation / Monitoring |
| Koshak et al., [61] | Wireless | RFID | Transportation, Pilgrims and Vehicles Mobility | Practical | Operation |
| Tayan et al., [134][135] | Wireless | WSN, GPS | Crowd Traffic Monitoring | Theoretical | Monitoring |

**TABLE 3.** *(Continued.)* **Summary of research article with the description of Hajj phases and technologies proposed and/or implemented by different researchers for the Hajj event.**

| | | | | | |
|---|---|---|---|---|---|
| Ahmad et al., [101] | Wireless | GPS | Location-Based Services | Theoretical | Monitoring |
| Ahmad et al., [1] | Wireless | GPS | Location-Based Services | Practical | Planning |
| Koshak et al. [82] | Wireless | GPS & GIS | Tracking and Monitoring | Practical | Planning/ Analysis |
| Yamin et al. [11] | Wireless | RFID | Pilgrims Tracking and Identification | Practical | Operation / Monitoring |
| Sonia et al. [53] | Wireless | RFID | Optimal Monitoring & Pilgrim's Evacuation | Theoretical | Monitoring |
| Parveen et al., [104] | Wireless | GPS | Missing Pilgrims Tracking System | Theoretical | Monitoring |
| Saqib et al., [63] | Computer Vision | Hierarchical Clustering | Crowd density and Crowd flow estimation | Theoretical | Monitoring |
| Arif et al. [64] | Computer Vision | Blob analysis | Crowd Counting | Theoretical | Monitoring |
| Sultan et al., [67] | Computer Vision | Machine Learning | Crowd Congestion detection and Crowd density | Theoretical | Operation |
| Hussain et al. [68] | Computer Vision | Neural network | Crowd density | Theoretical | Monitoring |
| Sultan et al., [69] | Computer Vision | Oscillation maps | Crowd Congestion detection | Theoretical | Monitoring |
| Musa et al. [70] | Computer Vision | Erosion techniques, Recursive traversing | Crowd Counting and Crowd density | Theoretical | Monitoring |
| Sajid et al., [72] | Computer Vision | Adaptive thresholding and Slit Window | Crowd Counting | Theoretical | Operation |
| Adnan et al. [74] | Computer Vision | Thermal Vision | Crowd Density | Theoretical | Operation |
| Dridi in [73] | Computer Vision | Neural Networks | Crowd Tracking | Practical | Monitoring |
| Al-Khaffaf et al. [75] | Computer Vision | Background modelling and Active Contours | Crowd Speed and density | Theoretical | Monitoring |
| Khozium et al. [76] | Computer Vision | Thermal vision and fuzzy logic | Crowd flow and density | Theoretical | Monitoring |
| Al-Sheary et al. [77] | Computer Vision | Image Segmentation | Crowd Density | Practical | Monitoring |
| Eldursi et al. [78] | Computer Vision | Feature Extraction and Classification | Crowd Density | Theoretical | Monitoring |
| Alharbi et al., [79] | Computer Vision | Viola–Jones object detection framework | Crowd Counting | Theoretical | Monitoring |
| Yan et al, [80] | Computer Vision | Feature Extraction and Classification | Crowd Density | Theoretical | Monitoring |
| Haase et al. [15] | Spatial Computing | Optimize Scheduling | Scheduling | Practical | Planning |
| Felemban et al. [16] | Spatial Computing | Preference-based Optimize Scheduling | Scheduling | Practical | Planning |
| Faizan et al. [17] | Spatial Computing | Preference-based Optimize Rescheduling | Emergency Rescheduling | Practical | Planning |
| Mahmood et al., [85] | Spatial Computing | Simulation | Evacuation Simulation | Theoretical | Planning |
| Felemban et al., [87] | Spatial Computing | Knowledge Extraction | Evacuating Pilgrim | Theoretical | Planning |
| Bilal et al., [88] | Spatial Computing | Big Data | Evacuating Pilgrim | Theoretical | Planning |
| Yang et al.,[89] | Spatial Computing | Spatial Anomaly Avoidance | Evacuating Pilgrim | Theoretical | Planning |
| Charles et al. [81] | Spatial Computing | GPS | Pilgrims Tracking | Practical | Planning / Operation |
| Haboubi et al.[142] | Spatial Computing | Spiral Path model | Congestion Alleviation | Theoretical | Planning |
| Abdelghany et al., [114] | Spatial Computing | Spatio-temporal analysis | Ritual levels of service and flow rate | Theoretical | Planning |
| Koshak et al., [82] | Spatial Computing | Agent-Based Modelling and Simulation (ABMS) | Ritual throughput and safety | Theoretical | Planning |
| Khan et al., [83] | Spatial Computing | Spiral Path model | Pilgrim movement, congestion alleviation | Practical | Planning/ Analysis |
| Shuaibu et al., [84] | Spatial Computing | Crowd Social Identification | Crowd density and safety | Practical | Planning/ Analysis |

**TABLE 3.** ***(Continued.)*** **Summary of research article with the description of Hajj phases and technologies proposed and/or implemented by different researchers for the Hajj event.**

| | | | | | |
|---|---|---|---|---|---|
| Mahmood et al. [85] | Spatial Computing | Mesoscale Bio-Inspired model, Shortest Distance of the Region (SDR) Algorithm | Crowd Evacuation, Capacity Evaluation | Theoretical | Planning/ Analysis |
| Ahmed et al., [86] | Spatial Computing | Spatial Web mapping | Emergency Reporting and Response | Theoretical | Planning |
| Akhlaq [12] | Social Media | Mobile App | Information diffusion | Theoretical | Planning / Operation |
| Ahmad et al., [90] | Social Media | Mobile App | Context-aware services | Practical | Planning / Operation |
| Mahmoud Elgamal [91] | Social Media | Big Data, Twitter and Mobile Sensors | Pilgrims Sentiment Analysis | Theoretical | Operation |
| Ghassan [92] | Social Media | Big Data, Twitter | Dashboard and visualization | Theoretical | Operation |
| Qurashi et al., [93] | Social Media | Mobile App | Data Analysis | Theoretical | Operation |
| Bilal et al., [94] | Social Media | GPS, Big Data, Mobile App | Pilgrims Geo-tagged Multimedia Contents | Theoretical | Monitoring |
| Yamin et al., [95] | Social Media | Mobile App | Disaster Management | Theoretical | Analysis |
| Faizan et al., [102] | Mobile Application | GPS | Location-Based Services | Practical | Planning/ Analysis |
| Ahmad et al. [2] | Mobile Application | Mobile Application, GPS | Pilgrims Tracking and Monitoring | Theoretical | Planning |
| Koshak et al. [61] | Mobile Application | RFID | Pilgrims Tracking and Monitoring | Theoretical | Planning |
| Rahman et al. [98] | Mobile Application | GPS | Pilgrims Tracking and Monitoring | Practical | Operation |
| Mohamed et al. [99] | Mobile Application | GPS | Pilgrims Tracking and Guidance | Practical | Operation |
| Faizan et al. [103] | Mobile Application | GPS | Pilgrims Tracking and Monitoring | Practical | Operation |
| Ahmed et al. [101] | Mobile Application | GPS | Pilgrims Geo-tagged Multimedia Contents | Practical | Operation |
| Emad Felemban [19] | Big Data Analytics | Visualization | Interactive Dashboard | Practical | Monitoring |
| Nafea [106], [113] | Big Data Analytics | Data Analytics | Dashboards and Visualization | Theoretical | Operation |
| S. Snoussi et. al. [107], [108] | Big Data Analytics | Mobile App, GPS | Pilgrimage steps based on geo-localization | Theoretical | Operation |
| Sadiq et al. [109] | Big Data Analytics | GPS | Pilgrim Sensory Data | Theoretical | Monitoring |
| Ahmad et al. [110] | Big Data Analytics | GPS, Camera, Mobile App | Pilgrims Geo-tagged Multimedia Contents | Theoretical | Operation |
| Sadiq et al. [94] | Big Data Analytics | GPS, Mobile App | Pilgrims Geo-tagged Multimedia Contents | Theoretical | Operation |
| Saeed et.al. [111] | Big Data Analytics | Smart Wearable Device | Pilgrim location and sensor data | Practical | Operation |
| Atta et. al. [112] | Big Data Analytics | Data Analytics | Dashboards and Visualization | Theoretical | Operation |
| Koshak [115] | Crowd Simulation | Spatial-temporal visualization | Pilgrim movement | Theoretical | Monitoring |
| Ramadan et al. [116] | Crowd Simulation | Simulation Language | Shuttle Bus service | Theoretical | Planning/ Analysis |
| Sarmady at el. [117] | Crowd Simulation | Micro-macro Crowd Simulator model | Tawaf Simulation | Theoretical | Planning |
| Narain et al, [118] | Crowd Simulation | Reciprocal velocity obstacles (RVO) model | Specific and Random movement of Pilgrims | Theoretical | Operation |
| Zainuddin et al. [119] | Crowd Simulation | Microscopic Pedestrian Simulation Model | Pilgrim Circumambulation | Practical | Planning/ Analysis |
| Mulyana et al. [120] | Crowd Simulation | Agent decision model | Pilgrim Simulation | Theoretical | Planning/ Analysis |
| Zainuddin et al. [121] | Crowd Simulation | Social Forces Model | Pedestrian Flow | Practical | Operation |
| Sarmady et al. [122] | Crowd Simulation | Cellular Automata Model | Circular Movement | Theoretical | Planning/ Analysis |
| Tunasar [123] | Crowd Simulation | Collision Avoidance Model | Movement pattern | Theoretical | Planning/ Analysis |
| Curtis et al. [124] | Crowd Simulation | Right of Way model | Pilgrim Movement | Practical | Operation |
| Curtis et al. [125] | Crowd Simulation | Right of Way model | Pilgrim Movement | Practical | Planning/ Analysis |

**TABLE 3.** *(Continued.)* **Summary of research article with the description of Hajj phases and technologies proposed and/or implemented by different researchers for the Hajj event.**

| | | | | | |
|---|---|---|---|---|---|
| Manenti et al. [126] | Crowd Simulation | Agent-Based Proxemics Model | Heterogeneous Cultural Proxemics of Pilgrims | Practical | Operation / Analysis |
| Reffat [127] | Crowd Simulation | Crowd Management Framework | Traffic Movement and Evacuation | Practical | Planning/ Analysis |
| Haghighati et al. [128] | Crowd Simulation | Discrete-event simulation, ARENA | Pilgrim Movement Pattern | Theoretical | Analysis |
| Crociani et al. [129] | Crowd Simulation | Utility-based agents | Crowd Management Planning, Simulation, and Evaluation | Theoretical | Planning/ Analysis |
| Alonso et al. [130] | Crowd Simulation | Discrete element model (DEM) | Pilgrim Movement Patterns and Panic Behaviour | Practical | Planning / Operation |
| Curtis et al. [131] | Crowd Simulation | Priority-based Reciprocal velocity obstacles (RVO) model | Mataaf Capacity and ritual completion time | Theoretical | Planning |
| Sakellariou et al. [132] | Crowd Simulation | X-Machine Model | Pilgrim movement pattern | Practical | Planning/ Analysis |
| Shuaibu et al. [133] | Crowd Simulation | Collision Avoidance path | Pilgrim movement for Tawaf | Theoretical | Analysis |
| Tayan et al. [134][135] | Crowd Simulation | WSN-based transportation system deployment approach | Traffic Monitoring and Control, Bottleneck modelling | Theoretical | Planning/ Analysis |
| Rahman et al. [136] | Crowd Simulation | Realistic Movement patterns | Pilgrim Movement | Theoretical | Planning / Operation |
| Kurdi et al. [137] | Crowd Simulation | Survey of recent technologies in simulation | Pilgrim Movement Behaviour | Theoretical | Operation / Analysis |
| Dridi et al. [138] | Crowd Simulation | PedFlow force models | High-density crowd behaviour. in crowded places | Theoretical | Analysis |
| Kim et al. [139] | Crowd Simulation | Velocity-based collision-avoidance algorithm | Physical Interaction among pilgrims while moving | Theoretical | Planning |
| Nasir et al. [140] | Crowd Simulation | Condition-based Social force model | Group Behaviour Movement | Practical | Operation |
| Majid et al. [141] | Crowd Simulation | Performance Optimization over GPGPU | Large Scale Pilgrim Movement | Practical | Palnning / Operation |
| Keith et al. [18] | Crowd Simulation | Crowd Simulation | Simulation | Practical | Planning / Operation |
| Abdelghany et al., [114] | Crowd Simulation | Cellular Automata Discrete System | Flow Rate | Theoretical | Planning |

entire Hajj event which lays the basis to explore new methods for better crowd management and improve the quality of services.

In the previous sections, we have presented a summary of previously published research papers (from 2007 to 2020) and articles discussing technologies. We have classified the papers into two categories based on whether the technologies proposed by researchers were just theoretical and/or were implemented for the Hajj crowd management. Table 3 summarizes the entire discussion, where phase column provides additional information about the classification of the scientific contributions into four phases of Hajj. Based on the information tabulated in Table 3. We have plotted a few graphs which will give an overview of the entire survey about the technologies proposed and/or implemented during the past Hajj events.

Fig 14 (a-d) is the summary of the research contributions that were published from the year 2007 to 2020. Most of the researchers focused on theoretical work (64%) and were successful in publishing their work in international journals (Fig 14 (a)). When these surveyed papers were categorized into four phases of Hajj (Fig 13), we found that most of the publications fall in the planning phase (32%) however both in Operational and Monitoring phases the publications were about (26%) each. With emerging Big Data analysis techniques and tools, we expect that the number of publications in addressing the analysis phase will increase. Fig 14 (c) is the summary of scientific contributions categorized into eight different technologies that were proposed or used by the researchers during the past Hajj events. Since Hajj is a massive heterogeneous crowd, crowd management is always prioritized with other necessary arrangements. This has been demonstrated by a large number of publications in the crowd modelling and simulation area. Fig 14 (d) presents Wireless Technology at the top that has been used in tracking individuals and pilgrims in the group and eventually helping the authorities to plan for better crowd management. Similar to (b), Fig 14 (d) demonstrates that the least number

of research papers have been published in the analysis area whereas the most number of papers have been published in technology areas.

## VII. CONCLUSION

Managing millions of pilgrims from all over the world gathering for Hajj event at Makkah is a daunting task. The Hajj crowd is diversified in terms of language, age, race and culture, and requires an adaptive set of services for better performance of Hajj rituals. Organizers are working at their best to ensure the smooth organization of the Hajj event and allow researchers to explore modern methods and apply latest technology techniques to improve the level of available services. In this paper, we presented a survey of advanced technologies that have been used for crowd management during past Hajj events, and the solutions to enhance the safety and security of the pilgrims throughout their stay in the KSA. We have also included current research work and its intended implementation during the Hajj 2020 event. Although advanced technologies provide remedies to tackle crowd management issues to a good extent, we propose the integration of added effective technology like data analysis that could aid in discovering useful information with the help of data mining, text analytics and data visualization. This can support the decision-making process. Moreover, the technology may allow the authorities to telecast official information of pilgrim status in real-time.

## REFERENCES


[1] A. Ahmad, M. A. Rahman, M. R. Wahiddin, F. U. Rehman, A. Khelil, and A. Lbath, "Context-aware services based on spatio-temporal zoning and crowdsourcing," *Behav. Inf. Technol.*, vol. 37, no. 7, pp. 736–760, Jul. 2018.

[2] A. Ahmad, M. A. Rahman, F. U. Rehman, A. Lbath, I. Afyouni, A. Khelil, S. O. Hussain, B. Sadiq, and M. R. Wahiddin, "A framework for crowd-sourced data collection and context-aware services in Hajj and Umrah," in *Proc. IEEE/ACS 11th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Nov. 2014, pp. 405–412.

[3] A. Ahmad, M. R. Wahiddin, M. A. Rahman, I. Afyoni, B. Sadiq, F. U. Rahman, and S. Ghani, "Scale free network analysis of a large crowd through their spatio-temporal activities," in *Proc. 4th Int. Conf. Adv. Comput. Sci. Appl. Technol. (ACSAT)*, Dec. 2015, pp. 127–132.

[4] Pew Research Center. *Why Muslims Are the World's Fastest-Growing Religious Group*. Accessed: Jul. 5, 2020. [Online]. Available: https://www.pewresearch.org/fact-tank/2017/04/06/why-muslims-are-the-worlds-fastest-growing-religious-group/

[5] Al-Arabia. (2014). *Saudi Arabia Has Hosted 25 Million Hajj Pilgrims in 10 Years*. Accessed: Jul. 26, 2020. [Online]. Available: https://english.alarabiya.net/en/perspective/features/2014/10/19/Saudi-Arabia-hosted-25m-hajj-pilgrims-in-past-10-years

[6] *General Authority of Statistics, Kingdom of Saudi Arabia*. Accessed: Jul. 27, 2020. [Online]. Available: https://www.stats.gov.sa/en

[7] H. Alnabulsi and J. Drury, "Social identification moderates the effect of crowd density on safety at the Hajj," *Proc. Nat. Acad. Sci. USA*, vol. 111, no. 25, pp. 9091–9096, Jun. 2014.

[8] D. Helbing, A. Johansson, and H. Z. Al-Abideen, "Dynamics of crowd disasters: An empirical study," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 75, no. 4, Apr. 2007, Art. no. 046109.

[9] B. Kantarci, P. M. Glasser, and L. Foschini, "Crowdsensing with social network-aided collaborative trust scores," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6.

[10] A. A. Khan and E. K. Noji, "Hajj stampede disaster, 2015: Reflections from the frontlines," *Amer. J. Disaster Med.*, vol. 11, no. 1, pp. 59–68, Jan. 2016.

[11] M. Yamin and M. A. Albugami, "An architecture for improving Hajj management," in *Proc. IFIP Adv. Inf. Commun. Technol.*, vol. 426, 2014, pp. 187–196.

[12] A. Ahmad, "Complex network modelling and analysis of Hajj crowd and MERS-CoV outbreak," Ph.D. dissertation, Dept. Comput. Sci., Kulliyah Inf. Commun. Technol., Int. Islamic Univ., Kuala Lumpur, Malaysia, 2017.

[13] J. J. Fruin, "The causes and prevention of crowd disasters," *Eng. Crowd Saf.*, vol. 1, no. 10, pp. 99–108, 1993.

[14] K. Shafique, B. A. Khawaja, F. Sabir, S. Qazi, and M. Mustaqim, "Internet of Things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios," *IEEE Access*, vol. 8, pp. 23022–23040, 2020.

[15] K. Haase, H. Z. Al Abideen, S. Al-Bosta, M. Kasper, M. Koch, S. Müller, and D. Helbing, "Improving pilgrim safety during the Hajj: An analytical and operational research approach," *Interfaces*, vol. 46, no. 1, pp. 74–90, Feb. 2016.

[16] E. Felemban, A. Fatani, and F. U. Rehman, "An optimized scheduling process for a large crowd to perform spatio-temporal movements safely during pilgrimage," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2019, pp. 6049–6051.

[17] F. U. Rehman and E. Felemban, "A preference-based interactive tool for safe rescheduling of groups for Hajj," in *Proc. IEEE/ACS 16th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Nov. 2019, pp. 1–2.

[18] G. K. Still. *Modelling the Jamarat bridge (2000–2005)*. Accessed: Aug. 10, 2020. [Online]. Available: https://www.gkstill.com/CV/Projects/Jamarat.html

[19] E. Felemban. (2020). *Designing a Multi-Level Dashboard to Monitor Mobility Progress in Hajj 1441–2020*. Accessed: Aug. 8, 2020. [Online]. Available: https://www.linkedin.com/pulse/designing-multi-level-dashboard-monitor-mobility-hajj-emad-felemban/?trackingId=jYOpXexWQri1iL3TOCpFFQ%3D%3D

[20] D. Schlosser, "Digital Hajj: The pilgrimage to mecca in muslim cyberspace and the issue of religious online authority," *Scripta Instituti Donneriani Aboensis*, vol. 25, pp. 189–203, Jan. 2013.

[21] M. 3D. *A Virtual World of Worship and Knowledge*. Accessed: Jul. 27, 2020. [Online]. Available: http://www.muslim3d.com/

[22] Labbaik. *Virtual Reality Hajj Simulator*. Accessed: Aug. 3, 2020. [Online]. Available: http://www.labbaikvr.com/

[23] E. A. Khan and M. K. Y. Shambour, "An analytical study of mobile applications for Hajj and Umrah services," *Appl. Comput. Informat.*, vol. 14, no. 1, pp. 37–47, Jan. 2018.

[24] M. S. M. Rahim, A. Z. A. Fata, A. H. Basori, A. S. Rosman, T. J. Nizar, and F. W. M. Yusof, "Development of 3D Tawaf simulation for Hajj training application using virtual environment," in *Proc. Int. Vis. Inform. Conf.*, Berlin, Germany. Cham, Switzerland: Springer, Nov. 2011, pp. 67–76.

[25] R. Nassr, A. A. H. S. Aborujilah, H. M. Almalki, and S. Musa, "Pilgrims' acceptance of using augmented reality applications while performing the Hajj," *Int. J. Eng. Technol.*, vol. 7, no. 4, pp. 69–71, 2018.

[26] A. Owaidah, D. Olaru, M. Bennamoun, F. Sohel, and N. Khan, "Review of modelling and simulating crowds at mass gathering events: Hajj as a case study," *J. Artif. Societies Social Simul.*, vol. 22, no. 2, pp. 1–9, 2019.

[27] A. Owaidah, "Hajj crowd management via a mobile augmented reality application: A case of The Hajj event, Saudi Arabia," Ph.D. dissertation, Univ. Glasgow, Glasgow, U.K., 2015.

[28] M. Taileb, E. Al-Ghamdi, N. Al-Ghanmi, A. Al-Mutari, K. Al-Jadani, M. Al-Ghamdi, and A. Al-Mutari, "Manasek AR: A location-based augmented reality application for Hajj and Umrah," in *Proc. Int. Conf. Virtual, Augmented Mixed Reality*, Heraklion, Crete, Greece. Cham, Switzerland: Springer, 2014, pp. 134–143.

[29] NewscastStudio. *Al Jazeera Uses Augmented Reality to Explain Complexities of Hajj*. Accessed: Dec. 7, 2020. [Online]. Available: https://www.newscaststudio.com/2019/08/21/hajj-augmented-reality/?utm_source=youtube&utm_medium=youtubefullcoveragelink&utm_campaign=youtubefullcoveragelink

[30] C. Flavián, S. Ibáñez-Sánchez, and C. Orús, "The impact of virtual, augmented and mixed reality technologies on the customer experience," *J. Bus. Res.*, vol. 100, pp. 547–560, Jul. 2019.

[31] M. Y.-C. Yim and S.-Y. Park, "'I am not satisfied with my body, so I like augmented reality (AR)': Consumer responses to AR-based product presentations," *J. Bus. Res.*, vol. 100, pp. 581–589, Jul. 2019.

[32] A.-C. Haugstvedt and J. Krogstie, "Mobile augmented reality for cultural heritage: A technology acceptance study," in *Proc. IEEE Int. Symp. Mixed Augmented Reality (ISMAR)*, Nov. 2012, pp. 247–255.
[33] M. K. Bekele, R. Pierdicca, E. Frontoni, E. S. Malinverni, and J. Gain, "A survey of augmented, virtual, and mixed reality for cultural heritage," *J. Comput. Cultural Heritage*, vol. 11, no. 2, pp. 1–36, Jun. 2018.
[34] M. Farshid, J. Paschen, T. Eriksson, and J. Kietzmann, "Go boldly!: Explore augmented reality (AR), virtual reality (VR), and mixed reality (MR) for business," *Bus. Horizons*, vol. 61, no. 5, pp. 657–663, 2018.
[35] M. F. Mohamed, A. E.-R. Shabayek, and M. El-Gayyar, *IoT-Based Framework for Crowd Management*. Cham, Switzerland: Springer, 2019, pp. 47–61.
[36] N. Nasser, M. Anan, M. F. C. Awad, H. Bin-Abbas, and L. Karim, "An expert crowd monitoring and management framework for Hajj," in *Proc. Int. Conf. Wireless Netw. Mobile Commun. (WINCOM)*, Nov. 2017, pp. 1–8.
[37] S. Islam, A. Kafi, M. Z. Islam, N. Islam, and M. N. Ullah, "IoT based crowd congestion and stampede avoidance in Hajj using wemos d1 with machine learning approach," in *Proc. 4th Int. Conf. Electr. Inf. Commun. Technol. (EICT)*, Dec. 2019.
[38] M. Yamin, A. M. Basahel, and A. A. Abi Sen, "Managing crowds with wireless and mobile technologies," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–15, Aug. 2018.
[39] Internet of Things. (2019). *Mobile IoT Innovators Spotlight: Hajj Gear*. Accessed: Jun. 25, 2020. [Online]. Available: https://www.gsma.com/iot/news/mobile-iot-innovators-spotlight-hajj-gear/
[40] A. Al Jassem, F. Farasha, S. Abdul-Nabi, A. Bazzi, and I. El Sayad, "Offline group locator and tracking system," in *Proc. Sensors Netw. Smart Emerg. Technol. (SENSET)*, Jan. 2017, pp. 1–4.
[41] A. Basalamah, "Crowd mobility analysis using WiFi sniffers," *Int. J. Adv. Comput. Sci. Appl.*, vol. 7, no. 12, pp. 374–378, 2016.
[42] M. Anis and Z. Saeed, "Wireless network architecture and RF transceiver front-end to provide multilingual speech translation and local positioning system for Hajj operations," in *Proc. Saudi Int. Electron., Commun. Photon. Conf. (SIECPC)*, Apr. 2011, pp. 1–3.
[43] M. Mohandes, M. A. Haleem, A. Abul-Hussain, and K. Balakrishnan, "Pilgrims tracking using wireless sensor network," in *Proc. IEEE Workshops Int. Conf. Adv. Inf. Netw. Appl.*, Mar. 2011, pp. 325–328.
[44] M. Mohandes, "An RFID-based pilgrim identification system (a pilot study)," in *Proc. 11th Int. Conf. Optim. Electr. Electron. Equip.*, May 2008, pp. 107–112.
[45] M. Mohandes, M. Haleem, M. Deriche, and K. Balakrishnan, "Wireless sensor networks for pilgrims tracking," *IEEE Embedded Syst. Lett.*, vol. 4, no. 4, pp. 106–109, Dec. 2012.
[46] M. A. Mohandes, "Mobile technology for socio-religious events: A case study of NFC technology," *IEEE Technol. Soc. Mag.*, vol. 34, no. 1, pp. 73–79, Mar. 2015.
[47] S. Jamil, A. Basalamah, A. Lbath, and M. Youssef, "Hybrid participatory sensing for analyzing group dynamics in the largest annual religious gathering," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. (UbiComp)*, 2015, pp. 547–558.
[48] A. Basalamah, "Sensing the crowds using Bluetooth low energy tags," *IEEE Access*, vol. 4, pp. 4225–4233, 2016.
[49] A. Jabbari, S. Song, and M. Aal, "DEMO: Dense mode mobile crowd sensing for collision prediction and protection," pp. 164–172.
[50] M. Yamin and Y. Ades, "Crowd management with RFID & wireless technologies," in *Proc. 1st Int. Conf. Netw. Commun. NetCoM*, 2009, pp. 439–442.
[51] A. H. Al-Hashedi, M. R. H. M. Arshad, A. S. Baharudin, H. H. Mohamed, and O. Osman, "Strategic information systems planning for RFID implementation in Hajj management systems," in *Proc. 6th Int. Conf. Inf. Technol. Multimedia UNITEN Cultivating Creativity Enabling Technol. Through Internet Things (ICIMU)*, 2014, pp. 146–150.
[52] M. Naser, M. Rafie, R. Budiarto, and W. A. H. A. Alsalihy, "Security considerations in embedding RFID in 'Hajj' system," *Eur. J. Sci. Res.*, vol. 42, no. 1, pp. 133–138, 2010.
[53] S. Hashish and M. Ahmed, "Efficient wireless sensor network rings overlay for crowd management in Arafat area of Makkah," in *Proc. IEEE Int. Conf. Signal Process., Informat., Commun. Energy Syst. (SPICES)*, Feb. 2015, pp. 1–6.
[54] M. Mohandes, "A case study of an RFID-based system for pilgrims identification and tracking," in *Sustainable Radio Frequency Identification Solutions*. Vienna, Austria: IntechOpen, 2010, pp. 87–104.
[55] M. Mohandes, "RFID-based system for pilgrims identification and tracking," *Appl. Comput. Electromagn. Soc. J.*, vol. 25, no. 3, pp. 273–282, 2010.
[56] H. Binsalleeh, N. Mohammed, P. S. Sandhu, F. Aljumah, and B. C. M. Fung, "Using RFID tags to improve pilgrimage management," in *Proc. Int. Conf. Innov. Inf. Technol. (IIT)*, Dec. 2009, pp. 1–5.
[57] C. W. Hidayat, F. S. Rozak, F. A. Aziz, and B. S. R. Purwanti, "Implementation of RFID as tracking for Hajj pilgrims connected with GPS (IM RFID secure GPS)," in *Proc. AIP Conf.*, vol. 2088, no. 1, 2019, Art. no. 020032.
[58] A. M. Alsubhy, A. A. A. Sen, B. A. Alahmadi, N. M. Bahbouh, and H. A. A. Sen, "A model for tracking people and property in crowds," in *Proc. 7th Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, Mar. 2020, pp. 244–248.
[59] R. O. Mitchell, H. Rashid, F. Dawood, and A. AlKhalidi, "Hajj crowd management and navigation system: People tracking and location based services via integrated mobile and RFID systems," in *Proc. Int. Conf. Comput. Appl. Technol. (ICCAT)*, Jan. 2013, pp. 1–7.
[60] E. A. Khan, "An RFID-based system for pilgrim management in King Abdul Aziz international airport," in *Proc. Int. Conf. Inf. Manage., Innov. Manage. Ind. Eng.*, vol. 1, Nov. 2011, pp. 124–129.
[61] N. Koshak and A. Nour, "Integrating RFID and GIS to support urban transportation management and planning of Hajj," in *Proc. 13th Int. Conf. Comput. Urban Planning Urban Manage. Planning Support Syst. Sustain. Urban Develop. (CUPUM)*, 2013, pp. 1–19.
[62] B. Yogameena and C. Nagananthini, "Computer vision based crowd disaster avoidance system: A survey," *Int. J. Disaster Risk Reduction*, vol. 22, pp. 95–129, Jun. 2017.
[63] M. Saqib, S. Daud Khan, N. Sharma, and M. Blumenstein, "Extracting descriptive motion information from crowd scenes," in *Proc. Int. Conf. Image Vis. Comput. New Zealand (IVCNZ)*, Dec. 2017, pp. 1–6.
[64] M. Arif and S. Daud, "Institute of advanced engineering and science counting of people in the extremely dense crowd," *IAES Int. J. Artif. Intell.*, vol. 2, no. 2, pp. 51–58, 2013.
[65] K. B. Atkinson, "Introduction to modern Photogrammetry.," *Photogramm. Rec.*, vol. 18, no. 104, pp. 329–330, Dec. 2003.
[66] C. F. Olson, "Maximum-likelihood template matching," in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit.*, vol. 2, Jun. 2000, pp. 52–57.
[67] S. D. Khan, M. Tayyab, M. K. Amin, and A. Nour, "Towards a crowd analytic framework for crowd management in Majid-al-Haram," Tech. Rep., Sep. 2017, pp. 1–11.
[68] N. Hussain, H. S. M. Yatim, N. L. Hussain, J. L. S. Yan, and F. Haron, "CDES: A pixel-based crowd density estimation system for Masjid Al-Haram," *Saf. Sci.*, vol. 49, no. 6, pp. 824–833, Jul. 2011.
[69] S. D. Khan, "Congestion detection in pedestrian crowds using oscillation in motion trajectories," *Eng. Appl. Artif. Intell.*, vol. 85, pp. 429–443, Oct. 2019.
[70] A. Musa, M. M. Rahman, M. S. Sadi, and M. S. Rahman, "Crowd reckoning towards preventing the repeat of 2015 Hajj pilgrims stampede," in *Proc. 2nd Int. Conf. Electr. Electron. Eng. (ICEEE)*, Dec. 2017, pp. 1–4.
[71] S. N. Kane, A. Mishra, and A. K. Dutta, "International conference on recent trends in physics 2016 (ICRTP2016)," *J. Phys. Conf. Ser.*, vol. 755, no. 1, Oct. 2016, Art. no. 011001.
[72] M. Sajid, A. Hassan, and S. A. Khan, "Crowd counting using adaptive segmentation in a congregation," in *Proc. IEEE Int. Conf. Signal Image Process. (ICSIP)*, Aug. 2016, pp. 745–749.
[73] M. H. Dridi, "Tracking individual targets in high density crowd scenes analysis of a video recording in Hajj 2009," *Current Urban Stud.*, vol. 3, no. 1, pp. 35–53, 2015.
[74] A. A. Adnan, M. Khozium, and E. Abdrabou, "Real-time crowd monitoring using infrared thermal video sequences," *J. Amer. Sci.*, vol. 8, no. 3, pp. 133–140, 2012.
[75] H. S. M. Al-Khaffaf, F. Haron, S. Sarmady, A. Z. Talib, and I. M. Abu-Sulyman, "Crowd parameter extraction from video at the main gates of Masjid al-Haram," *Adv. Intell. Soft Comput.*, vol. 133, pp. 727–736, 2012.
[76] M. O. Khozium, "A hybrid intelligent information system for the administration of massive mass of Hajjis," *Life Sci. J.*, vol. 9, no. 4, pp. 171–180, 2012.
[77] A. Al-Sheary and A. Almagbile, "Crowd monitoring system using unmanned aerial vehicle (UAV)," *J. Civil Eng. Archit.*, vol. 11, no. 11, pp. 1014–1024, Nov. 2017.

[78] S. Eldursi, N. Alamoudi, F. Haron, F. Aljarbua, and G. Albakri, "Crowd density estimation system for Al-Masjid Al-Haram," *Int. J. Comput. Commun. Instrum. Eng.*, vol. 4, no. 1, pp. 60–63, Feb. 2017.

[79] A. Alharbi, A. Aloufi, E. Hamawi, F. Alqazlan, S. Babaeer, and F. Haron, "Counting people in a crowd using viola-jones algorithm," *Int. J. Comput. Commun. Instrum. Eng.*, vol. 4, no. 1, pp. 57–59, 2017.

[80] J. Liew, F. Haron, Y. M. Alginahi, and M. N. Kabir, "A preliminary crowd monitoring framework for Al-Haram," *Proc. Int. Conf. Commun. Inf. Technol.*, Jul. 2014, pp. 111–116, 2012.

[81] A. Charnes, S. Duffuaa, and A. Yafi, "A non-linear congestion network model for planning internal movement in the Hajj," *Eur. J. Oper. Res.*, vol. 40, no. 3, pp. 292–298, Jun. 1989.

[82] N. Koshak and A. Fouda, "Analyzing pedestrian movement in Mataf using GPS and GIS to support space redesign," in *Proc. 9th Int. Conf. Design Decis. Support Syst. Archit. Urban Planning*, 2008, pp. 1–14.

[83] I. Khan and R. McLeod, "Managing Hajj crowd complexity: Superior throughput, satisfaction, health, & safety," *Kuwait Chapter Arab. J. Bus. Manag. Rev.*, vol. 2, no. 4, pp. 45–59, 2012.

[84] N. A. Shuaibu, I. Faye, M. T. Simsim, and A. S. Malik, "Spiral path simulation of pedestrian flow during Tawaf," in *Proc. IEEE Int. Conf. Signal Image Process. Appl.*, Oct. 2013, pp. 241–245.

[85] I. Mahmood, M. Haris, and H. Sarjoughian, "Analyzing emergency evacuation strategies for mass gatherings using crowd simulation and analysis framework: Hajj scenario," in *Proc. ACM SIGSIM Conf. Princ. Adv. Discrete Simul.*, May 2017, pp. 231–240.

[86] A. S. A. Ahmed, "Hajj emergency management system," M.S. thesis, Dept. Geoinform., Univ. Salzburg, Salzburg, Austria, 2019.

[87] E. Felemban, F. U. Rehman, H. Wadood, and A. Naseer, "Towards building evacuation planning platform using multimodal transportation for a large crowd," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2019, pp. 4063–4066.

[88] B. Sadiq, A. Ahmad, S. Atta, E. Felemban, and K. Qahtani, "STSM—A model to detect and predict large crowd anomalies for optimized path recomendation," in *Proc. 4th Int. Conf. Softw. Defined Syst. (SDS)*, May 2017, pp. 14–19.

[89] K. Yang, A. H. Shekhar, F. U. Rehman, H. Lahza, S. Basalamah, S. Shekhar, I. Ahmed, and A. Ghafoor, "Intelligent shelter allotment for emergency evacuation planning: A case study of Makkah," *IEEE Intell. Syst.*, vol. 30, no. 5, pp. 66–76, Sep. 2015.

[90] A. Ahmad, I. Afyouni, A. Murad, A. Rahman, and F. Ur, "Quality and context-aware data collection architecture from crowd-sourced data," in *Proc. 4th Int. Multi-Topic Conf. (IMTIC)*, 2015, pp. 73–83.

[91] M. Elgamal, "Sentiment analysis methodology of Twitter data with an application on Hajj season," *Int. J. Eng. Res. Sci.*, vol. 2, no. 1, pp. 82–87, 2016.

[92] G. F. J. Bati, "Using big data tools to analyze tweets related to Hajj sentimentally," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, Madinah, Saudi Arabia, 2016.

[93] J. Qurashi and R. Sharpley, "The impact of smart media technologies on the spiritual experience of Hajj pilgrims," *Int. J. Religious Tourism Pilgrimage*, vol. 6, no. 3, pp. 37–48, 2018.

[94] B. Sadiq, M. A. Rahman, A. Murad, M. Shahid, F. U. Rehman, A. Lbath, A. Ahmad, and A. Qamar, "Crowdsourced multimedia enhanced spatio-temporal constraint based on-demand social network for group mobility," in *Proc. 23rd ACM Int. Conf. Multimedia (MM)*, 2015, pp. 761–762.

[95] M. Yamin, H. M. Al-Ahmadi, and A. Al Muhammad, "Integrating social media and mobile apps into Hajj management," in *Proc. 3rd Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, New Delhi, India, 2016, pp. 1368–1372.

[96] S. Basalamah and F. U. Rehman, "A survey on Hajj mobile applications," *Int. J. Comput. Sci. Netw. Secur.*, vol. 20, no. 1, pp. 15–30, 2020.

[97] E. A. Khan and M. K. Y. Shambour, "An analytical study of mobile applications for Hajj and Umrah services," *Appl. Comput. Informat.*, vol. 14, no. 1, pp. 37–47, Jan. 2018.

[98] A. Rahman, E. Hassanain, and M. S. Hossain, "Towards a secure mobile edge computing framework for Hajj," *IEEE Access*, vol. 5, pp. 11768–11781, 2017.

[99] H. H. Mohamed, M. R. H. M. Arshad, N. A. Rashid, Z. Zainol, W. Husain, O. A. Majid, M. Ghazali, M. Y. A. Rahim, and A. R. H. Mahmod, "M-Umrah: An android-based application to help pilgrims in performing Umrah," in *Proc. Int. Conf. Adv. Comput. Sci. Appl. Technol.*, Dec. 2013, pp. 385–389.

[100] A. Ahmad, M. A. Rahman, I. Afyouni, F. U. Rehman, B. Sadiq, and M. R. Wahiddin, "Towards a mobile and context-aware framework from crowdsourced data," in *Proc. 5th Int. Conf. Inf. Commun. Technol. Muslim World (ICT4M)*, Nov. 2014, pp. 1–6.

[101] A. Ahmad, I. Afyouni, A. Murad, M. A. Rahman, F. U. Rehman, B. Sadiq, S. Basalamah, and M. R. Wahiddin, "ST-diary: A multimedia authoring environment for crowdsourced spatio-temporal events," in *Proc. 8th ACM SIGSPATIAL Int. Workshop Location-Based Social Netw. (LBSN)*, 2015, pp. 1–7.

[102] F. U. Rehman, A. Lbath, A. Murad, M. A. Rahman, B. Sadiq, A. Ahmad, A. Qamar, and S. Basalamah, "A semantic geo-tagged multimedia-based routing in a crowdsourced big data environment," in *Proc. 23rd ACM Int. Conf. Multimedia (MM)*, 2015, pp. 759–760.

[103] F. Ur Rehman, A. Lbath, B. Sadiq, M. A. Rahman, A. Murad, I. Afyouni, A. Ahmad, and S. Basalamah, "A constraint-aware optimized path recommender in a crowdsourced environment," in *Proc. IEEE/ACS 12th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Nov. 2015, pp. 1–8.

[104] Z. Parveen and K. Aldhlan, "Missing pilgrims tracking system using GPS, GSM and arduino microcontroller," in *Proc. Int. Conf. Recent Adv. Comput. Syst.*, 2016, pp. 23–27.

[105] T. Mantoro, A. D. Jaafar, M. F. M. Aris, and M. A. Ayu, "HajjLocator: A Hajj pilgrimage tracking framework in crowded ubiquitous environment," in *Proc. Int. Conf. Multimedia Comput. Syst.*, Apr. 2011.

[106] I. Nafea, "Mobile health application running on public cloud during Hajj," in *Proc. Int. Conf. Mobile Web Inf. Syst.*, Prague, Czech Republic. Cham, Switzerland: Springer, 2017, pp. 129–136.

[107] S. Snoussi Maddouri, B. Al-Anesi, Z. Bokhari, R. Alqurashi, and A. T. Jamal, "A smart arabic signboard image reader for mobile devices," in *Proc. Int. Conf. Document Anal. Recognit. Workshops (ICDARW)*, Sep. 2019, pp. 7–12.

[108] S. Snoussi and Y. Wahabi, "Arabic document segmentation on a smartphone towards big data HAJJ rules extraction," in *Proc. 1st Int. Workshop Arabic Script Anal. Recognit. (ASAR)*, Apr. 2017, pp. 109–113.

[109] B. Sadiq, F. U. Rehman, A. Ahmad, M. A. Rahman, S. Ghani, A. Murad, S. Basalamah, and A. Lbath, "A spatio-temporal multimedia big data framework for a large crowd," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Oct. 2015, pp. 2742–2751.

[110] A. Ahmad, F. U. Rehman, M. A. Rahman, A. Murad, A. Qamar, B. Sadiq, S. Basalamah, and M. R. Wahiddin, "i-Diary," in *Proc. 23rd ACM Int. Conf. Multimedia (MM)*, 2015, pp. 809–810.

[111] S. N. Saeed, A. Abid, E. U. Waraich, S. Atta, A. Naseer, A. A. Sheikh, and E. Felemban, "ICrowd—A framework for monitoring of identifiable crowd," in *Proc. 12th Int. Conf. Innov. Inf. Technol. (IIT)*, Nov. 2016, pp. 1–7.

[112] S. Atta, B. Sadiq, A. Ahmad, S. N. Saeed, and E. Felemban, "Spatial-crowd: A big data framework for efficient data visualization," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2016, pp. 2130–2138.

[113] I. Nafea, "Utilizing big data analysis for diseases prevention and control during Hajj," in *Proc. 2nd Int. Conf. Open Big Data (OBD)*, Aug. 2016, pp. 52–56.

[114] A. Abdelghany, K. Abdelghany, H. S. Mahmassani, and S. A. Al-Gadhi, "Microsimulation assignment model for multidirectional pedestrian movement in congested facilities," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1939, no. 1, pp. 123–132, 2006.

[115] N. Koshak, "A GIS-based spatial-temporal visualization of pedestrian groups movement to and from Jamart area," in *Proc. Int. Conf. Comput. Urban Plan. Urban Manag. (CUPUM)*, Jul. 2005, pp. 1–12.

[116] S. Al-Sabban and H. Ramadan, "A simulation study of the shuttle-bus pilgrim transportation system between the holy sites for the 1422H Hajj season," *J. King Abdulaziz Univ.-Eng. Sci.*, vol. 16, no. 2, pp. 71–93, 2005.

[117] S. Sarmady, F. Haron, and A. Talib, "Agent-based simulation of crowd at the Tawaf area," in *Proc. Nat. Seminar Hajj Best Practices Through Adv. Sci. Technol.*, 2007, pp. 129–136.

[118] R. Narain, A. Golas, S. Curtis, and M. C. Lin, "Aggregate dynamics for dense crowd simulation," *ACM Trans. Graph.*, vol. 28, no. 5, pp. 1–8, Dec. 2009.

[119] Z. Zainuddin, K. Thinakaran, and I. M. Abu-Sulyman, "Simulating the Circumambulation of the Ka'aba using SimWalk," *Eur. J. Sci. Res.*, vol. 38, no. 3, pp. 454–464, 2009.

[120] W. W. Mulyana and T. S. Gunawan, "Hajj crowd simulation based on intelligent agent," in *Proc. Int. Conf. Comput. Commun. Eng. (ICCCE)*, May 2010, pp. 1–4.

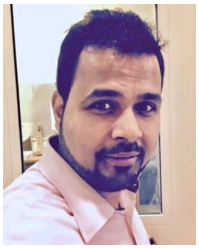
[121] Z. Zainuddin, K. Thinakaran, and M. Shuaib, "Simulation of the pedestrian flow in the Tawaf area using the social force model," *World Acad. Sci. Eng. Technol.*, vol. 48, pp. 908–913, Dec. 2010.

[122] S. Sarmady, F. Haron, and A. Z. Talib, "A cellular automata model for circular movements of pedestrians during tawaf," *Simul. Model. Pract. Theory*, vol. 19, no. 3, pp. 969–985, Mar. 2011.

[123] C. Tunasar, "Analytics driven master planning for mecca: Increasing the capacity while maintaining the spiritual context of HAJJ pilgrimage," in *Proc. Winter Simulations Conf. (WSC)*, Dec. 2013, pp. 241–251.
[124] S. Curtis, S. J. Guy, B. Zafar, and D. Manocha, "Virtual Tawaf: A case study in simulating the behavior of dense, heterogeneous crowds," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops (ICCV Workshops)*, Nov. 2011, pp. 128–135.
[125] S. Curtis, B. Zafar, A. Gutub, and D. Manocha, "Right of way: Asymmetric agent interactions in crowds," *Vis. Comput.*, vol. 29, no. 12, pp. 1–16, Dec. 2012.
[126] L. Manenti, S. Manzoni, G. Vizzari, K. Ohtsuka, and K. Shimura, *An Agent-Based Proxemic Model for Pedestrian and Group Dynamics: Motivations and First Experiments* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 7124, D. Villatoro, J. Sabater-Mir, and J. Sichman, Eds. Berlin, Germany: Springer, 2012, pp. 74–89.
[127] R. Reffat, "An intelligent computational real-time virtual environment model for efficient crowd management," *Int. J. Transp. Sci. Technol.*, vol. 1, no. 4, pp. 365–378, Dec. 2012.
[128] R. Haghighati and A. Hassan, "Modeling the flow of crowd during Tawaf at Masjid Al-Haram," *J. Mekanikal*, vol. 36, no. 1, pp. 2–18, 2013.
[129] L. Crociani, L. Manenti, and G. Vizzari, "MAKKSim: MAS-based crowd simulations for designer's decision support," in *Proc. 11th Int. Conf., Adv. Practical Appl. Agents Multi-Agent Syst. (PAAMS)*, Salamanca, Spain, vol. 7879, Y. Demazeau, T. Ishida, J. M. Corchado, and J. Bajo, Eds. Berlin, Germany: Springer, May 2013, pp. 25–36.
[130] F. Alonso-Marroquín, J. Busch, Á. Ramírez-Gómez, and C. Lozano, "A discrete spheropolygon model for calculation of stress in crowd dynamics," in *Proc. Traffic Granular Flow Conf.*, Jülich, Germany. Cham, Switzerland: Springer, Sep. 2013, pp. 179–186.
[131] S. Curtis, S. J. Guy, B. Zafar, and D. Manocha, "Virtual Tawaf: A velocity-space-based solution for simulating heterogeneous behavior in dense crowds," in *Modeling, Simulation and Visual Analysis of Crowds*, vol. 11. New York, NY, USA: Springer, 2013, pp. 181–209.
[132] I. Sakellariou, O. Kurdi, M. Gheorghe, D. Romano, P. Kefalas, F. Ipate, and I. Niculescu, "Crowd formal modelling and simulation: The Sa'yee ritual," in *Proc. 14th UK Workshop Comput. Intell. (UKCI)*, Sep. 2014, pp. 1–8.
[133] A. N. Shuaibu, I. Faye, A. S. Malik, and M. Talal, "Collision avoidance path for pedestrian agent performing Tawaf," in *Proc. 1st Int. Conf. Adv. Data Inf. Eng. (DaEng)*, vol. 285, 2014, pp. 361–368.
[134] O. Tayan and A. Al-binali, "Evaluation of a proposed intelligent transportation framework using computer network concepts: A case study for Hajj-pilgrim traffic monitoring and control," *Int. J. Comput. Sci. Issues*, vol. 10, no. 2, pp. 325–331, 2013.
[135] O. Tayan, A. M. Al BinAli, and M. N. Kabir, "Analytical and computer modelling of transportation systems for traffic bottleneck resolution: A Hajj case study," *Arabian J. Sci. Eng.*, vol. 39, no. 10, pp. 7013–7037, Oct. 2014.
[136] A. Rahman, N. A. W. A. Hamid, A. R. Rahiman, and B. Zafar, "Towards accelerated agent-based crowd simulation for Hajj and Umrah," in *Proc. Int. Symp. Agents, Multi-Agent Syst. Robot. (ISAMSR)*, no. 1, Aug. 2015, pp. 65–70.
[137] O. Kurdi, M. Stannett, and D. Romano, "Modeling and simulation of Tawaf and Sa'yee: A survey of recent work in the field," in *Proc. Eurosis ESM*, 2015, pp. 1–7.
[138] M. H. Dridi, "Simulation of high density pedestrian flow: Microscopic model," 2015, *arXiv:1501.06496*. [Online]. Available: http://arxiv.org/abs/1501.06496
[139] S. Kim, S. J. Guy, K. Hillesland, B. Zafar, A. A.-A. Gutub, and D. Manocha, "Velocity-based modeling of physical interactions in dense crowds," *Vis. Comput.*, vol. 31, no. 5, pp. 541–555, May 2015.
[140] F. M. Nasir and M. S. Sunar, "Simulating large group behaviour in Tawaf crowd," in *Proc. Asia–Pacific Conf. Multimedia Broadcast. (APMediaCast)*, Nov. 2016, pp. 42–46.
[141] A. R. M. A. Majid, N. A. W. A. Hamid, A. R. Rahiman, and B. Zafar, "GPU-based optimization of pilgrim simulation for Hajj and Umrah rituals," *Pertanika J. Sci. Technol.*, vol. 26, no. 3, pp. 1019–1038, 2018.
[142] M. H. Al-Haboubi and S. Z. Selim, "A design to minimize congestion around the Ka'aba," *Comput. Ind. Eng.*, vol. 32, no. 2, pp. 419–428, Apr. 1997.

**EMAD A. FELEMBAN** (Senior Member, IEEE) received the master's and Ph.D. degrees from Ohio State University, in 2003 and 2009, respectively. He is currently an Associate Professor with the Computer Engineering Department, Umm Al-Qura University. He is the Founder of Crowd Management Technologies, a consultation office specialized in applying advanced technologies for crowd and mobility management. He is also a Consultant with the Ministry of Hajj and Umrah. His research interests include wireless sensor networks, the IoT, optimization, and scheduling, mobility, and crowd management. He won many research funding projects from KACST, NPSTI, SABIC, and the Ministry of Education.

**FAIZAN UR REHMAN** (Member, IEEE) received the bachelor's and master's degrees in computer applications from Jamia Hamdard, New Delhi, India, in 2005 and 2008, respectively, and the Ph.D. degree from the University of Grenoble Alpes, France, in 2018. He is a Research Associate and a Consultant at Umm Al-Qura University, where he is currently working as a Principal Investigator in a couple of projects. He has previously worked as a Research Assistant at the Science and Technology Unit, Umm Al-Qura University. He is also a postdoctoral candidate with the Department of Computer Science, University of Grenoble Alpes. He also has the industrial experience, working as a Software Engineer in Aricent and Samsung Engineering Laboratory, India. His research interests include spatiotemporal databases, algorithms, and human–computer interaction.

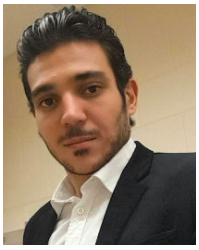


**SARDAR ASAD ALI BIABANI** received the bachelor's degree in engineering from Jawaharlal Nehru Technological University (JNTU), Hyderabad, India, in 2006, and the master's degree in microelectronic & communications engineering from the University of Northumbria Newcastle U.K., in 2008. He worked as a Research Assistant and Project Management Consultant at the Center of Research Excellence in Hajj and Umrah and later joined as a Research Projects Manager at the Transportation and Crowd Management Centre of Research Excellence (TCMCORE), Umm Al-Qura University (UQU), Makkah, Saudi Arabia, where he is currently working as a Research Associate and faculty member at the Science and Technology Unit. His current research interests include artificial intelligence, crowd management, knowledge engineering, big data, the Internet of Things (IoT), traffic engineering, intelligent transportation system (ITS), data visualizations, and visual databases.

**AKHLAQ AHMAD** (Member, IEEE) received the M.S. degree in physics and the M.S. degree in computer science, in 1997 and 2010, respectively, and the Ph.D. degree in computer science from KICT-IIUM, Malaysia. From 2005 to 2018, he has served as a faculty member at Umm Al Qura University, where he is currently working as a Research Associate. His research interests include network science, crowdsensing, as well as context-aware modeling and services. He has authored and coauthored several patents and research articles, including refereed IEEE/ACM Journals, conference papers, and workshops. He is a member of the ACM. He has achieved Best Paper Awards in ICT4M in 2014 and ACSAT in 2015.

**ATIF NASEER** is currently pursuing the Ph.D. degree in video analytics with the Universidad de Malaga, Spain. He is an Academician and Researcher by profession and is currently serving as a Researcher at Umm Al Qura University. He has been attached to academia for over ten years and has been part of many research and development projects. His current research interests include artificial intelligence, computer vision, big data analytics, the Internet of Things, middleware modeling of wireless sensor networks, and semantic interoperability.

**ABDUR RAHMAN MUHAMMAD ABDUL MAJID** received the B.E. degree in computer and information systems engineering from the NED University of Engineering and Technology, Pakistan, and the M.Sc. degree in computer science from University Putra Malaysia, with a focus on parallel and distributed computing. He has worked as a Research Assistant and Research and Development Engineering, working with crowd simulation and other technologies related to Hajj and Umrah. He is currently working as a Senior GIS Developer at the Institute of Consulting Research and Studies (ICRS), Umm Al Qura University, Saudi Arabia. His research interests include spatial computing, parallel and distributed computing, crowd simulation, and dynamics.



**OMAR K. HUSSAIN** received the master's degree in transportation systems engineering from the University of Central Florida, Orlando, FL, USA, in 2013. He is currently a Research Assistant with the Science and Technology Unit, Umm Al-Qura University. His research interests include intelligent transportation system (ITS), simulation modeling, prediction systems, flow theory and operation, and statistical modeling and analysis.

**AHMAD MUAZ QAMAR** received the BCS degree in computer science from the FAST Institute of Computer Science, University of the Punjab, Lahore, Pakistan, in 1996, and the M.S. degree from the University of Southern California, Los Angeles, CA, USA, in 1998. He is currently pursuing the Ph.D. degree in computer science with University Sains Malaysia. His areas of interest include serious games for rehabilitation and crowd management.

**ROWID FALEMBAN** received the Diploma degree in optician from Umm Al Qura University, College of Makkah Community College, Saudi Arabia, in 2011, and the bachelor's degree in computer information systems from Widener University, Chester, PA, USA, in 2018. He has worked as a Lab Teacher at Wall Street English, Makkah, and has worked in Captains Engagement and IT Solution for Careem Transportation and Information Technologies, practically focusing on databases. He is currently working as a Research Assistant with the Science and Technology Unit, Umm Al-Qura University. His research interests include crowd simulation, immersive technologies, artificial intelligence, opticals, and health information systems.

**FAKHRI ZANJIR** is currently a Researcher in knowledge engineering with the University of Grenoble Alpes. He has been working in technology transfer and commercialization with Umm Al-Qura University and has worked in many projects related to Hajj technologies and smart Hajj.