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SURVEY

Solving Hajj and Umrah Challenges Using Information and Communication Technology: A Survey

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ABSTRACT Hajj and Umrah are Muslims' religious pilgrimages to Makkah, Saudi Arabia. Hajj is considered the largest annual gathering in the world. In Islam, every adult is obligated to conduct Hajj and Umrah at least once if he/she is in good health and can afford to do so. Hajj takes place between the 8th and the 13th day of Dhul Hijjah, which is the last month of the Islamic year while Umrah, the minor pilgrimage, could be done any time of the year. In Hajj, pilgrims, also known as Hajjis, travel around 15 km and pilgrims have the choice to do it by foot, bus or by train. The Hajj journey starts from Mina, which is considered the largest tent city in the world because it hosts more than 10,000 fire resistant tents, and includes various religious rituals. Around 3 million Muslims from more than 183 countries make Hajj every year and the Kingdom of Saudi Arabia is working on increasing this number. Since 1989, researchers in various ICT domains have tried leveraging their expertise in solving challenges and issues related to Hajj and Umrah. Although several papers have surveyed efforts using technology in Hajj and Umrah research, none of them was comprehensive. In this paper, I classified research efforts that used information and communication technologies for solving Hajj and Umrah challenges over the past 33 years based on their applications in 10 categories. I also identified more than 30 technologies used by researchers all over the world to address Hajj and Umrah issues and group research efforts based on these technologies for ease of access. Furthermore, open challenges were discussed and new technologies that could be used to address these challenges were proposed.

INDEX TERMS Crowdsourcing, global positioning system, Internet of Things, RFID, wearable sensors, wireless sensor network.

I. INTRODUCTION

Hajj is the Muslims' annual pilgrimage. It is considered one of the world's largest gatherings, as millions of people flock to Makkah, Saudi Arabia, to participate in the fifth pillar of Islam. Hajj takes place between the 8th and the 13th day of Dhul Hijjah, which is the last month of the Islamic year. Muslims from countries all over the world gather together for five to six days to celebrate their history. From the Grand Masjid to the mount of Arafat, the rituals include Ka'ba circumambulation and walking between Safa and Marwa hills. The journey length is around 15 km and pilgrims have the choice to do it by foot, bus or by train. Prior to COVID-19, Hajj used to attract more than three million pilgrims every year, as shown in Table 1. Through the Doyof Al-Rahman Vision Realization Program [1], Saudi Arabia is trying hard to increase this number by the year 2030.

Visitors to the two holy cities face many challenges during various phases in Hajj. First and foremost, all the pilgrims must stay in a specific geographic area for a specific period of time. For example, all pilgrims must pass by Arafat in the daytime of the 9th of Dhul Hijjah and stay there until sunset. Managing the crowd movement of millions of pilgrims is challenging. Also, the diversity of the pilgrims imposes an additional communication barrier, as they come from more than 183 countries around the world [2] and speak many

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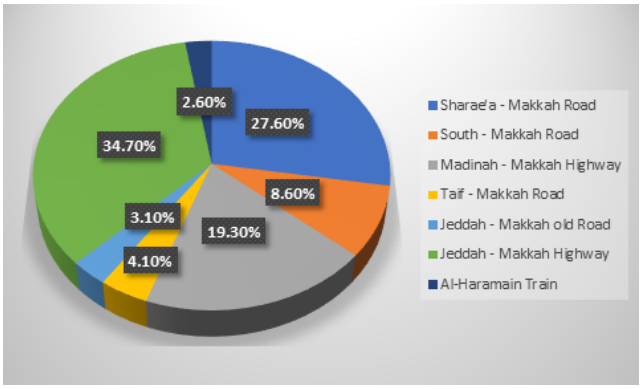

FIGURE 1. Transportation means used to carry domestic pilgrims to Makkah in 2019 Hajj classified by way of arrival.

different languages. Moreover, the timing for Hajj follows the lunar calendar system and hence, it could occur in the hottest month in the summer or in the coldest month in the winter. Furthermore, the restriction on what the pilgrims can wear or do, called Mahdhorat Al-Ihram, poses another set of challenges. For example, men cannot cover their heads during Ihram. In addition, pilgrims are often in close contact with each other. Thus, there is an increased risk of viral infections. As 75% of the pilgrims are usually between 35 and 64 years old [3], the majority of the pilgrims could be classified as elderly and chronically ill patients.

Over the last three decades, researchers from all over the world were proposing ICT as an efficient way to solve pressing Hajj needs. Most of the efforts focused on crowd management in order to avoid stampedes similar to the one that happened in 2015 resulting in the death of a thousand pilgrims [4]. Other researchers focused on providing additional services to pilgrims in their preferred languages. Moreover, researchers tackled the issue of tracking and guiding lost pilgrims using wearables and smart devices. Taking care of pilgrims' health was also a key area that many researchers were focusing on. Teaching and learning in Hajj was also one of the areas that benefited a lot from ICT. As shown in Fig. 1, buses and cars are used the main transportation method taking pilgrims to/from the sacred sites. Hence, many research papers tackled the issue of making these buses smarter through intelligent transportation systems. Finally, future planning was proposed in the literature to help improve the smoothness of various steps performed by the Hajjis.

Many technologies were proposed in order to tackle Hajj and Umrah challenges [5]. Communication and networking technologies were among the most suggested of technologies. In fact, various types of networking protocols were utilized and several novel network infrastructure architectures were proposed to ease the communication between pilgrims and the authorities in case of emergencies or disasters. However, the utilization of the latest wireless technologies, such as IEEE 802.11ax and 6G, in supporting pilgrims communication is yet to be considered. Also, GPS plays a vital role in many proposals that target location tracking. Moreover, modeling and simulation were used heavily in an effort to understand the crowd behavior and dynamics in various stages of the Hajj journey. Image processing and computer vision technologies were also applied to leverage the great CCTV infrastructure that is readily available in the sacred places. Also, AI was proposed to overcome several challenges that the pilgrims are suffering from. Last but not least, smartphones and social media applications were also proposed massively in the literature to help provide a better experience for Hajjis. However, these technologies could have a negative impact on the spiritual experience of the pilgrims [6]–[8].

Using ICT in solving Hajj and Umrah challenges is still an open challenge despite the great effort that has been put forward until now [9]. In 2018, the Saudi Federation for Cybersecurity, Programming and Drones organized the Hajj Hackathon to bridge the gap between technology and pilgrims' needs on the ground [10]. With around 3000 programmers from 100 countries, Hajj Hackathon was featured in the Guinness Book of World Records as the hackathon with the most participants. Similarly, The Institute of Hajj and Umrah Research is organizing a similar hackathon in 2022, called Hajjathon [11]. The goal of Hajjathon is to motivate software developers and innovators to solve open Hajj challenges in 11 fields, including transportation, health, crowd management, housing, travel arrangements, among others. In fact, one of the fields that I expect many Hajjathon participants will be focusing on is fintech solutions for pilgrims. Fintech is important to ease the difficulty faced by pilgrims while buying goods and gifts. Waste management is also among the fields of the Hajjathon. Just imagining the amount of waste generated by over 3 million pilgrims during this 6-day journey is enough to understand the size of the problem. Tourism and sightseeing are other fields targeted by the Hajjathon because they are underserviced from the technology point of view [12].

To the best of my knowledge, this is the first comprehensive work that surveyed the use of ICT in solving Hajj and Umrah challenges. The contribution of this paper is threefold:

- Classify efforts using Information and Communication Technologies in solving Hajj and Umrah challenges in the past based on the use and need to ten categories.
- Identify thirty three technologies proposed by researchers all over the world to address Hajj and Umrah issues and group research efforts based on these technologies for ease of referencing.
- Discuss nine open challenges and new technologies that could be leveraged to address pilgrims' pressing needs.

The remaining parts of this paper are organized as follows. In the beginning, I briefly describe the journeys of Hajj and Umrah, and illustrate various terminologies to provide context to the readers in Sec. II. After that, I discuss related survey papers in the literature and their shortcomings in Sec. III. Following to that, Sec. IV presents the classification of research efforts using ICT in the Hajj and Umrah field based on the need and the application. Then, I grouped all referenced papers based on the technology used in Sec. V for ease of accessing. After that, the open challenges in Hajj and

TABLE 1. Total number of pilgrims between 2010 and 2019 [13].

Year	Number of Pilgrims
2010	2,789,399
2011	2,927,717
2012	3,161,573
2013	1,980,249
2014	2,085,238
2015	1,952,817
2016	1,862,909
2017	2,352,122
2018	2,371,675
2019	2,489,406

Umrah were discussed in Sec. VI, along with future avenues of research. Finally, I conclude the survey paper in Sec. VII.

II. BACKGROUND

Hajj, or the pilgrimage to Makkah, is one of the five pillars of Islam. Hajj is obligatory once in the life time for each Muslim if he/she is able. Makkah is considered one of the most sacred places in Islam, as it witnessed the birth of the Prophet Mohammad PBUH. In the early 7th century, Prophet Mohammad received the first revelations in Makkah. Moreover, Makkah is where the Ka'ba, the cube-shaped building, is located, which is the holiest site for Muslims all over the world. In fact, pilgrimage to Makkah used to happen even before Islam. Ka'ba, which is located in the center of the Grand Mosque, is believed to be built by Prophet Abraham and his son Prophet Ishmael a long time back. Arab tribes from various parts of the Arabian Peninsula gathered for Hajj in the sacred month. In this month, violence was forbidden resulting in flourishing trade.

The typical duration of Hajj is six days and could be completed in as short as four days. During this period, Hajjis are involved in a series of rituals that must be completed in a specific order and at specific timings and locations, mimicking Prophet Muhammad's Hajj that he led back in in 632, the year of his death. These rituals take place in Makkah and in the areas around it. In the rest of this section, we will describe each of these rituals briefly. We will outline the locations that the pilgrim will be visiting in sequence, as shown in Fig. 2. Umrah is a shorter version of Hajj and normally lasts a couple of hours. In Umrah, pilgrims are required basically to do only two rituals, which are Tawaf and Sa'i. Both the rituals could be completed in the Grand Mosque. The main difference between Hajj and Umrah is the fact that the latter does not have a specific timing, i.e., Umrah could be done any time of the year. This is why pilgrims come to Makkah for Umrah all over the year. In fact, Umrah and Hajj could be combined together in what is called Qiran. If they are spaced out, then they are called Tamattu. Finally, Hajj is called Ifrad if it is done alone.

A. THE RITUALS

1) IHRAM

Ihram is the state of ritual purity that pilgrims must be wearing at the beginning of both Hajj and Umrah.

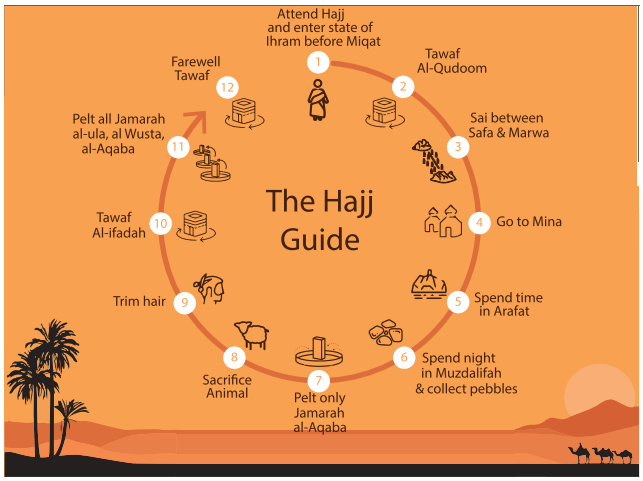

FIGURE 2. Step by step pilgrimage to Makkah journey.

2) TAWAF

Tawaf is the process of circumambulation around the Ka'bah for seven times in an anti-clockwise direction. Pilgrims start the process of Tawaf from the Black Stone, and complete seven rounds. It is recommended to kiss or touch this stone while passing by it.

3) SA'I

Sa'i is the act of walking seven times between Safa and Marwah, mimicking the act of Hajar, the mother of the Prophet Ishmael who was looking for water. Safa and Marwah are two famous hills located to the south and north of the Ka'ba, respectively. These hills used to be beside the Grand Mosque, but after multiple expansions, they are inside the mosque nowadays.

4) STONING

This ritual symbolizes stoning the devil where pilgrims collect twenty-one pebbles every day and throw seven pebbles each at the three stone monuments, also known as Jamarat,. Jamrat Al-Aqabah is the main stoning monument.

5) SACRIFICING

Depending on the type of Hajj, pilgrims might be required to offer an animal sacrifice to God. Nowadays, pilgrims do it though sacrifice voucher instead of doing it individually.

6) SHAVING

To exit the state of Ihram, men should either shave or trim their hair. On the other hand, women clip strands or locks of their hair to exit the state of Ihram.

B. THE LOCATIONS

1) MIQAT

Hajj and Umrah must be started from the Miqat, except for the people of Makkah. In fact, there are five Miqats, also known as Mawaqeet, that are geographically distributed

around Makkah to make it easier for pilgrims coming to Makkah from different directions. For example, Dhulhulaifah is located to the north of Makkah, whereas Yalamlam is located to the south. While passing through the Miqat, men will put on the Ihram, the two white cloths without seam hems or buttons, and make the intention to start the Hajj or Umrah.

2) AL-MASJID AL-HARAM

The Grand Mosque, also known as Al-Masjid Al-Haram, is the mosque that surrounds the Ka'ba. Hence, pilgrims will perform Tawaf and Sa'i in it, as the Grand Mosque also contains the Safa and Marwah hills.

3) MINA

Mina is the place where pilgrims spend most of their time during Hajj. Most people live in air-conditioned, fire-resistant tents. Recently, several towers have been built in Mina to accommodate more pilgrims. Usually, men will have separate tents from women.

4) ARAFAT

On the second day of Hajj, all pilgrims are required to move to Arafat and stay there until sunset. Arafat is named after a nearby mount called Arafat. Standing in Arafat is one of the most important rituals of Hajj.

5) MUZDALIFAH

Muzdalifah is located between Mina and Arafat. Pilgrims head to Muzdalifah after sundown and spend the night there until dawn. Before the sun rises, they go to Mina again to do the stoning ritual.

6) AL-MASJID AL-NABAWI

Although visiting Madinah, which is 400 Km north of Makkah, is not an obligatory act during Hajj, a lot of pilgrims do visit Madinah either before Hajj or after completing their rituals to pray in the Prophet's Mosque, also known as Al-Masjid Al-Nabawi, and visit the Prophet's tomb. Having the crowd separated over two phases indeed simplify the burden of managing the crowds in Madinah. However, managing a million plus visitors is still a challenging task.

III. RELATED SURVEYS

To the best of my knowledge, this is the first comprehensive effort that surveys various aspects of ICT usage in Hajj and Umrah. As shown in Table 2, previous efforts either focused on a specific challenge, such as crowd management and tracking, or simply restricted their research to a few years back. For example, Osman and Shaout surveyed Hajj-guide systems used for tracking the movement of pilgrims [14]. In a similar effort, Yasein and Alharthi surveyed pilgrim tracking technologies [15]. The authors classified tracking technologies into large area technologies such as GPS and cellular towers, and limited area technologies such as Bluetooth, WiFi, NFC, RFID, among others. Visual surveillance efforts for Hajj and Umrah were also surveyed [16].

FIGURE 3. Taxonomy of Hajj and Umrah ICT research based on use.

According to the author, most of these efforts focused on counting pilgrims through either trained algorithms, such as the Nearest Neighbor and Beyesian models or background removal techniques, such as median filter and foreground ratio. Intelligent evacuation management systems have also been reviewed [17]. Moreover, mobile applications related to Hajj were surveyed [18], [19]. In fact, more than 240 applications in Google Play have been included in this survey. The study analyzed the applications in terms of the diversity of offered services, the number of languages supported as well as the rate of installation. The authors found that half of the applications support the English language. They also found that the application installation rate is proportional to the availability of live streaming services. Felemban *et al.* recently surveyed the literature for technologies targeting crowd management in Hajj [20]. They covered several technologies including computer vision, mobile applications, wireless networks, among others. Related to crowd management as well, Nasir and Sunar surveyed the models used to simulate crowds in real time [21]. Also, Shambour *et al.* surveyed the technology related research papers that were published in the Scientific Forum for Hajj, Umrah and Madinah Visit Research in the past five years [22]. According to the authors, the top two used technologies by researchers in this field are Artificial Intelligence (AI) and modeling/simulation. Technologies targeting Health challenges in Hajj and Umrah were surveyed as well [23]. Last but not least, Shambour and Gutub surveyed papers that proposed IoT usage in serving Hajj and Umrah [24].

IV. TAXONOMY OF ICT EFFORTS IN HAJJ AND UMRAH

During the past 30 years, many researchers all over the world have suggested using ICT to solve various Hajj and

TABLE 2. Comparison of this paper with existing survey and review papers on using technology in Hajj and Umrah. (Legend: ✓means covered; × means not covered; ≈ means partially covered.)

Year	Authors	Publisher	# Papers	Crowd	Health	Tracking	Learning	Services
2014	Osman & Shaout [14]	Int. Journal of Emerging Tech. & Adv. Eng.	45	≈	×	✓	×	×
2015	Othman [16]	Scientific Forum for Hajj & Umrah Research	18	✓	×	×	×	×
2015	Nasir & Sunar [21]	ICIDM	35	✓	×	×	×	×
2016	Ibraim et al. [17]	ACM Trans. on Intelligent Syst. & Tech.	114	✓	×	✓	×	×
2017	Yasein & Alharthi [15]	Scientific Forum for Hajj & Umrah Research	13	≈	×	✓	×	≈
2018	Khan & Shambour [18]	Applied Computing and Informatics	42	×	≈	×	✓	✓
2018	Al-Masud [23]	Journal of Theoretical and Appl. Info. Tech.	38	×	✓	×	×	×
2020	Felemban et al. [20]	IEEE Access	142	✓	≈	✓	×	≈
2021	Shambour et al. [22]	Scientific Forum for Hajj & Umrah Research	31	✓	×	✓	×	✓
2021	Shambour and Gutub [24]	Arabian Journal for Science and Engineering	154	✓	≈	✓	×	≈
2022	My Paper		330	✓	✓	✓	✓	✓

Umrah challenges. I have used mainly three search engines to look for papers that tackled Hajj and Umrah challenges from an ICT perspective, namely: IEEE Xplore, ACM Digital Library, and Google Scholar. In these professional search engines, I used the following two keywords to search for papers: "Hajj" and "Pilgrim". After carefully analyzing these papers, I was able to classify them based on their use into ten categories, as shown in Fig. 3. The first category is services where I gathered papers that used smartphone and social media applications to provide services to Hajjis. It also includes papers on location based and AI customized services. The second category gathers all the papers targeting tracking and navigation whether with or without GPS support. The third category discusses emergency response initiatives as well as disaster recovery in Hajj. The fourth category is expert systems and learning which basically summarizes efforts to answer Hajjis' questions on real time as well as Hajj training systems. The Sixth category is Hajj digitization that gathers all the papers related to Hajj management. The seventh category is health informatics outlining papers about disease control and prevention during Hajj. Also, health informatics covered papers about real-time pilgrims' health monitoring and medical facilities planning. The eighth category is crowd management. As the name implies, it covers papers on crowd prediction, detection, estimation, evacuation, and control. The seventh category is transportation that focuses on intelligent transportation systems and traffic simulation in the holy cities. The ninth category is about the infrastructure of the Hajj sites and efforts to improve it. It also covers planning proposals for better Hajj experience. The last category covers efforts in the literature that address the issue of cybersecurity during Hajj and privacy of pilgrims' data.

In the rest of this section, similar papers were grouped together in the aforementioned ten categories. Moreover, the differences between similar efforts were highlighted. Fig. 4 shows the percentage of papers for each category in my proposed taxonomy. With no surprise, crowd management got the bigger chunk with 28% of the papers reviewed, followed by both the tracking and navigation category and the health informatics category. The distribution of papers per year is shown in Fig. 5. It is clear from the figure that there are two peaks. The first peak is around 2015, which could be explained by the deadly stampede in Mina causing around 1,000 deaths and severe injuries [4]. The second peak happened during the time of COVID-19 pandemic.

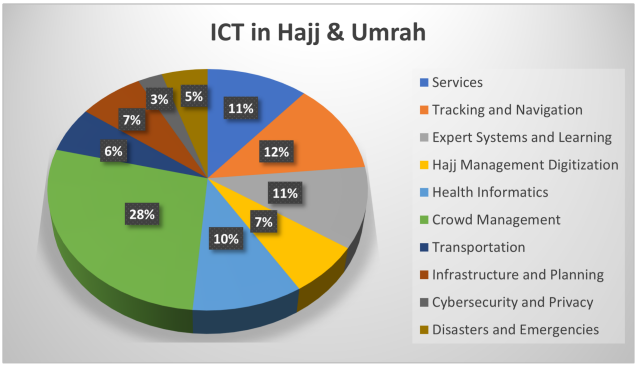

FIGURE 4. Percentage of surveyed papers per each category.

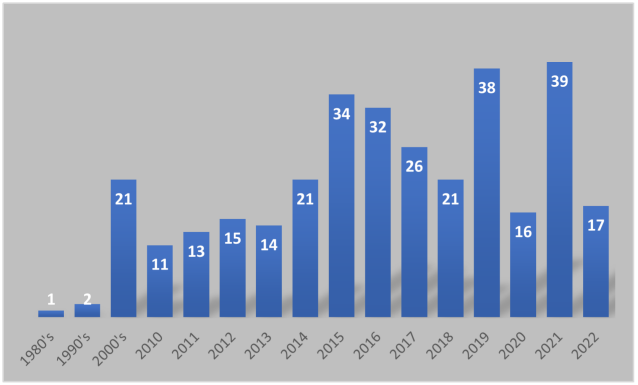

FIGURE 5. Distribution of surveyed papers over publication year.

A. SERVICES

Many mobile applications are proposed in the literature to provide services to pilgrims [25], [26]. For example, Ahmad *et al.* proposed a context-aware smartphone framework to offer services to pilgrims [27]. Their framework depends on the cloud to provide the services. These services are adopted based on the need of the pilgrim. Another smartphone based service is real-time Hajj rule extraction [28].

This is made possible because of Arabic document segmentation, which allows the polygons' construction of the binary image of connected components. In a similar effort, Snoussi proposed a smartphone application to translate an Arabic signboard on a real-time basis [29], [30]. This application uses Outer Isothetic Cover (OIC) for segmenting the text and Transparent Neural Network (TNN) for recognizing the text. Sun Dial is a smartphone application that reminds pilgrims on their five daily prayers [31]. What makes this application unique is the sacred religious imagery that connects Muslims to their religion. Yusur is a mobile application that uses a preferences-based search algorithm to help pilgrims find the Hajj and Umrah agencies that satisfy their requirements [32]. Al-Aidaroos *et al.* developed a smartphone application to help pilgrims in reciting recommended Duas (sayings) while performing the rituals [33]. Recently, Ilias and her colleagues developed an android based mobile app specifically designed to help group leaders managing their pilgrims [34].

A framework to transform Makkah into a smart city is proposed in the literature [35]. This framework will help in delivering personalized services to the pilgrims during their journey. Location Based Services (LBS) is also proposed in the literature with the help of Spatial Database [36]. HajjCPS is another effort to provide location-aware services to pilgrims during Hajj [37].

In order to provide pilgrims with the right set of services they need, it is important to analyze the situation of pilgrims and visitors during a specific period of the year. With the help of deep learning, Alharthi and Alshamrani managed to analyze the pilgrims' characteristics during their Hajj [38]. Similarly, Elgamal and Alshamrani used machine learning to predict the most important features of Ramadan visitors [39]. They also used data mining methods to find the characteristics of pilgrims over an eight-year period [40].

The government of Saudi Arabia is also providing many services for pilgrims whether they are coming for Umrah or Hajj. The general administration for Hajj, Umrah and Visit in the Principality of Madinah Region proposed using Business Intelligence (BI) to support the decision-making process and develop services and initiatives that overcome real challenges [41]. The Deputy of Al-Masjid An-Nabawi Affairs under the supervision of the Presidency for the Affairs of the Two Holy Mosques used electronic screens, SMS, a web-based portal, and smartphone applications to provide electronic services and to communicate with pilgrims and visitors [42]. The effectiveness of digital signage around the Prophet's Mosque in Madinah has been studied as well [43]. In fact, several recommendations were given to improve the digital signage system. NFC was also used to deliver a wide range of services, such as, but not limited to: faster checkpoint processing as NFC-enabled smart devices could hold official documents as well as medical records, faster check-in at hotels, e-wallets, pilgrim identification following a disaster, easy access to awareness material through kiosks, guiding lost pilgrims, among others [44] [45]. A recent study showed high satisfaction among pilgrims with regards to the services they got during Hajj [46].

Social media-based services were also proposed in the literature. Yamin *et al.* proposed Hajj Mabrour, which is a smartphone application that is integrated with social media to help in Hajj management [47]. This App enhances situational awareness by sending real-time notifications for users. Musleh proposed TAGHREED, which is a comprehensive real-time analysis and visualization tool for tweets [48]. This analysis is beneficial in understanding pilgrims' opinions about the services they received. Also, big data analysis tools, such as Spring XD, Hadoop, Hive, and MS Excel, were used to collect, refine, and visualize tweets about services in Hajj [49]. Sentiment analysis helps in measuring pilgrims' opinions about a specific service, and hence, enhances that service. In fact, Holy Tweets is another initiative that analyzes the Quranic verses shared by Muslims in Twitter [50]. These verses were categorized into 14 categories, one of them was worship where verses expound on various acts of worship, such as pilgrimage.

Services offered for pilgrims in airports were evaluated from the moment of arrival until departure by bus using information systems business process evaluation techniques [51]. On the other hand, Majrashi studied the user experience of pilgrims using of several Hajj mobile applications by interviewing 16 pilgrims [52]. The study also reviewed the needs for services among pilgrims. Since many of the services are delivered using websites and web services, Shambour and his colleagues evaluated the websites of three main Hajj service providers [53] [54]. The authors evaluated the performance of the websites according to the four criteria approved by Alexa [55]. The best websites were the Islamic Network with a score of 4.13 out of 5 and the website of the Ministry for Hajj and Umrah with a score of 4.07 out of 5. Similarly, Al-Khalifa used heuristics to evaluate the usability of the Ministry of Hajj and Umrah's website in Saudi Arabia [56]. Al-Khalifa *et al.* also evaluated the accessibility and usability of many services of the Saudi E-government initiative [57]. Among these services was the Hajj Public Query that was offered by the Ministry of Interior in the Kingdom of Saudi Arabia [58]. Lubis *et al.* proposed using CRM for managing Hajj portal websites [59]. Saiful Islam *et al.* proposed using computational techniques to analyze human-survey interaction [60]. The goal of the study was to find unreliable data collectors based on the data they collected.

B. TRACKING AND NAVIGATION

Pilgrims' tracking was addressed by many papers in the literature [61]. PilgrimTrackr [62] and e-Mutawwif [63] are just two examples of many initiatives to track pilgrims on a real-time basis through web-based systems. In a similar effort, Touir *et al.* proposed an architecture enabling the tracking of pilgrims during Hajj [64]. Alhazmi *et al.* proposed using a web-based spatial crowdsourcing application to

allow campaign leaders to track their respective pilgrims [65]. Mantoro and his colleagues proposed a smartphone-based tracking system for Hajj [66]. The idea behind this proposal is to use the already available devices with pilgrims instead of introducing new devices to them, which makes this solution more affordable compared to others. The system will help locating lost pilgrims. Moreover, systems using the Internet of Things (IoT) were also proposed to monitor, locate and track lost pilgrims [67], [68]. Missing-pilgrims tracking using GPS and Arduino board was also proposed in the literature [69]. Also for tracking missing pilgrims, Hidayat *et al.* recently proposed using both RFID and GPS to achieve this goal [70]. Wireless Sensor Networks (WSNs) have also been heavily used for tracking pilgrims. In one of the examples, mobile sensor units have been given to pilgrims [71], [72]. These units are composed of nothing but a microcontroller, an antenna and a GPS chip. Through a pre-installed network of fixed units, pilgrims' locations are mapped into a geographical information system (GIS). Specifically for Tawaf, Koshak and Fouda [73] used GPS enabled devices to track pedestrians. The goal of their study was to analyze the changes in the pedestrian movement behavior over time. They concluded that it is necessary to move obstacles in order to allow smoother crowd movement. Kanakri *et al.* proposed using a cloud-based decision system to alert the pilgrims in case of any violation of the rituals [74]. The system could detect the location of the pilgrim using GPS and inform him/her through a dedicated smartphone application. In fact, tracking is not only for people. Al-Subhy *et al.* proposed a way to track lost objects during Hajj using invisible Radio-Frequency IDentification (RFID) tags [75]. Pilgrims can inquire about lost items through a web-based portal.

Not all pilgrim tracking proposals in the literature depend on GPS. For instance, RF-based compact ear connected devices were used to form a low-energy local wireless network for local positioning. These devices are super cheap and do not require high power consumption. The RF transceiver uses multichannel super-regenerative configuration [76]. In addition to local positioning, this system is able to provide multilingual speech translation as well. UbiTrack is another example of a smartphone-based tracking system that is not dependent on GPS [77]. Instead, it uses Human Activity Recognition (HAR) through various advanced sensors in the smart device to expect human activity in real time. In another effort, HAR is used to predict the probability of a pilgrim being lost in a crowd by looking at a pilgrim's movements and comparing them to typical lost person movements [78]. In another GPS independent effort, Anwar *et al.* proposed an offline tracking initiative that is based on an ad-hoc network connection [79]. Furthermore, smartphones can also help in the tracking and identification of pilgrims [80]. Via cellular networks, pilgrim locations are shared with a central server governed by Hajj authorities. Moreover, deep learning and convolutional neural networks had been used for pilgrims' detection [81]. To solve the challenge of identifying pilgrims with no IDs, Elgamal *et al.* proposed using the Viola-Jones algorithm for pilgrims' face recognition [82]. To make the proposal more practical, the authors used Discrete Fourier Transformation (DFT) to reduce dimensionality, and hence, shorten the algorithm run-time. Similarly, Alharbey *et al.* proposed using Yolo v4 for detecting human faces during Hajj for crowd management purposes [83].

Several proposals were given for Hajj electronic guides. Shout and Othman proposed an intelligent guide system for Hajj using GPS [84], [85]. This system will help pilgrims navigate through unfamiliar areas and find points of interest in their language. The engineering requirements for the Personal Hajj E-guide are studied as well [86]. The main idea of this guide is to cross check the location of the pilgrim with the ritual and alert him/her in case of any discrepancies. Also, it helps the government officials send location-specific alerts. In addition, the proposed E-guide is capable of counting the number of rounds in specific rituals, such as Tawaf and Sa'i. A similar effort, but for Umrah, was proposed by Alhogail *et al.* and named Umrah E-Guide [87]. Moreover, crowdsourced social network data could be used to optimize navigation to points of interest (POIs) [88]. Similarly, Kanakri and Tawalbeh invented an iOS-based mobile application that provides pilgrims with dynamic interactive maps and the optimum routes to their destinations [89]. The application determines the optimal path based on the crowdedness level gathered by the WSN. Semantic Multimedia Routing Algorithm (SMRA) was also suggested to find the fastest or shortest path in real-time by answering multimedia spatio-temporal queries through an indexed spatial big data environment [90]. Furthermore, Hamhoum and Kary proposed using dynamic public signage to help pilgrims navigating densely crowded spots at the sacred places [91]. As a last example, Seraj is a location-aware smartphone application that tracks location through image recognition and geo-location [92]. Augmented Reality (AR) is used in this application to enrich the pilgrim experience when visiting heritage cites.

Systems used for managing pilgrims generate a lot of data. Hence, researchers proposed several initiatives to track pilgrims using data analysis. Felemban *et al.* proposed a framework to analyze the data gathered from the applications of Hajj services [93]. The gathered data could be analyzed to find out the behavior of pedestrian movements during Hajj. Muaremi and others monitored the activities of many pilgrims using smartphones and wearable devices for 8 days [94]. The study highlighted the challenges in collecting such a large amount of data in such a difficult environment. The goal of the study was to recognize the various types of activities as well as discover stressful situations and health issues for pilgrims. The authors also used wearable devices to detect the type of pilgrims' prayer [95]. ST-Diary is another initiative by Ahmad and his colleagues to allow pilgrims to add collocated points of interest (CPOI) in a crowdsourcing manner [96]. A similar project is called I-Diary where geo-tagged multimedia are leveraged to allow users to generate a digital diary

through aggregating multimedia files [97]. In fact, tracking individuals and vehicles could be made possible by analyzing crowdsourced multimedia data [98], [99].

C. DISASTERS AND EMERGENCIES

Systems that deal with emergency situations were also proposed in the literature. Dirgahayu and Hidayat proposed an emergency system based on geo-fencing alerts [100]. In case of an emergency, a signal locating the pilgrim will be sent to the officials for fast action. Also, a detailed study has been conducted to determine potential RFID use in Hajj [101]. Furthermore, Suhaib proposed a realistic evacuation simulation that is based on collision avoidance [102]. Moreover, researchers proposed systems that help in case of natural disasters. For example, rescuing alive pilgrims should be given priority. This could be easily known by monitoring the heartbeat signals of pilgrims. In case of detected signals, the location will be shared through the WPAN network using the Zigbee protocol to the command and control center [103]. In fact, GPS enabled wearable devices can be used to solve the problem of detecting and guiding astray pilgrims [104]. Since pilgrims are expected to be at certain places on certain timings, it is easy to infer the potentially lost pilgrims. On a similar effort, Mohandes developed a pilgrim identification system that is based on RFID technology [105]. The system is used to identify pilgrims and had been tested on 1000 pilgrims from Ivory Coast. Chandio and others proposed a similar system but using both radio frequency and GSM network [106]. Also using RFID, Binsalleeh *et al.* used RFID tags to track pilgrims in case of emergency [107]. ML-EPIC (Multi-Language Empowering the Public with Information in Crisis) is an effort to get insight from tweets written in multiple languages during crisis events such as Hajj crushes [108]. Another model called STSM (Spatio Temporal Service Model) was used to predict and detect very large crowds [109]. The model is also used to guide officials into the optimal path to shelters in case of disasters. Similarly, intelligent shelter allotment (ISA) [110] was suggested to optimize the evacuation activities and define the best routes and shelter locations. Priority-based Routing Framework for Flying Adhoc Networks (PRoFFAN) is recently suggested for expediting the delivery of critical image data to control centers in case of natural disasters [111]. Hajj Gear is another proposed system that allows pilgrims to press an SOS button that they have in their wearable sensor in case of an emergency. Using NB-IoT and LTE-M technologies, Hajj Gear will immediately inform their group leaders with the information and exact location of the pilgrims in need [112]. Furthermore, Hameed proposed in 2010 comprehensive Hajj model, including a database and a multi-lingual education model, to solve Hajj challenges [113]. His model included an emergency and rescue component. Lastly, Smart Pilgrim is another effort to assist pilgrims and authorities in case of emergency [114]. Smart Pilgrim is a contactless, and paper-less application that leverages multiple technologies available in today's smartphone, such as Wi-Fi, Bluetooth, and GPS.

D. EXPERT SYSTEMS AND LEARNING

Sulaiman *et al.* proposed Hajj-QAES [115], which is an expert system that is smart enough to answer all the questions the pilgrim might have in real time. Hajj-QAES is designed to handle both basic and advanced questions. It could help in educating pilgrims in the Hajj preparation phase as well. M-Hajj [116] is a similar initiative that uses Case Based Reasoning (CBR) and Decision Trees to come up with the optimal answers. It was implemented on Android as a proof for the concept of the Mobile Decision Support System (M-DSS). A hybrid approach for answering complex questions about Hajj was also proposed in the literature [117]. This framework used both the rule and frame approach in building the tool. Zeki and others proposed a mobile dictionary that is able to use voice recognition to solve the issue of pilgrims' lack of knowledge [118]. The proposed mobile application supported three languages and targets on closing the gap of knowledge that many pilgrims have. In reality, many pilgrims rely on YouTube videos to find answers for their ritual questions. A video search engine has been proposed in the literature to help pilgrims efficiently search for useful videos that are related to Hajj and Umrah topics [119]. Actually, this project is composed of two initiatives, a recommendation system to verify if the video belongs to a specific topic, and a database sorting mechanism. Also, a knowledge-based expert system to ease the process of answering the questions during Hajj has been proposed in the literature [120]. The idea is to install kiosks in various locations in the sacred places to facilitate the question-and-answer process. Sharef *et al.* worked towards allowing self-guided education for Umrah pilgrims [121]. The authors proposed a semantic-based question and answering system that uses ontology for knowledge representation. Ali *et al.* proposed a context-aware smartphone application called Mobile Muslim Companion that provides personalized information to pilgrims based on the user's context [122]. Caidi highlighted the difficulty of finding gender-specific information rrlated to Hajj and Umrah [123]. This is important as female pilgrims fear missing out on important rituals because of menstruation. Last but not least, GuideMe is an initiative to remind pilgrims with the appropriate sayings (doaa) based on the GPS location of the smart devices [124]. As an alternative, Deep Learning (DL) is used to analyze captured photos and predict the location whenever the GPS signal is not available.

It is very important to teach prospective pilgrims the basics of the Hajj rituals. In 2004, Harmain *et al.* proposed a web-based Hajj training system [125]. Also using web, Fathnan and others proposed a web-based simulation for Hajj in order to teach the pilgrims the rituals before actually traveling to Makkah [126]. M-Umrah is an Android based application designed to help Malaysian Umrah pilgrims with a step-by-step guide to complete the rituals [127]. GPS was used to implement the location tracking functionality.

Similarly, V-Hajj is a learning tool designed based on virtual environment and multimedia technologies to motivate elderly people to learn about the rituals before visiting the holy land [128]–[130]. HajjGame [131] is an interesting way proposed in the literature to teach pilgrimage the rituals in a fun way. It is an educational-based game that follows the Role Playing Game (RPG) methodology. Yasin and his colleagues proposed replacing walk-through scaled models with situated learning for training pilgrims before they arrive to the holy lands [132]. In fact, they proposed utilizing an avatar in the 3D virtual reality environment to train pilgrims with various rituals such as Tawaf and Sa'i. Another effort to educate the pilgrims before coming to the holy land used Virtual Reality (VR) [133]. It has been implemented on a mobile application and tested with pilgrims from Bangladesh. Also using VR, Rahim *et al.* developed a 3D Tawaf simulation for educating Malaysian pilgrims [134]. Recently, Salleh *et al.* also proposed a VR-based Hajj teaching system [135]. The Free Hajj [136] is another VR-based mobile app that offers six services, namely: Hajj series, Hajj series guide, Arabic language translation, floor plans, FAQs, and an instruction guide. Also, the use of 360 degree videos was proposed in addition to the VR engine to help the pilgrims to practice the rituals before arriving to the holy land [137]. Moreover, Myo Armband [138] was used to simulate the throwing experience in Jamaraat [139]. The author also measured the speed of the stone using a specialized application called sport speed gun. Computer Games were also used in teaching pilgrims. Abdur Rahman and Hossian proposed a cyber game that acts as a training tool for potential pilgrims [140]. The game could also be played physically during the ritual to incentivize pilgrims to share data on a crowdsourcing fashion. Sultan also proposed a game for teaching prospective pilgrims the rituals [141]. The same author also designed an interactive digital story map application for Makkah [142]. Through smart phones, this story map could be considered as an electronic tour guide that every pilgrim can have in his pocket. In a similar effort, Alzahrani *et al.* proposed a mobile application that is using Integrated Multimedia Maps (IMM) through which users can enjoy interactive storytelling [143]. Pilgrim Trail is an idea suggested to allow people who cannot join the Hajj physically to experience what it looks like through a website or mobile app [144]. Pilgrim Trail also enables the pilgrim to remotely participate in various types of activities and to record thoughts and feelings, and share them with other virtual pilgrims. In fact, pilgrims can now see the development of the Prophet's Mosque in Madinah over centuries using 3D imagery [145]. With the help of a VR headset, a real-time navigation experience is now possible for all who are interested in understanding the history of this heritage. A similar effort has been made for Makkah, called Digital Makkah [146]. Finally, Bhatti *et al.* proposed a learning system architecture that is based on multimedia. The proposed system is composed of animated and interactive videos that would create a virtual tour for performing Hajj [147].

E. HAJJ MANAGEMENT DIGITIZATION

A Hajj management system, also known as e-Hajj, supports the Hajj candidates in their journey starting from the registration phase until the repatriation [148], [149]. In a similar effort, Sami and AlHakami proposed an online Hajj management system [150]. Al-Hashedi and others designed a comprehensive Hajj management solution for Hajj that is based on RFID technology [151]. The proposed system includes several services, such as luggage tagging, visa support, as well as pilgrim tagging. Al-Hashedi also defined all the processes for the RFID implementation in the Hajj management system using Strategic Information Systems Planning (SISP) [152]. Recently, the blockchain technology was proposed to help issuing and controlling Hajj and Umarh Permits [153], [154] Especially in countries with large Muslim populations, governments usually assign special Hajj organizers in order to ease the process of registration. In order to digitize such services, the first step is to do Business Process Re-engineering (BPR) [155]. In fact, many people will not get a chance to perform Hajj specially in Islamic countries with large populations. For example, the Hajj quota in Indonesia was 150,000 pilgrims/year, but the number of people registered for Hajj is 40 million. Hence, it is typical to wait for more than 10 years after registration before getting a chance to perform Hajj. Another effort used both fuzzy logic and hill-climbing optimization models to objectively decide who should go for Hajj [156]. The authors build their optimization model based on seven parameters, including age, health, and job. Solving the same issue, Putri *et al.* developed a conceptual model of the pilgrimage system in Indonesia [157]. This model demystifies the complex problem of Hajj digitization and paves the road to maintain customer trust and loyalty in using electronic services for Hajj and Umrah. Another idea was proposed recently in the literature to solve this issue of transparent pilgrims' selection. Shaheen suggested implementing a centralized mobile based Hajj reservation system in Saudi Arabia that chooses the pilgrims using a well-defined points based policy [158]. Bangladesh is another example of an Islamic country with a large population. As part of the Digital Bangladesh campaign, the government launched an online Hajj information management system [159]. The portal provides many services, such as information verification, location registration, health status logging and flight details for each pilgrim, among others [160]. The system allows effective communication between pilgrims and their relatives back home during Hajj. Finally, Alharthi suggested using digital currencies to help in the organization and management of Hajj and Umrah activities [161].

F. HEALTH INFORMATICS

The Ministry of Health in Saudi Arabia is collaborating with the Centers for Disease Control and Prevention (CDC) in the USA to initiate a Hajj Mobile Disease Surveillance System (Hajj-MDSS), which allows rapid detection of infectious diseases during Hajj. Hajj-MDSS will help enhance

prevention and control measures through real-time surveillance [162]. Al-Shammari *et al.* proposed a computational epidemic simulation framework that helps analyze the transmission of diseases during Hajj [163]. Al-Shammari and Mikler also used modeling to better understand the spread of infectious diseases, such as influenza (H1N1) and MERS-CoV (Middle East respiratory syndrome coronavirus) [164]. Recently, agent-based modeling was used to predict the possible scenarios of disease spread in the Grand Mosque during the SARS-CoV-2 pandemic [165], [166]. Also, a conceptual framework for a Hajj Health Control System has been proposed in the literature [167]. The main idea behind it is to use big data analytics in order to prevent diseases. The same authors surveyed the approaches leveraging big data analytics to detect outbreaks of diseases in global mass gatherings like Hajj [168]. Furthermore, Alanezi *et al.* studied the use of social networking for managing infectious diseases during Hajj [169]. Through questionnaires and interviews, they concluded that social networking could be used as a tool for Infectious Disease Management (IDM). A similar effort used supervised machine learning methods in order to detect self-reported flu cases in twitter [170]. Recently, the Saudi Data and Artificial Intelligence Authority (SDAIA) developed a couple of mobile applications to manage and control COVID-19 in the Kingdom, such as Eatamarna, Sehhaty and Tawakkalna [171]. The role of these applications to manage Hajj and Umrah was highlighted by Basahel and her colleagues [172]. Furthermore, a recent study showed that the Eatamarna application, used for booking Umrah slots, was greatly improving the pilgrims' Umrah experience [173]. In reality, the Kingdom was ready to fight COVID-19 as it had experience with fighting MERS-CoV. The information technology based efforts used to deal with MERS-CoV in 2014 was highlighted by Al-Tawfiq and Memish [174]. In an effort to suppress the outbreak of disease during Hajj, aerial photography had been used to estimate the use of face masks during the Hajj [175], [176].

To provide medical care for pilgrims during Hajj, the Kingdom of Saudi Arabia prepared 25 hospitals with a total capacity of 5000 beds, 500 of which are for Intensive Care Units. These hospitals and healthcare centers are connected to the central Command and Control Center in Makkah, which uses the latest e-health surveillance systems for real-time reporting of medical emergencies during Hajj [177]. In fact, many papers proposed using technology to improve health care facilities. For example, Hijry and Olawoyin used machine learning algorithms to predict the length of stay of pilgrims in the emergency department during Hajj [178]. The length of stay is an important metric to measure the quality of medical care of any hospital. Also targeting emergency rooms, Jassas *et al.* designed and implemented an e-health smart networked system that decreases the required time of serving a large number of patients during Hajj, particularly in emergency and accident situations [179]. This was made possible by transferring data from patients' bodies gathered by medical sensors to the cloud via WSN. In addition, Saudi Red Crescent analyzed the effect of automatic call center localization of the caller on the ambulance resource management [180]. This study found that the caller location helped expediting the emergent response of medical service. Moreover, digital pen and paper technology was proposed to facilitate capturing the information quickly and accurately in the health sector [181]. Business intelligence will then kick in to represent the captured data in statistical accumulations and generate graphs for real-time decision making. Furthermore, Reinforcement Learning was used to support decisions with regard to disaster management in the medical centers [182]. In fact, the importance of using pilgrims health information instantaneously is obvious. Nafea *et al.* proposed a framework for health tracking using Electronic Health Records (EHR) [183]. This framework is believed to minimize the time taken to act in case of any emergency in Hajj. Recently, Aljohani *et al.* recommended integrating several health platforms in order to provide instantaneous access to pilgrims' medical information, which lead to improved performance and better decision-making [184]. Lastly, the severity level of electromagnetic fields generated by telecommunications companys' towers had been studied in the central area of Makkah and the holy sites in order to assess the possible effect on the health of the pilgrims and visitors [185]. The authors concluded that the levels are within acceptable national and international standards.

Researchers suggested using wearable devices to monitor various aspects of pilgrims' health. For Instance, the relationship between stress that pilgrims are facing and sleep patterns is studied in the literature, thanks to the wearable sensors [186]. In a similar effort, the vital signs of pilgrims, such as heartbeat and temperature, had been monitored [187]. The system uses GPRS to communicate any emergencies to the Command and Control Center. GPS is used to locate the pilgrim in need. Another health monitoring system that is based on Adroiuno wearable devises was proposed in the literature [188]. These wearable devises enable a timely response in case of medical emergencies. In addition, Abu Elkhail and Baroudi proposed a real-time health monitoring system that is based on mobile clustering [189]. In their proposal, the crowd is divided into small clusters called piconets. The intra-piconet communication happens via Bluetooth, while inter-piconet communication happens either via Wi-Fi or 3G/4G. In a similar effort, Alabsi and Abdulrahman invented an e-medical interpreter which is a smartphone application that bridges the communication gap between the pilgrims and healthcare workers [190]. The application was supplied with images and sounds from various languages, such as Arabic, English, French, Urdu, Hindi and Malay. A medical bracelet was also suggested as an identification tag in case of medical emergency [191]. Finally, machine learning was used to classify the ability of potential pilgrims to perform Hajj [192]. The authors used supervised learning to analyze millions of EHR to prioritize pilgrims with good health conditions.

G. CROWD MANAGEMENT

Hajj Crowd management is one of the hottest areas in Hajj and Umrah research when it comes to utilizing ICT. More than one fourth of all papers surveyed in this paper were targeting crowd management in one way or another. This is because stampedes have caused fatalities in the past. Isam and his colleagues proposed a stampede avoidance system that uses an E-wrist belt and Wemos D1 [193]. They have used machine learning to estimate the likelihood of stampedes by assessing the data gathered from various kinds of sensors. Also on stampede avoidance, the viola-jones algorithm was used for stampede monitoring [194]. In addition, the effect of panic on crowd evacuation has been studied as well [195]. Information entropy was used to model the panic. The stampede in 2015 has been simulated to verify the linkage between the number of pedestrians and entropy. Furthermore, Mitchell *et al.* used the RFID technology through a mobile app to control the crowd [196]. In a similar effort, Yamin *et al.* suggested using RFID tags and wireless technologies in order to implement a crowd management system [197], [198]. Hashish and Ahmed used WSN rings overlay in addition to RFID tags to control the crowd [199]. Alqahtani also proposed using WSN along with Massive MIMO for crowd monitoring [200]. In fact, game theory was also suggested for the purpose of optimally moving the crowd from one holy site to the other [201]. Mean field games are used to optimize the velocity and direction to each ritual. Similarly, a framework for smart crowd monitoring and management has been proposed in the literature [202]. What makes this framework unique is the fact that the focus is on monitoring paths that interconnect sites in the sacred places. This helps in the proactive discovery of potential issues and the ability to predict big crowds faster. iCrowd is another framework that uses wearables to monitor the crowd movement in real time [203]. It is able to do this by saving the location of millions of pilgrims and do the analytics online. Crowds also had been analysed using social network analysis with the Scale Free Network (SFN) [204]. An AR based smartphone application was also used to manage the crowd during Hajj [205]. Last but not least, smart street was proposed to solve the Hajj crowd issue [206]. With the help of wireless sensor networks and distributed fog nodes, LED lights are used for managing the crowd.

Some efforts focused on solving the issue of managing the crowd in a specific location such as the Grand Mosque [207], [208] and, [209]. Yassein used simulation to regulate access of the crowd to El-Salam gate at Al-Masjid Al-Haram during peak times [210]. Also, researchers worked on solving the crowd issue in the Prophet's Mosque. As an example, simulation was used to manage the crowd entering public washrooms next to AlMasjid AlNabawi [211]. Also related to Al-Masjid Al-Nabawi, Al-Ahmadi and others studied the crowd dynamic in the visiting corridor in front of the prophet's tomb [212]. The goal of this simulation is to optimize the flow rate of pilgrims and visitors. In Virtual Tawaf, Finite State Machine (FSM) was used to find out collision-free trajectories during tawaf [193]. Another effort used FSM to simulate the crowd movement for kissing the Black Stone during Tawaf [207]. Also targeting Tawaf, A* algorithm was suggested in addition to the RVO sensor to simulate the pilgrims' movement during the circumference activity [213]. The social force model was also used to simulate multi-group crowds in the Tawaf area [214]. Cellular Automata was also proposed for multi-floor tawaf simulation [215]. In fact, neural network was proposed to determine pedestrians' ability to make movements out of their route. Wulansari proposed using steering behavior to simulate the crowd in the tawaf area [209]. Controlling the crowd at the Sa'i site was also tackled [216]. Almoaid *et al.* studied Tawaf and Sa'i jointly using ExtendSim, which is a discrete event simulation tool [217]. Other efforts focused on crowd management in Mina, which is a very important part of a pilgrim's journey, as pilgrims stay in Mina the most. IoT was used in addition to cloud computing to achieve congestion avoidance in the Mina area [218]. Felebman and Rehman designed and implemented a portal that helps scheduling the movements of pilgrims based on their Hajj establishments on specific parts of the rituals such as the stoning [219]. Also trying to solve the issue of crowd management in the Jamarat area, Almshat and his colleagues proposed using an interconnected system of computer surveillance devices to control crowd movements and provide guidance in the stoning areas [220], [221]. Alternatively, Amer and Almatrafi proposed using a multi-agent architecture to handle the negotiation between Hajj authorities and Hajj establishments to set up the times [222].

One of the main challenges in crowd management is how to accurately measure the number of people in the crowd. Musa *et al.* proposed crowd reckoning to estimate pilgrims' headcount through still images [223]. Such a mechanism works best in large crowds, which makes it very much suitable for Hajj. In fact, social media applications could be a good source for high-quality gigapixel images uploaded by pilgrims [224]. Sajid *et al.* used adaptive thresholding to count the people in the crowd [225]. Also targeting crowd prediction, He *et al.* proposed two deep architectures for predicting crowd flow accurately [226]. Smartcrowd is another initiative that uses mobile cloud computing for crowd estimation [227]. In addition, machine learning was used to solve the problem of counting pilgrims. Using R-CNN, it is possible now not only to count the number of pilgrims in the crowd, but also to determine their gender and estimate their age [228]. Likewise, Habib *et al.* suggested using Faster Region CNN to achieve accurate computer vision-based crowd management [229]. CNN was also used for crowd density estimation at Al-Masjid Al-Haram in Makkah with 70% accuracy [230]. In fact, crowd density is one of the major threats to crowd safety [231]. Moreover, fuzzy logic was used to control the crowd. It enabled researchers to create an alert system to keep the crowd safe in case of emergency [232]. The same group

also used Long Short Term Memory (LSTM) to predict the direction of dense crowds [233]. Additionally, Seddiq *et al.* utilized unsupervised clustering to detect crowd congestion during Hajj and Umrah [234]. Bamaqa *et al.* proposed using Hierarchical Temporal Memory (HTM) to allow the prediction of potential overcrowding through anomalies in crowd movements [235]. Moreover, bracelets were given to pilgrims to alert the officials in case of congestion [236]. These bracelets talk to towers via Bluetooth Low Energy (BLE). Also using BLE, Jamil *et al.* proposed a hybrid participatory sensing architecture for hajj crowd management [237], [238]. The proposed system offloaded the location advertisement to BLE tags through smart phones. Hamid and Mousatfa proposed a radio prorogation model that minimizes distance estimation errors in crowded environments [239]. This model was verified experimentally in the Prophet's Mosque by measuring the Received Signal Strength Indicator (RSSI) of BLE devices in both crowded and uncrowded settings. Finally, Khan *et al.* proposed analyzing video feed using computer vision algorithms to measure the crowdedness of a specific location [240].

Since early 2000's, computerized systems were proposed to guide and control the crowds in Hajj [241]. Likewise, Al-shalani *et al.* proposed a GPS-based mobile app for crowd control [242]. This application is Android based and is available in six languages, namely: Arabic, English, French, Spanish, Italian, and Turkish. Rehman and Felemban implemented an interactive tool to help scheduling crowd movements safely [243]. A recent initiative to ease the crowd movement by the government is to group all the pilgrims into several establishments based on their countries. Felemban and others also proposed an advanced scheduling mechanism for these establishments that is safe during Hajj. This scheduling mechanism adheres to the spatio-temporal constraints of the ritual. It specifies which train, route and stops every group will pass by [244]. A pilgrim-centric crowd management approach had also been proposed in the literature [245]. Electronic means, such as electronic billboards (EBBs), SMS messages, audio- video Hajj podcasts, pre-recorded TV clips, among others, were used to increase the pilgrims awareness on the hazards of poor crowd management and how stampedes are avoided. Additionally, Jiang *et al.* proposed ULCM (Ultra Large-scale Crowd Monitoring) initiative [246]. To be able to achieve crowd intelligence in real time, UCLM used UAV (Unmanned Aerial Vehicles) that are equipped with LiDAR sensors and HD cameras. Miao *et al.* also suggested using UAVs with the help of airborne LiDAR (ALORID) to manage the crowd [247]. Dealing with pilgrims in a flow as particles in a fluid is what Moore *et al.* tried to do [248]. Thanks to hydrodynamic lenses, visual surveillance is now possible. This will help in detecting abnormal crowd behavior early on to prevent serious injuries. Zawbaa *et al.* went the extra mile by classifying the behavior of the cloud using machine learning algorithms. They have used K-Nearest Neighbor (KNN), Support Vector Machine (SVM), and Random Forests (RF) classifiers to identify human events, such as walking, sitting, and even smiling. They manage to do so by analyzing real-time videos. Furthermore, operation research was proposed to control the crowd in the stoning sight [249], as well as in the pilgrims' journey between Arafat and Muzdalifa which is called "Alnafra" [250].

Simulation and modeling were heavily used in Hajj crowd management. Back in 2009, Narain *et al.* proposed a novel crowd simulation technique using both discrete agents as well as continuous systems [251]–[253]. Similarly, a crowd simulation based on an intelligent agent was proposed in the literature [254]. The intelligent agent is able to mimic natural crowd behavior. AbdurRahman and his colleagues also proposed an agent-based crowd simulation for Hajj [255]. His model utilizes parallel programming advancement using Graphics Processing Units (GPUs) to be able to simulate large crowds and check organization plans beforehand. Similarly, Abdul Majid *et al.* proposed useing GPUs to simulate in a parallel fashion the navigational behaviors of agent-based crowd models during Hajj. The use of GPUs boosted the performance of the simulator [256]. In fact, the idea of using computer simulation in crowd management was proposed earlier as well [257], [258]. Mahmood *et al.* suggested using an agent-based simulation framework to assess the crowd evacuation strategies during Hajj [259]. Felemban *et al.* proposed a platform called CAEPM (Capacity Aware Evacuation Planning using Multimodal Transportation) which used multi-modal transportation to evacuate pilgrims in case pf disasters [260]. Train location and bus movements were tracked through GPS and used to build the platform. The same author recently proposed a novel modeling tool for scheduling crowd movement in Mina [261]. Also targeting crowd evacuation plans, Alqurashi and Altman proposed an agent-based framework that is multi-level and multi-stage to automate the decision-making process in case of emergency [262]. They have used their model to simulate the crowd dynamics on the rooftop of Al-Masjid Al-Haram. Likewise, the crowd visiting the prophet's graveyard and praying in Rawdah had also been simulated [263]. Also, Golas *et al.* suggested applying a continuum model that replicates crowd turbulence [264]. Other researchers tried to approach the crowd management issue by comparing it to complex network management [265]. By doing so, the crowd data could be analyzed using degree centrality, closeness centrality and betweenness centrality. Recently, the impact of panic propagation dynamics on high density crowd movement has been analyzed. The degree of panic is measured through panic entropy. Numeric simulation is used to find the relationship between density and velocity of the crowd [266]. Similarly, Zhao *et al.* modeled pedestrian merging dynamics at T-shaped street junctions using Aw-Rascle dynamic-flow model [267]. Furthermore, an agent-based model was proposed to analyze pedestrians dynamics. Researchers studied the effect of changing density, configurations of the environment of groups of pedestrians using computer

simulation [268], [269]. Recently, Kurdi *et al.* used modeling to simulate the emergency evacuation in the stoning area [270].

H. TRANSPORTATION

Transportation used to be one of the main challenges in Hajj and Umrah. Statistics show that 94% of foreign pilgrims arriving to Saudi Arabia in 2019 came by Air [13]. Since the airport is not located in Makkah, buses used to be the main transportation method to and from the sacred sites. To understand bus movements in Hajj, Felemban and his colleagues implemented an interactive platform that analyzes GPS traces of more than 20,000 buses during Hajj [271], [272]. Abdeen *et al.* invented a parking spot allocation algorithm for parking allocation. The proposed system considered real-time street traffic while choosing the optimal parking spot [273]. Al-Shariff *et al.* suggested using an Intelligent Transportation System (ITS) that is based on both Autonomous Electric Vehicles (AEVs) and IoT [274]. A pilot project had been implemented to regulate the traffic on Quba Boulevard in Madinah. Also in Madinah, Tayan *et al.* modeled the transportation system in the central district [275]. The simulation showed a big room for improvement and recommendations were given to improve both the traffic movement as well as the evacuation plan. Tayan and Binali used computer simulations to model the road traffic during hajj using networking concepts [276]. IoT was also proposed to help in solving traffic jams during Hajj [277]. Likewise, IoT was also recommended to manage the road traffic lights in the city of Makkah during Hajj [278]. By sensing the level of crowdedness in the road, real time decisions will help in easing the jams instantaneously. Moreover, RFID gates were proposed to automatically detect buses moving in prohibited times or locations [222]. Similarly, RFID was also suggested for tracking and controlling pilgrims' shuttle buses [279]. Moreover, Dhaou proposed using RFID to stop unauthorized pilgrims from riding buses [280]. The author also suggested using GPS to track buses in the sacred places during their journeys. In fact, Automatic Sorting Centers are also proposed in the literature to help in easing traffic congestion at the entrance of Makkah city as well as at the holy sites [281]. Using an RFID bracelet, there is no need for manual checking of individual pilgrims at checkpoints. RFID and GIS technologies were combined together in order to monitor and control bus movements from Arafat to Muzdalifah, which is considered on of the major bottlenecks during Hajj [282]. Tayan *et al.* used modeling to resolve traffic bottlenecks in the Holy sights transportation system [283]. Recently, Alhuthali and his colleagues invented a traffic flow monitoring system that is based on MATLAB vision tool. The system not only can count vehicles, but is able also to classify these vehicles into small, medium and large in order to facilitate traffic management [284]. Finally, Multi-Modal Transportation Network (MMTK) was developed to ease the planning of pilgrims' transportation during Hajj days [36]. The network includes various transportation modes, such as bus routes, train networks and pedestrian paths.

I. INFRASTRUCTURE AND PLANNING

Mina is considered the largest tent city in the world because it hosts more than 10,000 tents during Hajj. One of the main issues with tents is the fact that they might catch fire quickly. In fact, several fire incidents were reported in the Mina area that resulted in fatalities. Mojamed proposed Smart Mina, which is a wireless network infrastructure for smart-fire detection in Mina using LoRaWAN [302]. Also, optimization techniques were used to find the optimal distribution of tents in Mina to improve the efficiency and increase the capacity [311]. In addition, Yasein *et al.* proposed the use of IoT to transform the camps in Mina into smart ones [298]. In fact, IoT could be utilized in other ways. For example, Elhassan proposed a smart waste management system based on IoT [285]. The system uses ultrasonic and humidity sensors to sort out organic waste in the trash bins. Aziz and his colleagues laid down the engineering requirements for implementing an indoor smart space in Al-Masjid Al-Haram in Makkah [300]. The proposed smart space uses IoT technology to provide convenient and intelligent services to the pilgrims as well the local authorities. Smart surveillance cameras were also suggested for managing access and achieving a high level of security control during Hajj [290]. Furthermore, Al-Otaibi *et al.* designed an intelligent system to control pedestrian tunnels in Makkah and Madinah [319]. The system ensures good ventilation and fast response in the case of emergency. In a similar effort, Murad *et al.* proposed an IoT- based system to monitor air quality of pedestrian tunnels in Makkah [297]. In addition, UAV is proposed to be used as an aerial base station in order to help absorb the huge need for wireless coverage during Hajj [310]. UAVs could be used for crowd analytics as well [317]. Particle Swarm Optimization (PSO) and K-means with ternary search (KTS) algorithms are used to theoretically solve the problem of optimal placement of UAVs. Mohandes suggested combining RFID and license plate recognition (LPR) technologies to provide access control to vehicles during pilgrimage [313]. Simply, authorized vehicles will be detected either through the RFID readers or by getting their plate scanned using the LPR algorithm. Last but not least, Spatial Data Infrastructure (SDI) was proposed to support a decision-making process in case of emergency situations [36].

ICT was used in planning various aspects of Hajj and Umrah as well. For instance, Deep Learning (DL) was used to estimate the number of pilgrims visiting the holy sites in the coming three years [306]. Moreover, Ahmed *et al.* used Neural Networks (NN) and Fuzzy Inference Rules (FIR) to estimate the Short Term Load Forecasting (STLF) of power during Hajj [303]. STLF is very important for the planning and maintenance optimization of power systems. In a similar effort, Shambor *et al.* used Artificial Neural Networks to forecast the electricity and water needs of pilgrims [305]. On the other hand, Gutub and Alharthi suggested

TABLE 3. Technology based classification for the papers surveyed.

Technology	References
Ad-Hoc Networks	[79], [111]
Adrouino Microcontroller	[69], [188], [285]
Augmented Reality (AR)-Virtual Reality (VR)-Mixed Reality (MR)	[92], [132]–[137], [139], [143], [145], [205], [209]
Business Intelligence (BI)	[41], [181]
Big Data Analytics	[49], [168]
Bluetooth Low Energy (BLE)	[67], [114], [189], [236]–[239], [286]
Blockchain	[153], [154], [161], [287]–[289]
Closed-Circuit TeleVision (CCTV)	[246], [290]
Cellular Networks	[69], [70], [80], [106], [114], [185], [187], [189], [194]
Cloud Computing	[74], [218], [227], [265], [291], [292]
Cryptography	[293]
Data Visualization	[294]
Fog Computing	[206], [291], [295]
Game Theory	[201]
Global Positioning System (GPS) /Geographic Information System (GIS)	[62]–[64], [70], [73], [74], [80], [84], [86], [87], [89], [90], [97], [100], [104], [114], [124], [142], [180], [187], [189], [194], [203], [237], [260], [271], [272], [280], [282], [290]
Graphics Processing Units (GPU)	[255], [256]
Image Processing and Computer Vision	[82], [83], [146], [224], [225], [240], [248], [250], [284]
Internet of Things (IoT)	[67], [68], [112], [193], [218], [274], [277], [278], [285], [287], [296]–[301]
Light Detection and Ranging (LiDAR)	[247]
Low-Power Wide-Area Network (LPWAN)	[112], [302]
Machine Learning/Deep Learning	[81], [83], [182], [226], [228]–[230], [234], [303]–[306]
Modeling and Simulation	[36], [102], [109], [110], [163]–[166], [195], [202], [207]–[217], [251], [256]–[259], [261]–[264], [266]–[270], [272], [273], [275], [276], [283], [307]–[310]
Near Field Communication (NFC)	[44], [45]
Ontology	[121]
Optimization	[156], [311]
Radio Frequency (RF/RFID)	[70], [72], [75], [76], [101], [105]–[107], [114], [151], [152], [196]–[199], [222], [279]–[282], [312]–[314]
Software-Defined Networking	[246]
Smartphone and Social Media	[26], [27], [29]–[35], [37], [42], [44], [45], [47], [48], [50], [66], [74], [77]–[80], [87], [88], [92]–[94], [96], [98], [108], [114], [118], [122], [124], [127], [140], [158], [169], [170], [189], [190], [196], [204], [224], [237], [238], [315]–[317]
Steganography	[293]
Text Segmentation	[28], [29], [313]
Unmanned Aerial Vehicle (UAV)	[111], [246], [247], [310], [317]
Wearable Technology	[94], [95], [112], [191]
Web	[53], [54], [125], [126], [144], [159], [318]
Wireless LAN (WiFi)	[114], [189]
Wireless Sensor Network (WSN)	[71], [89], [179], [199], [200], [206], [296], [297], [301], [319]
Zigbee Protocol	[103]

using data visualization for proper planning for Hajj and Umrah [294], [320]. A case study on the benefit of data utilization in housing distribution was also presented. In addiiton, AI was used to solve the pilgrims' housing problem with more than 70% accuracy [304]. Furthermore, WSN and IoT were used to estimate the food demand and necessary supply during Hajj [296]. Also targeting food management in Hajj, Radain *et al.* suggested using blockchain technology as a quality control method for the pilgrims meals [289]. Morgan and Khayyat used Genetic Algorithm (GA) to optimize the distribution of service points in holy sites as well as Makkah and Madinah [321]. This methodology could be used to optimally locate police cars, ambulances, fire trucks, and surveillance cameras, among others. In order to find the optimal number of sensors to be deployed in the sacred places, Morgan *et al.* used Integer Linear Programming (ILP). This is important in order to avoid wasting money on unnecessary sensors [301]. As a proof of the concept, the authors analyzed the needed number of smoke detectors in the second Saudi extension of the Prophet's Mosque in Madinah. Lastly, Barhamain discussed various plans to transform Makkah and Madinah into smart cities [322]. Challenges and potential obstacles were also discussed in this paper.

J. CYBERSECURITY AND PRIVACY

There is a limited amount of work in the literature that addresses the issue of Cyber Security and Privacy in Hajj and Umrah. Himdi and Sandhu proposed a lattice-based model that allows sharing the information securely between ministries during Hajj [323]. In 2010, Naser *et al.* presented nine possible security attacks affecting RFID systems deployed in Hajj [314]. Also, IoT as a service was proposed to manage services during Hajj [287]. The transactions are being secured using blockchain and off-chain technologies. Recently, Mandourah and Yamin proposed using blockchain to manage Hajj and Umrah [288]. In their proposed framework, they tried to solve the permit fraud, accommodation, and healthcare issues using blockchain technology. Samkari

and Gutub proposed a 3-layer security system for protecting Electronic Medical Records (EMRs) of pilgrims against cybercrimes [293]. In fact, the suggested model combined two well-known methodologies to ensure the security of the EMRs. The two methodologies are hybrid cryptography and steganography. In 2017, Khan *et al.* surveyed around 250 mobile applications related to Hajj [18]. Recently, Shambour and Gutub evaluated 471 Hajj and Umrah related apps in Google Playstore for data privacy preservation [324]. Also, fog computing was prposed to enhance the security and privacy of pilgrims' data [295]. Unfortunately, other efforts could not be found that tackle privacy preservation of pilgrims' private information. With the increase in number of smart sensors and relevant applications, Blockchain and similar technologies could be used to ensure pilgrims that their data is stored securely.

V. TECHNOLOGY BASED CLASSIFICATION

Table 3 groups the surveyed papers based on the technology used. As expected, smartphone and social media is by far the largest group. This is because of the high smartphone penetration rates worldwide. Modeling and simulation comes second with around 40 surveyed papers. The advancements in computation power made it possible to simulate more complex scenarios when it comes to crowd management. The third largest group is for GPS, with no surprise, as this technology is vital when it comes to tracking guidance and outdoor navigation. On the other hand, it was surprising to see very limited usage of Zigbee, Ad-Hoc networks and Wi-Fi. These are indeed great avenues for future research in this field.

VI. OPEN CHALLENGES AND RESEARCH OPPORTUNITIES

In this section, I highlight open challenges in Hajj and Umrah that I could be solved using information and communication technologies. Below is a brief discussion on nine research opportunities in the filed of using ICT to service pilgrims.

A. FINTECH

Pilgrims coming to the holy land from around the globe would love to have an easy and secure way to buy goods and gifts without worrying about currency exchange and transfer rates. Also, many Muslims around the world demand a financial e-assistant to help them go on Hajj using savings and investment programs.

B. TOURISM

According to Kingdom's vision 2030, the number of Umrah visitors will be increased from 8 million to 30 million per annum [325]. In fact, the holy land is full of historic sites that are of extreme importance to pilgrims and visitors. For example, Madinah has tens of prophetic mosques that were built after incidents related to Prophet Mohammad PBUH. Nowadays, many pilgrims visit Madinah without getting a chance to see these mosques or pray in them. Using mobile apps with advanced AR/VR technologies will definitely improve their spiritual experience.

C. LANGUAGE

Imagine that level of difficulty you face when visiting a country that you cannot speak its language? The diversity of the pilgrims poses many serious challenges [326]. The fact that pilgrims come from more than 183 countries around the world imposes additional communication barrier as well [2]. One way to solve this issue is using offline Arabic Handwritten Text Recognition [327]. Such technology will help in several aspects and will for sure improve the quality of the pilgrim experience.

D. HARSH WEATHER

Hajj timing is based on the lunar Islamic calendar and hence varies with respect to the Gregorian calendar. As a result, Hajj could happen in July or August when daytime temperatures can reach up to 50°C. The dress code in Hajj places an extra challenge, as men could not cover their heads. Using some sort of wearables could help in reducing the chance of pilgrims getting heat exhaustion and heatstroke.

E. FOOD AND BEVERAGE

Due to the potential risk of fire, the government of Saudi Arabia does not allow pilgrims to erect their own tents or prepare their own food during Hajj. In fact, around 86% of the pilgrims depended on the either hotels or Hajj establishments as their primary source of food, and less than 9% of pilgrims cooked their food themselves. [289]. I believe that using heat detectors and smart firefighting technology might solve this issue.

F. PANDEMIC

Hajj is crowded in nature as densities can reach up to 9 pilgrims/m^2 [2]. Such crowded environments increase the probability of respiratory disease transmission. Thus, new technologies could help in educating pilgrims, preventing illness transmission and creating a healthier Hajj [328].

G. WASTE MANAGEMENT

During Hajj, Makkah city receives 4706 tons of waste per day and around 2.5 million animals are slaughtered [329]. Makkah municipality has approximately 138 ground warehouses and around 1,300 waste compressor boxes to deal with waste generated from the holy sites. ICT could be used in waste management automation as well as educating pilgrims on the proper way to deal with different kinds of waste.

H. COMMUNICATION

As expected, many pilgrims experience difficulty in accessing wireless telecommunication services using smartphones during Hajj. What happens then is that pilgrims typically claim that the network is congested and try repeatedly to access the network with their smartphones. As a result, pilgrim frustration increases and network congestion gets

worse! Advancement in 5G as well 802.11ax could be utilized in solving this issue.

I. ILLEGAL PILGRIMS

The main reason for overcrowding in Hajj is the large number of illegal pilgrims who do not have valid Hajj permits [330]. These pilgrims can also be the source of the spread of disease or security issues. Despite the fact that the harsh penalties imposed by the government had decreased the number of unauthorized In-Kingdom pilgrims, they still find ways to sneak in.

VII. CONCLUSION

Hajj is considered on of the largest annual gatherings in the world. Managing around three million people is very challenging. Researchers from various ICT disciplines have tried for decades to tackle these challenges using state of the art technologies. Although several papers have surveyed technology usage for Hajj and Umrah in the past, none of them was comprehensive. In this survey paper, 330 references were surveyed covering the past three decades. The surveyed papers tried to address Hajj and Umrah challenges using various ICT solutions. In this work, I classified prior research efforts in the literature based on the use and need to ten categories. In addition, I have also grouped the research efforts into thirty three categories based on the technology used to solve problems related to Hajj and Umrah. Finally, I presented nine directions for future research in this area by discussing open challenges and emerging technologies that could be leveraged to address these challenges.

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REFERENCES

[1] *Doyof Al Rahman Vision Realization Program*. Accessed: Jul. 16, 2022. [Online]. Available: https://www.vision2030.gov.sa/v2030/vrps/darp/

[2] S. Parker and J. Gaines. *Saudi Arabia: Hajj/Umrah Pilgrimage*. Accessed: Jul. 16, 2022. [Online]. Available: https://wwwnc.cdc.gov/travel/yellowbook/2020/popular-itineraries/saudi-arabia-hajjumrah-pilgrimage

[3] M. R. Azarpazhooh, R. B. Shahripour, M. K. Kapral, N. Mokhber, A. Shoeibi, M. T. Farzadfard, M. R. Rafati, A. G. Thrift, N. Morovatdar, S. A. Sajedi, and A. Azarpazhooh, "Incidence of first ever stroke during Hajj ceremony," *BMC Neurol.*, vol. 13, no. 1, p. 193, Dec. 2013.

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

[5] (2019). *Faith 2.0: How Hajj Pilgrims Have Embraced Technology*. [Online]. Available: https://www.arabianbusiness.com/industries/technology/425715-faith-20-how-hajj-pilgrims-have-embraced-technology

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

[7] S. Amanullah, "Hajj 2.0: Technology's impact on the muslim pilgrimage," *Georgetown J. Int. Affairs*, vol. 10, no. 2, pp. 75–82, 2009. [Online]. Available: http://www.jstor.org/stable/43133576

[8] J. Qurashi and R. A. Sharpley, "SMART media technologies impact on the spiritual experience of Hajj pilgrims," in *Proc. 9th Annu. Int. Religious Tourism Pilgrimage Conf.*, Jun. 2017, pp. 1–8.

[9] S. Lazem, M. Saleh, and E. Alabdulqader, "ArabHCI: Five years and counting," *Commun. ACM*, vol. 64, no. 4, pp. 69–71, Mar. 2021, doi: 10.1145/3447733.

[10] *Hajj Hackathon*. Accessed: Jul. 16, 2022. [Online]. Available: https://hajjhackathon.devpost.com/

[11] *2022. Hajjathon*. [Online]. Available: https://hajjathon.com/

[12] H. Brdesee, B. Corbitt, and S. Pittayachawan, "Barriers and motivations affecting information systems usage by Hajj–Umrah religious tourism operators in Saudi Arabia," *Australas. J. Inf. Syst.*, vol. 18, no. 1, pp. 5–23, Nov. 2013.

[13] General Authority for Statistics. *Hajj Statistics 2019*. Kingdom of Saudi Arabia. Accessed: Dec. 14, 2021. [Online]. Available: https://www.stats.gov.sa/sites/default/files/haj_40_en.pdf

[14] M. Osman and A. Shaout, "Hajj guide systems—Past, present and future," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 4, no. 8, pp. 25–31, 2014.

[15] M. Yassin and N. Alharthi, "A review of tracking technologies in Hajj and Umrah research," in *Proc. 17th Sci. Forum Res. Hajj, Umrah Madinah Visit*, 2017, pp. 153–163.

[16] Y. Othman, "Visual surveillance for Hajj and Umrah: A review," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 170–176.

[17] A. M. Ibrahim, I. Venkat, K. G. Subramanian, A. T. Khader, and P. D. Wilde, "Intelligent evacuation management systems: A review," *ACM Trans. Intell. Syst. Technol.*, vol. 7, no. 3, pp. 1–27, Feb. 2016, doi: 10.1145/2842630.

[18] 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.

[19] M. Shambour, E. Khan, and M. Al-Shamrani, "Evaluating of Al-Rahman guests mobile applications on smart devices," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 286–297.

[20] E. A. Felemban, F. U. Rehman, S. A. A. Biabani, A. Ahmad, A. Naseer, A. R. M. A. Majid, O. K. Hussain, A. M. Qamar, R. Falemban, and F. Zanjir, "Digital revolution for Hajj crowd management: A technology survey," *IEEE Access*, vol. 8, pp. 208583–208609, 2020.

[21] F. M. Nasir and M. S. Sunar, "A survey on simulating real-time crowd simulation," in *Proc. 4th Int. Conf. Interact. Digit. Media (ICIDM)*, Dec. 2015, pp. 1–5.

[22] M. Shambour, O. Salem, H. Jaradat, B. Bataineh, A. AlShaar, M. Yasein, and M. Jaber, "An analytical survey study of the technology research and its applications in the Hajj and Umrah system," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 272–285.

[23] S. M. R. A. Masud, A. A. Bakar, and S. Yussof, "A systematic review of technological issues in monitoring pilgrims' health during Hajj: Current state, challenges and future directions," *J. Theor. Appl. Inf. Technol.*, vol. 96, no. 7, pp. 1935–1950, Mar. 2018.

[24] M. K. Shambour and A. Gutub, "Progress of IoT research technologies and applications serving Hajj and Umrah," *Arabian J. Sci. Eng.*, vol. 47, no. 2, pp. 1253–1273, Feb. 2022.

[25] M. Osman and A. Shaout, "Overview of mobile help for performing Hajj Rituals," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 5, no. 11, pp. 14–19, 2015.

[26] A. Shaout and S. Khan, "AlHajj—Hajj app for iOS," *IIUM Eng. J.*, vol. 17, no. 1, pp. 1–27, 2016.

[27] 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.

[28] 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.

[29] S. Snoussi, "Smartphone Arabic signboards images reading," in *Proc. IEEE 2nd Int. Workshop Arabic Derived Script Anal. Recognit. (ASAR)*, Mar. 2018, pp. 52–56.

[30] S. S. 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.

[31] S. P. Wyche, K. E. Caine, B. K. Davison, S. N. Patel, M. Arteaga, and R. E. Grinter, "Sacred imagery in techno-spiritual design," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Assoc. Comput. Machinery, Apr. 2009, pp. 55–58, doi: 10.1145/1518701.1518710.

[32] E. Khairullah and R. Ashari, "User preferences-based recommendation algorithm case study: Hajj and Umrah agencies," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 149–158.

[33] A. S. A. Al-Aidaroos, A. N. Zulkifli, and R. C. Mat, "Development of mobile Dua and Zikr for Hajj (MDZ4H)," *TELKOMNIKA Indonesian J. Electr. Eng.*, vol. 11, no. 5, pp. 2723–2730, May 2013.

[34] N. S. Ilias, M. A. M. Azmi, and K. N. M. Nor, *Development of Mobile Applications for Monitoring and Managing Hajj and Umrah Pilgrimage*. Cham, Switzerland: Springer, 2022, pp. 233–243, doi: 10.1007/978-3-030-92964-0_23.

[35] M. A. Rahman, "A framework to support massive crowd: A smart city perspective," in *Proc. IEEE Int. Conf. Multimedia Expo Workshops (ICMEW)*, Jul. 2016, pp. 1–6.

[36] R. Al-Yaqubi, "Developing a spatial data infrastructure (SDI) for pilgrims' movement and transportation during Hajj days in holy places," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 108–116.

[37] M. A. Rahman and A. Ahmad, "Demo abstract: HajjCPS—A cyber physical environment for providing location-aware services to a very large crowd," in *Proc. ACM/IEEE 7th Int. Conf. Cyber-Phys. Syst. (ICCPS)*, Apr. 2016, p. 1.

[38] N. Alharthi and M. Al-Shamrani, "Analyzing the characteristics of pilgrims during their residence in Makkah using machine learning algorithms of clustering analysis," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 327–333.

[39] M. Elgamal and M. Al-Shamrani, "An analytical study for the characteristics of Omrah pilgrims' and predicting the most important variables using modern machine learning algorithems for prediction analysis," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 314–325.

[40] M. Elgamal and M. Al-Shamrani, "An analytical study of the most important characteristics of the guests of Al-Rahman and their representation using modern technologies to mining large data to support the decision making process," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 285–294.

[41] M. Al-Bejawi, "Experience of public administration for the Hajj and Umrah and visit in applying business intelligence technology," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 391–397.

[42] A. Alobied, "The means used to communicate with the visitors and prayers at Al-Masjid an-Nabawi," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 617–624.

[43] O. Gazzaz and F. Khan, "Exposure to digital signage and message recall: Determining the effectiveness of the billboard outside the prophet's (PBUH) mosque at Madinah Almunawwarah," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 138–165.

[44] M. A. Mohandes, "Near field communication for pilgrim services," in *Proc. 8th Int. Conf. Comput. Technol. Inf. Manage.*, vol. 2, Apr. 2012, pp. 771–774.

[45] 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.

[46] D. A.-A. Ayyad, "The role of e-management in improving the crowd management from the perspective of the employees in the Hajj and Umrah system," *J. Econ. Administ. Sci.*, vol. 6, no. 6, pp. 116–148, 2022. [Online]. Available: https://journals.ajsrp.com/index.php/jeals/article/view/4760

[47] 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)*, 2016, pp. 1368–1372.

[48] M. Musleh, "Spatio-temporal visual analysis for event-specific tweets," in *Proc. ACM SIGMOD Int. Conf. Manage. Data*. New York, NY, USA: Assoc. Comput. Machinery, Jun. 2014, pp. 1611–1612, doi: 10.1145/2588555.2612666.

[49] G. Bati, "Using big data tools to analyze tweets related to Hajj sentimentally," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 177–184.

[50] N. Abokhodair, A. Elmadany, and W. Magdy, "Holy tweets: Exploring the sharing of the Quran on Twitter," *Proc. ACM Hum.-Comput. Interact.*, vol. 4, no. 2, pp. 1–32, Oct. 2020, doi: 10.1145/3415230.

[51] S. Sha'rawi, M. Al-Jamal, R. Almwari, and A. Al-Hawsawi, "Evaluation of services offered to the pilgrims in the airports: A comparative study," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 379–390.

[52] K. Majrashi, "User need and experience of Hajj mobile and ubiquitous systems: Designing for the largest religious annual gathering," *Cogent Eng.*, vol. 5, no. 1, Jan. 2018, Art. no. 1480303.

[53] M. Shambour and M. Al-Shamrani, "Criteria for evaluating the Al-Rahman guests websites," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 289–311.

[54] M. Shambour, M. Yassin, M. Elgamal, and B. Bitainah, "Technical evaluation of Hajj and Umrah services' websites, an analytical study," in *Proc. 18th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2018, pp. 154–162.

[55] *Alexa*. Accessed: Feb. 24, 2022. [Online]. Available: https://www.alexa.com/

[56] H. S. Al-Khalifa, "Heuristic evaluation of the usability of e-government websites: A case from Saudi Arabia," in *Proc. 4th Int. Conf. Theory Pract. Electron. Governance (ICEGOV)*. New York, NY, USA: Assoc. Comput. Machinery, 2010, pp. 238–242, doi: 10.1145/1930321.1930370.

[57] H. S. Al-Khalifa, "Exploring the accessibility of Saudi Arabia e-government websites: A preliminary results," in *Proc. 4th Int. Conf. Theory Pract. Electron. Governance (ICEGOV)*. New York, NY, USA: Assoc. Comput. Machinery, 2010, pp. 274–278, doi: 10.1145/1930321.1930378.

[58] A. Al-Faries, H. S. Al-Khalifa, M. S. Al-Razgan, and M. Al-Duwais, "Evaluating the accessibility and usability of top Saudi e-government services," in *Proc. 7th Int. Conf. Theory Pract. Electron. Governance*. New York, NY, USA: Assoc. Comput. Machinery, Oct. 2013, pp. 60–63, doi: 10.1145/2591888.2591898.

[59] M. Lubis, A. A. Ananto, and M. Afifudin, "Digital ecosystem development in customer relationship management (CRM) for Hajj portal website," in *Proc. 7th Int. Conf. E-Bus. Appl.* New York, NY, USA: Assoc. Comput. Machinery, Feb. 2021, pp. 47–53, doi: 10.1145/3457640.3457654.

[60] S. I. Salim, N. A. Al-Nabhan, M. Rahaman, N. Islam, T. R. Toha, J. Noor, A. Quaium, A. Mostak, M. Hossain, M. M. Mushfiq, and A. B. M. A. A. Islam, "Human-survey interaction (HSI): A study on integrity of human data collectors in a mass-scale Hajj pilgrimage survey," *IEEE Access*, vol. 9, pp. 112528–112551, 2021.

[61] T. Mantoro, M. Ayu, M. Mahmud, M. Akhtaruzzaman, and M. Ayu, "Hajj pilgrims tracking and monitoring system," in *Proc. Web, Utilisation, Eval. Secur.* Selangor, Malaysia: IIUM Press, 2012, pp. 11–22.

[62] F. Sarli, S. Kasim, R. Hassan, N. Ismail, M. A. Salamat, H. Ruslai, K. Jahidin, and M. S. Arshad, "PilgrimTrackr: Developing a pilgrim tracker system," in *Proc. 6th ICT Int. Student Project Conf. (ICT-ISPC)*, May 2017, pp. 1–5.

[63] A. Amro and Q. Nijem, "Pilgrims 'Hajj' tracking system (e-Mutawwif)," *Contemp. Eng. Sci.*, vol. 5, no. 9, pp. 437–446, 2012.

[64] A. Touir, A. Al-Owaisheg, and H. Mathkour, "The architecture and the design of a pilgrim tracking system," in *Proc. 3rd Int. Conf. Inf. Commun. Technol., Theory Appl.*, Apr. 2008, pp. 1–5.

[65] E. S. Alhazmi, R. A. Alraddadi, and L. Syed, "Spatial crowdsourcing for social and government applications for Hajj-Umarah," in *Proc. 1st Int. Conf. Artif. Intell. Data Anal. (CAIDA)*, Apr. 2021, pp. 273–274.

[66] 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, pp. 1–6.

[67] A. Nadeem, K. Rizwan, A. Mehmood, N. Qadeer, F. Noor, and A. AlZahrani, "A smart city application design for efficiently tracking missing person in large gatherings in Madinah using emerging IoT technologies," in *Proc. Mohammad Ali Jinnah Univ. Int. Conf. Comput. (MAJICC)*, Jul. 2021, pp. 1–7.

[68] S. J. Ramson, S. Vishnu, and M. Shanmugam, "Applications of Internet of Things (IoT)—An overview," in *Proc. 5th Int. Conf. Devices, Circuits Syst. (ICDCS)*, 2020, pp. 92–95.

[69] 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.

[70] C. W. Hidayat, F. S. Rozak, F. A. Aziz, and D. B. S. R. Purwanti, "Implementation of RFID as tracking for Hajj pilgrims connected with GPS (IM RFID SECURE GPS)," in *Proc. AIP Conf.*, 2019, Art. no. 020032.

[71] 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.

[72] 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.

[73] H. J. P. Timmermans and B. de Vries, Eds., *Design & Decision Support Systems in Architecture and Urban Planning*. Eindhoven, The Netherlands: Univ. of Technology Eindhoven, 2008. [Online]. Available: http://papers.cumincad.org/cgi-bin/works/Show?ddss2008-08

[74] W. Kanakri, L. A. Tawalbeh, and A. AlHarbi, "Dos and donts integrated system based on GPS and cloud technologies for pilgrims," in *Proc. IEEE 14th Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS)*, Oct. 2017, pp. 622–627.

[75] 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.

[76] 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.

[77] M. O. Gani, G. M. T. Ahsan, D. Do, W. Drew, M. Balfas, S. I. Ahamed, M. Arif, and A. J. Kattan, "An approach to localization in crowded area," in *Proc. IEEE 18th Int. Conf. E-Health Netw., Appl. Services (Healthcom)*, Sep. 2016, pp. 1–6.

[78] M. Balfas, S. I. Ahamed, C. Tamma, M. Arif, A. J. Kattan, and W. Chu, "A study and estimation a lost person behavior in crowded areas using accelerometer data from smartphones," in *Proc. IEEE 42nd Annu. Comput. Softw. Appl. Conf. (COMPSAC)*, vol. 1, Jul. 2018, pp. 860–865.

[79] A. A. Jassem, F. Farasha, S. Abdul-Nabi, A. Bazzi, and I. E. Sayad, "Offline group locator and tracking system," in *Proc. Sensors Netw. Smart Emerg. Technol. (SENSET)*, Sep. 2017, pp. 1–4.

[80] M. Mohandes, "Pilgrim tracking and identification using the mobile phone," in *Proc. IEEE 15th Int. Symp. Consum. Electron. (ISCE)*, Jun. 2011, pp. 196–199.

[81] M. B. Jabra, A. Ammar, A. Koubaa, O. Cheikhrouhou, and H. Hamam, "AI-based pilgrim detection using convolutional neural networks," in *Proc. 5th Int. Conf. Adv. Technol. Signal Image Process. (ATSIP)*, Sep. 2020, pp. 1–6.

[82] M. Elgamal, E. Khan, and S. Shaarawi, "Facial image query system based on time series for pilgrims identification," in *Proc. 14th Sci. Symp. Hajj, Umrah Madinah Visit*, 2014, pp. 92–106.

[83] R. Alharbey, A. Banjar, Y. Said, M. Atri, A. Alshdadi, and M. Abid, "Human faces detection and tracking for crowd management in Hajj and Umrah," *Comput., Mater. Continua*, vol. 71, no. 3, pp. 6275–6291, 2022. [Online]. Available: http://www.techscience.com/cmc/v71n3/46545

[84] A. Shaout and M. Oman, "Towards developing an intelligent Hajj guide system," in *Proc. 8th Int. Conf. Inf. Technol. (ICIT)*, May 2017, pp. 280–285.

[85] M. Abbdelazeez and A. Shaout, "Towards developing an intelligent Hajj guide system–pilgrim tracking and identification using mobile phones," in *Proc. 7th Int. Conf. Inf. Technol. (ICIT)*, Amman, Jordan, May 2015, pp. 39–44.

[86] S. Tabassam and E. Al-Qahtane, "Comparative analysis on requirement engineering modelling techniques case study of personal Al-Haj E-guide," in *Proc. 2nd Int. Conf. Comput. Appl. Inf. Secur. (ICCAIS)*, May 2019, pp. 1–8.

[87] A. Alhogail, L. Alshabanat, N. Almusharraf, A. Alkharis, and B. Almusharraf, "Umrah electronic guide (Umrah E-guide)," in *Proc. Int. Conf. Inf. Commun. Technol. (ICOIACT)*, Jul. 2019, pp. 403–407.

[88] B. Sadiq, F. U. Rehman, A. Ahmad, M. Abdur 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.

[89] W. Kanakri and L. A. Tawalbeh, "WSN-based interactive dynamic maps for guidance in Al-Masjid Al-Haram," in *Proc. 6th Int. Conf. Internet Things, Syst., Manage. Secur. (IOTSMS)*, Oct. 2019, pp. 326–330.

[90] 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*. New York, NY, USA: Assoc. Comput. Machinery, Oct. 2015, pp. 759–760, doi: 10.1145/2733373.2807985.

[91] F. Hamhoum and C. Kray, "Supporting pilgrims in navigating densely crowded religious sites," *Pers. Ubiquitous Comput.*, vol. 16, no. 8, pp. 1013–1023, Dec. 2012, doi: 10.1007/S00779-011-0461-6.

[92] F. Bousbahi and B. Boreggah, "Mobile augmented reality adaptation through smartphone device based hybrid tracking to support cultural heritage experience," in *Proc. 2nd Int. Conf. Smart Digit. Environ.* New York, NY, USA: Assoc. Comput. Machinery, 2018, pp. 48–55.

[93] E. Felemban, F. U. Rehman, A. M. Qamar, and A. Ahmed, "A framework to extract trip informatics for individuals and groups using mobile sensory data in mass gathering events," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2020, pp. 5665–5667.

[94] A. Muaremi, J. Seiter, G. Tröster, and A. Bexheti, "Monitor and understand pilgrims: Data collection using smartphones and wearable devices," in *Proc. ACM Conf. Pervasive Ubiquitous Comput. Adjunct Publication*. New York, NY, USA: Assoc. Comput. Machinery, Sep. 2013, pp. 679–688, doi: 10.1145/2494091.2495989.

[95] A. Muaremi, J. Seiter, F. Gravenhorst, A. Bexheti, B. Arnrich, and G. Troester, "Monitor pilgrims: Prayer activity recognition using wearable sensors," in *Proc. 8th Int. Conf. Body Area Netw.*, 2013, pp. 161–164, doi: 10.4108/icst.bodynets.2013.253685.

[96] 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.* New York, NY, USA: Assoc. Comput. Machinery, Nov. 2015, pp. 1–7, doi: 10.1145/2830657.2830664.

[97] A. Ahmad, F. U. Rehman, M. A. Rahman, A. Murad, A. Qamar, B. Sadiq, S. Basalamah, and M. R. Wahiddin, "I-diary: A crowdsource-based spatio-temporal multimedia enhanced points of interest authoring tool," in *Proc. 23rd ACM Int. Conf. Multimedia*. New York, NY, USA: Assoc. Comput. Machinery, Oct. 2015, pp. 809–810, doi: 10.1145/2733373.2807983.

[98] 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*. New York, NY, USA: Assoc. Comput. Machinery, Oct. 2015, pp. 761–762, doi: 10.1145/2733373.2807986.

[99] F. U. Rehman, A. Lbath, I. Afyouni, A. Murad, M. A. Rahman, B. Sadiq, A. Ahmad, and S. Basalamah, "Semantic multimedia-enhanced spatio-temporal queries in a crowdsourced environment," in *Proc. 23rd SIGSPATIAL Int. Conf. Adv. Geograp. Inf. Syst.* New York, NY, USA: Assoc. Comput. Machinery, Nov. 2015, pp. 1–4, doi: 10.1145/2820783.2820798.

[100] T. Dirgahayu and S. Hidayat, "An architectural design of geo-fencing emergency alerts system for Hajj pilgrims," in *Proc. 8th Int. Conf. Comput. Sci. Inf. Technol. (CSIT)*, Jul. 2018, pp. 1–6.

[101] A. H. Al-Hashedi, M. R. M. Arshad, H. H. Mohamed, and A. S. Baharuddin, "Identifying the determinants of RFID adoption intention in Hajj organizations," in *Proc. Int. Conf. Res. Innov. Inf. Syst.*, Nov. 2011, pp. 1–6.

[102] M. M. Shuaib, "Modeling collision avoidance field for overtaking moving obstacles," in *Proc. Int. Arab Conf. Inf. Technol. (ACIT)*, Dec. 2019, pp. 102–106.

[103] S. Gunasekaran and M. Suresh, "A novel control of disaster protection (NCDP) for pilgrims by pan technology," in *Proc. IEEE 8th Int. Conf. Intell. Syst. Control (ISCO)*, Jan. 2014, pp. 103–107.

[104] M. A. R. Abdeen, "A distributed architecture and design challenges of an astray pilgrim tracking system," in *Proc. IEEE 16th Int. Conf. Dependable, Autonomic Secure Comput., 16th Int. Conf. Pervasive Intell. Comput., 4th Int. Conf. Big Data Intell. Comput. Cyber Sci. Technol. Congr. (DASC/PiCom/DataCom/CyberSciTech)*, Aug. 2018, pp. 1028–1033.

[105] 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.

[106] S. A. Chandio, J. A. Mahar, and M.-U.-R. Shaikh, "Gadget improved security alert monitoring, management and mitigation system to control the crowded occasions," in *Proc. Int. Conf. Innov. Electr. Eng. Comput. Technol. (ICIEECT)*, Apr. 2017, pp. 1–3.

[107] 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.

[108] A. M. Aldhahri and K. M. Anderson, "ML-EPIC: Collection and translation of multilingual social media data," in *Proc. 3rd Int. Conf. Big Data Technol.* New York, NY, USA: Assoc. Comput. Machinery, Sep. 2020, pp. 11–15, doi: 10.1145/3422713.3422734.

[109] 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.

[110] 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.

[111] E. Felemban, A. A. Sheikh, and A. Naseer, "Improving response time for crowd management in Hajj," *Computers*, vol. 10, no. 4, p. 46, Apr. 2021.

[112] (2019). *Mobile IoT Innovators Spotlight: Hajj Gear*. [Online]. Available: https://www.gsma.com/iot/news/mobile-iot-innovators-spotlight-hajj-gear/

[113] S. A. Hameed, "ICT to serve Hajj: Analytical study," in *Proc. Int. Conf. Comput. Commun. Eng. (ICCCE)*, May 2010, pp. 1–7.

[114] T. Kulshrestha, R. Niyogi, M. Misra, and D. Patel, "Smart pilgrim: A mobile-sensor-cloud based system to safeguard pilgrims through smart environment," in *Proc. 10th Int. Conf. Contemp. Comput. (IC3)*, Aug. 2017, pp. 1–6.
[115] S. Sulaiman, H. Mohamed, M. R. M. Arshad, N. A. A. Rashid, and U. K. Yusof, "Hajj-QAES: A knowledge-based expert system to support Hajj pilgrims in decision making," in *Proc. Int. Conf. Comput. Technol. Develop.*, 2009, pp. 442–446.
[116] H. H. Mohamed, M. R. H. M. Arshad, and M. D. Azmi, "M-HAJJ DSS: A mobile decision support system for Hajj pilgrims," in *Proc. 3rd Int. Conf. Comput. Inf. Sci. (ICCOINS)*, Aug. 2016, pp. 132–136.
[117] H. Mohamed, S. Sulaiman, and M. Sabudin, "A hybrid of rule and frame based approach in solving Hajj complex problems," in *Proc. Int. Conf. Soft Comput. Pattern Recognit.*, 2009, pp. 466–471.
[118] A. M. Zeki, H. Alsafi, R. M. Nassr, and T. Mantoro, "A mobile dictionary for pilgrims," in *Proc. Int. Conf. Inf. Technol. E-Services*, Mar. 2012, pp. 1–5.
[119] M. Haroon and S. Lajmi, "An efficient multi-language video search engine to facilitate the HAJJ and the UMRA," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 181–188.
[120] S. Sulaiman, H. Mohamed, M. R. M. Arshad, A. Ahmad, and S. Sulaiman, "A knowledge-based approach to facilitate queries by Hajj pilgrims," in *Proc. Int. Symp. Inf. Technol.*, vol. 2, Aug. 2008, pp. 1–9.
[121] N. M. Sharef, M. A. Murad, A. Mustapha, and S. Shishechi, "Semantic question answering of Umrah pilgrims to enable self-guided education," in *Proc. 13th Int. Conf. Intell. Syst. Design Appl.*, Dec. 2013, pp. 141–146.
[122] M. A. T. A. Ali, J. Berri, and M. J. Zemerly, "Context aware mobile muslim companion," in *Proc. 5th Int. Conf. Soft Comput. Transdisciplinary Sci. Technol. (CSTST)*. New York, NY, USA: Assoc. Comput. Machinery, 2008, pp. 553–558, doi: 10.1145/1456223.1456335.
[123] N. Caidi, "Pilgrimage to Hajj: An information journey," *Int. J. Inf., Diversity, Inclusion (IJIDI)*, vol. 3, no. 1, pp. 44–76, Feb. 2019.
[124] W. Boulila, A. Abuhamdah, M. Driss, S. Kammoun, and J. Ahmad, "GuideMe: A mobile application based on global positioning system and object recognition towards a smart tourist guide," in *Proc. Int. Congr. Adv. Technol. Eng. (ICOTEN)*, Jul. 2021, pp. 1–6.
[125] H. M. Harmain, H. Khatib, N. Saeed, and B. Aljohar, "Web services-based Hajj information system," in *Proc. Int. Conf. Inf. Comput. Sci. (ICICS)*, Dhahran, Saudi Arabia, 2004, pp. 1–9.
[126] A. A. Fathnan, C. P. Wibowo, N. F. Hidayat, D. A. Marenda, and R. Ferdiana, "Web-based Hajj simulation software learning Hajj through interactive software," in *Proc. 3rd Int. Conf. Inf. Commun. Technol. Moslem World (ICT4M)*, Dec. 2010, pp. A37–A41.
[127] 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.
[128] M. F. Yusoff, A. N. Zulkifli, and N. F. F. Mohamed, "Virtual Hajj (V-Hajj)—Adaptation of persuasive design in virtual environment (VE) and multimedia integrated approach learning courseware methodology," in *Proc. IEEE Conf. Open Syst.*, Sep. 2011, pp. 250–255.
[129] Y. M. Fitri, "Virtual Hajj (V-Hajj): A persuasive Hajj learning procedures courseware," Ph.D. dissertation, College Arts Sci., Universiti Utara Malaysia, Kedah, Malaysia, 2012.
[130] M. F. Yusoff, A. N. Zulkifli, and N. F. F. Mohamed, "The model of persuasive Hajj learning environment," *Jurnal Teknologi*, vol. 77, no. 5, pp. 141–147, Nov. 2015.
[131] A. Syaichu, "Player's score achievement schema using combination of experience point and educational-credit in HajjGame," in *Proc. 3rd Int. Conf. Inf. Commun. Technol. Moslem World (ICT4M)*, Dec. 2010, pp. A42–A45.
[132] A. M. Yasin, F. H. Yusoff, M. A. M. Isa, and N. H. M. Zain, "Avatar implementation in virtual reality environment using situated learning for 'sa'i'(Muslim Hajj ritual)," in *Proc. Int. Conf. Educ. Inf. Technol.*, Sep. 2010, pp. V2-286–V2-290.
[133] A. M. Kabir, S. T. Nisa, and M. M. Khan, "A virtual reality (VR) based interactive and educative experience of Hajj and Umrah for the people of Bangladesh," in *Proc. IEEE 11th Annu. Comput. Commun. Workshop Conf. (CCWC)*, Jan. 2021, pp. 0170–0173.
[134] M. S. M. Rahim, A. Z. A. Fata, A. H. Basori, A. S. Rosman, T. J. Nizar, and W. M. F. Yusof, "Development of 3D Tawaf simulation for Hajj training application using virtual environment," in *Proc. Int. Vis. Informat. Conf.* Berlin, Germany: Springer, 2011, pp. 67–76.
[135] S. M. Salleh, A. S. M. Hasan, N. M. Salleh, N. S. Sapiai, S. A. M. Ghazali, N. H. M. Rusok, and M. Z. M. Zawawi, "Virtual reality technology of Hajj practice: An innovation of the future," *J. Islam Contemp. Soc.*, vol. 22, no. 2, pp. 56–63, 2021.
[136] D. Sumardani, R. R. Saraswati, U. Widiastuti, K. Komala, and W. D. Listyasari, "The free Hajj: Virtual reality in Manasik Hajj training education," *Al-Hayat, J. Islamic Educ.*, vol. 4, no. 2, pp. 191–198, 2021.
[137] H. Rossa, N. Hudallah, B. Sunarko, and A. Mulwinda, "Virtual reality-based Hajj Manasik practice digitization system with 360 degree video," *Budapest Int. Res. Critics Inst., Humanities Social Sci.*, vol. 5, no. 1, pp. 4956–4970, 2022.
[138] *Myo Developer Blog*. Accessed: Jul. 16, 2022. [Online]. Available: https://developerblog.myo.com/
[139] I. Sabilirrasyad, M. Zikky, and R. Y. Hakkun, "Jamarat ritual simulation with Myo armband for precise throws speed," in *Proc. Int. Electron. Symp. Knowl. Creation Intell. Comput. (IES-KCIC)*, Oct. 2018, pp. 205–209.
[140] M. A. Rahman and M. S. Hossain, "A location-based mobile crowdsensing framework supporting a massive ad hoc social network environment," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 76–85, Mar. 2017.
[141] M. Sultan, "Applying game-based learning system to facilitate the Manasik of Hajj and Umrah," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 185–192.
[142] M. Sultan, "Creating tourist guide application for Makkah using GIS story maps," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 176–182.
[143] F. Alzhrani, K. Saeedi, and D. Aljeaid, "Using printable integrated multimedia maps for telling Islamic heritage sights in Al-Madinah Al-Monawarah," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 176–184.
[144] M. Blythe and E. Buie, "Chatbots of the gods: Imaginary abstracts for techno-spirituality research," in *Proc. 8th Nordic Conf. Hum.-Comput. Interact., Fun, Fast, Foundational*. New York, NY, USA: Assoc. Comput. Machinery, Oct. 2014, pp. 227–236, doi: 10.1145/2639189.2641212.
[145] M. I. Z. Abidin and A. A. Razak, "Modelling of the prophet mosque in virtual reality," in *Proc. 8th Int. Conf. Softw. Comput. Appl.* New York, NY, USA: Assoc. Comput. Machinery, Feb. 2019, pp. 320–324, doi: 10.1145/3316615.3320117.
[146] J. Schneider, D. Garatly, M. Srinivasan, S. J. Guy, S. Curtis, S. Cutchin, D. Manocha, M. C. Lin, and A. Rockwood, "Towards a digital Makkah–using immersive 3D environments to train and prepare pilgrims," in *Proc. Int. Conf. Digit. Media Appl. Cultural Heritage (DMACH)*, 2011, pp. 1–16.
[147] Z. Bhatti, A. Waqas, and H. Malik, "Multimedia based learning and virtual tour for performing Hajj," *J. Inf. Commun. Technol.*, vol. 12, no. 1, p. 6, 2018.
[148] A. Fauzie, I. Budi, D. I. Sensuse, R. Imanda, W. I. Satria, and W. Catur, "Definition of e-Hajj in Indonesia using hermeneutic approach," in *Proc. IEEE Student Conf. Res. Develop. (SCOReD)*, Dec. 2016, pp. 1–6.
[149] I. Budi, R. Imanda, A. F. Azmi, A. Fauzie, and D. I. Sensuse, "Business process model of e-Hajj in Indonesia," in *Proc. Int. Conf. Inf. Technol. Syst. Innov. (ICITSI)*, Oct. 2017, pp. 87–93.
[150] G. Sami and W. Alhakami, "Development of an online system to manage Hajj pilgrims in Saudi Arabia," in *Proc. Int. Conf. Inf. Commun. Technol. Syst. (ICTS)*, 2016, pp. 270–276.
[151] A. H. Al-Hashedi, M. R. M. Arshad, A. S. Baharudin, and H. H. Mohamed, "RFID applications in Hajj management system," in *Proc. IEEE Int. Conf. RFID-Technol. Appl. (RFID-TA)*, Sep. 2013, pp. 1–6.
[152] 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*, Nov. 2014, pp. 146–150.
[153] A. Alsharyufi and K. Ki-Hyung, "Prototype of blockchain in Hajj permits system in Saudi Arabia on TRON blockchain," *Int. Inf. Inst. Inf.*, vol. 25, no. 1, 2022, pp. 39–50.
[154] M. Alotaibi, M. Alsaigh, and M. Yamin, "Blockchain for controlling Hajj and Umrah permits," *IJcSNS*, vol. 19, no. 4, pp. 69–78, 2019.
[155] A. Hudiarto, N. R. Kamila, and N. A. Fitriyani, "Modeling of information system for licensing and extension of special Hajj pilgrimage organizer," in *Proc. Int. Conf. Inf. Manage. Technol. (ICIMTech)*, Sep. 2018, pp. 522–527.

[156] D. N. Utama, M. Faturrahman, M. Rusdi, I. Y. Saputra, F. S. Isnaeni, and B. Waspodo, "FHC-optimization model for deciding the objective Hajj pilgrims to restricted quota (Case study: Hajj pilgrimage procedure in Indonesia)," in *Proc. Int. Conf. Artif. Intell. Inf. Technol. (ICAIIT)*, Mar. 2019, pp. 302–309.

[157] D. Putri, A. D. Setiawan, and A. Hidayatno, "A conceptual model to maintain pilgrims trust and loyalty: A system dynamics approach," in *Proc. 3rd Asia Pacific Conf. Res. Ind. Syst. Eng.* New York, NY, USA: Assoc. Comput. Machinery, Jun. 2020, pp. 154–158, doi: 10.1145/3400934.3400963.

[158] A. S. Shaheen, "Using a suggested strategy for electronic Hajj reservation," *Turkish J. Comput. Math. Educ.*, vol. 13, no. 2, pp. 488–494, 2022.

[159] N. A. Siddiquee, "E-government and transformation of governance and service delivery in Bangladesh: A developing country perspective," in *Proc. 6th Int. Conf. Theory Pract. Electron. Governance (ICEGOV)*. New York, NY, USA: Assoc. Comput. Machinery, 2012, pp. 271–278, doi: 10.1145/2463728.2463782.

[160] M. Alam and K. Ahmed, "E-governance initiatives in Bangladesh," in *Proc. 2nd Int. Conf. Theory Pract. Electron. Governance (ICEGOV)*. New York, NY, USA: Assoc. Comput. Machinery, 2008, pp. 291–295, doi: 10.1145/1509096.1509157.

[161] W. Alharthi, "Proposing the use of digital currency in Hajj and Umrah," *Int. J. Sci. Eng. Res.*, vol. 12, no. 6, pp. 1388–1392, 2021.

[162] M. Gharawi and T. Pardo, "Factors influencing exchange activities in transnational knowledge networks: The case of the Hajj-MDSS," in *Proc. 6th Int. Conf. Theory Pract. Electron. Governance (ICEGOV)*. New York, NY, USA: Assoc. Comput. Machinery, 2012, pp. 113–122, doi: 10.1145/2463728.2463755.

[163] S. M. Alshammari, H. Gwalani, J. E. Helsing, and A. R. Mikler, "Disease spread simulation to assess the risk of epidemics during the global mass gathering of Hajj pilgrimage," in *Proc. Winter Simulation Conf. (WSC)*, Dec. 2019, pp. 215–226.

[164] S. M. Alshammari and A. R. Mikler, "Modeling disease spread at global mass gatherings: Hajj as a case study," in *Proc. Int. Conf. Healthcare Informat.*, Oct. 2015, pp. 574–577.

[165] M. Tofighi *et al.*, "Estimating social contacts in mass gatherings through agent-based simulation modeling: Case of Hajj pilgrimage," *Res. Square*, Jun. 2021, doi: 10.21203/rs.3.rs-595525/v2.

[166] M. Tofighi *et al.*, "Estimating social contacts in mass gatherings for disease outbreak prevention and management (case of Hajj pilgrimage)," *Res. Square*, Jan. 2022, doi: 10.21203/rs.3.rs-1244843/v1.

[167] 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.

[168] S. M. Alshammari and A. M. Mikler, "Big data opportunities for disease outbreaks detection in global mass gatherings," in *Proc. Int. Conf. Big Data Educ.* New York, NY, USA: Assoc. Comput. Machinery, Mar. 2018, pp. 16–21, doi: 10.1145/3206157.3206160.

[169] F. A. Alanezi, F. Hussain, and H. Q. Yu, "A study on perception of managing infectious disease through social networking in the kingdom of Saudi Arabia," in *Proc. IEEE Int. Conf. Comput. Sci. Eng. (CSE) IEEE Int. Conf. Embedded Ubiquitous Comput. (EUC) 15th Int. Symp. Distrib. Comput. Appl. Bus. Eng. (DCABES)*, Aug. 2016, pp. 652–655.

[170] S. M. Alshammari and R. D. Nielsen, "Less is more: With a 280-character limit, Twitter provides a valuable source for detecting self-reported flu cases," in *Proc. Int. Conf. Comput. Big Data (ICCBD)*. New York, NY, USA: Assoc. Comput. Machinery, 2018, pp. 1–6, doi: 10.1145/3277104.3277105.

[171] SDAIA (Saudi Data and AI Authority). *Tawakkalna*. [Online]. Available: https://ta.sdaia.gov.sa/en/index

[172] S. Basahel, A. Alsabban, and M. Yamin, "Hajj and Umrah management during COVID-19," *Int. J. Inf. Technol.*, vol. 40, pp. 259–272, Aug. 2021.

[173] T. H. Hassan, A. E. Salem, and S. A. Refaat, "The impact of Eatmarna application usability on improving performance expectancy, facilitating the practice of rituals and improving spirituality feelings during Umrah amid the COVID-19 outbreak," *Religions*, vol. 13, no. 3, p. 268, 2022. [Online]. Available: https://www.mdpi.com/2077-1444/13/3/268

[174] J. A. Al-Tawfiq and Z. A. Memish, "Mass gathering medicine: 2014 Hajj and Umra preparation as a leading example," *Int. J. Infectious Diseases*, vol. 27, pp. 26–31, Oct. 2014.

[175] Q. A. Ahmed and Z. A. Memish, "Hajj 2016: Required vaccinations, crowd control, novel wearable tech and the Zika threat," *Travel Med. Infectious Disease*, vol. 14, no. 5, p. 429, 2016.

[176] H. Elachola, E. Gozzer, J. Zhuo, and Z. A. Memish, "A crucial time for public health preparedness: Zika virus and the 2016 Olympics, Umrah, and Hajj," *Lancet*, vol. 387, no. 10019, pp. 630–632, Feb. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140673616002749

[177] Z. Memish, A. Zumla, R. Alhakeem, A. Assiri, A. Turkestani, K. Al-Harby, M. Alyemni, K. Dhafar, P. Gautret, M. Barbeschi, B. McCloskey, D. Heymann, A. Al-Rabeeah, and J. Al-Tawfiq, "Hajj: Infectious disease surveillance and control," *Lancet*, vol. 383, pp. 2073–2082, Jun. 2014.

[178] H. Hijry and R. Olawoyin, "Application of machine learning algorithms for patient length of stay prediction in emergency department during Hajj," in *Proc. IEEE Int. Conf. Prognostics Health Manage. (ICPHM)*, Jun. 2020, pp. 1–8.

[179] M. Jassas, A. Qasem, and Q. Mahmoud, "An intelligent system connecting medical sensors and the cloud to decrease the required time of serving a large number of patients during Hajj," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 295–301.

[180] Y. Samkary, H. Nafi, M. Awad, M. A. Shareef, M. A. Shamrani, H. Milibari, I. A. Yamani, K. Alhobshi, and R. AlEid, "The influence of the modern technologies on the employment of emergency resources management in Saudi red crescent authority during Hajj 1436 h," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 592–603.

[181] B. Alhemsi, "Digital pen and paper; a practical quick win for Hajj automation needs," in *Proc. 14th Sci. Symp. Hajj, Umrah Madinah Visit*, 2014, pp. 107–112.

[182] M. Khoj and H. Esa, "Health centers decision support system for disaster management in the Holy city," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 573–591.

[183] I. Nafea, M. N. Bhairy, and Z. A. Zeidan, "Health tracking framework for Hajj pilgrims using electronic health records for Hajj," in *Proc. IEEE Int. Conf. Bioinf. Biomed. (BIBM)*, Nov. 2014, pp. 605–607.

[184] A. Aljohani, S. Nejaim, M. Khayyat, and O. Aboulola, "E-government and logistical health services during Hajj season," *Bull. Nat. Res. Centre*, vol. 46, no. 1, pp. 1–8, Dec. 2022.

[185] W. A. Al-Saud, T. Habibuallah, E. Morsi, and A. Fathi, "Spatial distribution of electromagnetic waves of the telecommunications company's towers in the central area of the holy mosque and the holy sites," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 220–238.

[186] A. Muaremi, A. Bexheti, F. Gravenhorst, B. Arnrich, and G. Troster, "Monitoring the impact of stress on the sleep patterns of pilgrims using wearable sensors," in *Proc. IEEE-EMBS Int. Conf. Biomed. Health Informat. (BHI)*, Jun. 2014, pp. 185–188.

[187] S. Sangle and S. Kadam, "Real time tracking and EHR for pilgrim," in *Proc. Int. Conf. Appl. Theor. Comput. Commun. Technol. (iCATccT)*, Oct. 2015, pp. 116–120.

[188] K. C. Rajwade and D. H. Gawali, "Wearable sensors based pilgrim tracking and health monitoring system," in *Proc. Int. Conf. Comput. Commun. Control Autom. (ICCUBEA)*, Aug. 2016, pp. 1–5.

[189] A. A. Elkhail and U. Baroudi, "Real-time healthcare monitoring system using smartphones," in *Proc. IEEE/ACS 15th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Oct. 2018, pp. 1–6.

[190] T. Alabsi and R. Abdulrahman, "The development of e-medical interpreter during Hajj," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 138–145.

[191] N. Ibrahim, N. M. Yakub, Y. Yakub, M. Husin, I. Yamani, and N. A. Rahman, "Medical identifier technology for pilgrims during the Hajj season," in *Proc. 2nd Annu. Int. Quranic Conf.*, 2012, pp. 164–178.

[192] N. M. Huda and M. Albarda, "Design of istitaah classification system based on machine learning using imbalanced dataset," in *Proc. 7th Int. Conf. Cyber IT Service Manage. (CITSM)*, Nov. 2019, pp. 1–6.

[193] 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, pp. 1–5.

[194] M. Penna, K. Tulasi, N. R. Vasavi, N. Swathi, and S. R. Swapna, "Stampede monitoring and alarm system using Viola-Jones algorithm," in *Proc. 3rd IEEE Int. Conf. Recent Trends Electron., Inf. Commun. Technol. (RTEICT)*, May 2018, pp. 2303–2307.

[195] R. Zhao, Q. Hu, C. Li, D. Dong, Q. Liu, Y. Ma, and Q. Zhang, "Macroscopic crowd panic quantification model of crowd evacuation based on information entropy," in *Proc. IEEE 3rd Inf. Technol., Netw., Electron. Autom. Control Conf. (ITNEC)*, Mar. 2019, pp. 388–392.
[196] 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.
[197] M. Yamin, M. Mohammadian, X. Huang, and D. Sharma, "RFID technology and crowded event management," in *Proc. Int. Conf. Comput. Intell. Modeling Control Autom.*, 2008, pp. 1293–1297.
[198] M. Yamin and Y. Ades, "Crowd management with RFID and wireless technologies," in *Proc. 1st Int. Conf. Netw. Commun.*, 2009, pp. 439–442.
[199] 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.
[200] A. Alqahtani, "Multi-purpose wireless sensors network using massive MIMO technology over Hajj area," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 173–180.
[201] N. Nasser, A. E. Ouadrhiri, M. E. Kamili, A. Ali, and M. Anan, "Crowd management services in Hajj: A mean-field game theory approach," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2019, pp. 1–7.
[202] 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.
[203] 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.
[204] 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.
[205] A. A. Owaidah, "Hajj crowd management via a mobile augmented reality application: A case of the Hajj event, Saudi Arabia," Ph.D. dissertation, Dept. Comput. Sci., Univ. Glasgow, Glasgow, Scotland, 2015.
[206] A. A. A. Sen, Y. Alsaawy, A. Alkhodre, N. M. Bahbouh, and M. Alhaboob, "Smart street design for managing crowds in Hajj," in *Proc. 8th Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, 2021, pp. 385–389.
[207] 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.
[208] E. Felemban, K. Alqahtani, A. Howsawi, and A. Alshehri, "Towards simulating crowd movement around holy Kaba," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 727–737.
[209] O. D. E. Wulansari, "Steering behavior analysis and implementation to simulate crowd Tawaf ritual on augmented reality Manasik," in *Proc. Int. Conf. Distrib. Frameworks Multimedia Appl.*, 2010, pp. 1–7.
[210] M. Yasein, "Regulating access to El-Salam gate in the prophet's mosque at peak times during holidays using simulation," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 151–160.
[211] Y. Alginahi, O. Tayan, and M. Kabir, "Simulation of people entering and exiting the public utilities (washrooms) at Al-Masjid an-Nabawi," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 185–198.
[212] A. Hasan, I. Reza, A. Jamal, W. Alhalabi, and K. Assi, "Preparedness for mass gatherings: A simulation-based framework for flow control and management using crowd monitoring data," *Arabian J. Sci. Eng.*, vol. 46, pp. 1–13, Jan. 2021.
[213] M. Zikky, M. J. Arifin, and K. Fathoni, "Tracks record's behavior of virtual Tawaf simulation using a algorithm and RVO sensor," in *Proc. Int. Electron. Symp. Knowl. Creation Intell. Comput. (IES-KCIC)*, Oct. 2018, pp. 349–354.
[214] 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.
[215] Z. Zarita and E. A. Lim, "Refined cellular automata model for Tawaf simulation," in *Proc. IEEE Symp. Comput. Informat. (ISCI)*, Mar. 2012, pp. 46–51.
[216] 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.
[217] A. A. Owaidah, D. Olaru, M. Bennamoun, F. Sohel, and R. N. Khan, "Modelling mass crowd using discrete event simulation: A case study of integrated Tawaf and Sayee rituals during Hajj," *IEEE Access*, vol. 9, pp. 79424–79448, 2021.
[218] N. Al-Nabhan, S. Alenazi, S. Alquwaifili, S. Alzamzami, L. Altwayan, N. Alaloula, R. Alowaini, and A. B. M. A. A. Islam, "An intelligent IoT approach for analyzing and managing crowds," *IEEE Access*, vol. 9, pp. 104874–104886, 2021.
[219] E. Felemban and F. Rehman, "Electronic portal for Tafweej scheduling in Mashaer," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 156–166.
[220] A. Al-Mshat, A.-H. Al-Baqmi, and N. Albarhamtoshi, "The design and implementation of computer system for the control of the conduct of pilgrims in the area carbuncles (Al-Jamarat)," in *Proc. Custodian Two Holy Mosques Inst. Hajj Umrah Res.*, 2004.
[221] A. Mushat, A.-H. Al-Barhamtosh, M. Kamel, and I. Al-Bedawi, "Assessing the numbers of people on the carbuncles (Aljamarat) bridge: Hajj 1425 h," in *Proc. Custodian Two Holy Mosques Inst. Hajj Umrah Res.*, 2005.
[222] M. Amer and A. Almatrafi, "Using a multi-agent architecture to handle the negotiation between the Hajj authorities and the Hajj travel agents," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 168–174.
[223] 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.
[224] D. Atiyah, N. Albuqmi, and R. Almoarai, "Gigapixel images: Towards a novel social network for Hajj and Umrah," in *Proc. 14th Sci. Symp. Hajj, Umrah Madinah Visit*, 2014, pp. 113–123.
[225] 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.
[226] J. He, J. Wang, and Y. Luo, "Deep architectures for crowd flow prediction," in *Proc. 2nd Int. Conf. Data Sci. Inf. Technol.* New York, NY, USA: Assoc. Comput. Machinery, Jul. 2019, pp. 236–241, doi: 10.1145/3352411.3352448.
[227] M. F. Ali, A. Bashar, and A. Shah, "SmartCrowd: Novel approach to big crowd management using mobile cloud computing," in *Proc. Int. Conf. Cloud Comput. (ICCC)*, Apr. 2015, pp. 1–4.
[228] J. H. Muzamal, Z. Tariq, and U. G. Khan, "Crowd counting with respect to age and gender by using faster R-CNN based detection," in *Proc. Int. Conf. Appl. Eng. Math. (ICAEM)*, Aug. 2019, pp. 157–161.
[229] S. Habib, A. Hussain, M. Islam, S. Khan, and W. Albattah, "Towards efficient detection and crowd management for law enforcing agencies," in *Proc. 1st Int. Conf. Artif. Intell. Data Anal. (CAIDA)*, Apr. 2021, pp. 62–68.
[230] B. Alkhuzaim and A. Altahhan, "Using convolution neural network for crowd density estimation for the holy Masjed," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 133–141.
[231] 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.
[232] A. Edris, A. Alajlan, F. Sheldon, T. Soule, and R. Heckendorn, "An alert system: Using fuzzy logic for controlling crowd movement by detecting critical density spots," in *Proc. Int. Conf. Comput. Sci. Comput. Intell. (CSCI)*, Dec. 2020, pp. 633–636.
[233] A. Alajlan, A. Edris, F. Sheldon, and T. Soule, "Machine learning for dense crowd direction prediction using long short-term memory," in *Proc. Int. Conf. Comput. Sci. Comput. Intell. (CSCI)*, Dec. 2020, pp. 686–689.
[234] Y. Seddiq, A. Alharbiy, and M. Ghunaim, "Crowd congestion assessment using multi-resolution clustering," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 142–148.
[235] A. Bamaqa, M. Sedky, T. Bosakowski, and B. B. Bastaki, "Anomaly detection using hierarchical temporal memory (HTM) in crowd management," in *Proc. 4th Int. Conf. Cloud Big Data Comput.* New York, NY, USA: Assoc. Comput. Machinery, Aug. 2020, pp. 37–42, doi: 10.1145/3416921.3416940.
[236] A. Jbari, S. Song, and M. Alsalem, "Dense mode mobile crowd sensing for collision prediction and protection," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 164–172.

[237] 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)*. New York, NY, USA: Assoc. Comput. Machinery, 2015, pp. 547–558, doi: 10.1145/2750858.2807548.

[238] S. Jamil, A. Basalamah, and A. Lbath, "Crowdsensing traces using Bluetooth low energy (BLE) proximity tags," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput., Adjunct Publication*. New York, NY, USA: Assoc. Comput. Machinery, Sep. 2014, pp. 71–74, doi: 10.1145/2638728.2638760.

[239] G. S. Humaid and A. I. Moustafa, "Experimental analysis of received signals strength in Bluetooth low energy in crowd environments," in *Proc. 9th Int. Conf. Comput. Commun. Manage.* New York, NY, USA: Assoc. Comput. Machinery, Jul. 2021, pp. 136–142, doi: 10.1145/3479162.3479183.

[240] S. Khan, A. Basalamah, A. Noor, M. Taieb, K. Amin, S. Basalamah, and S. Khan, "Towards a crowd analytic framework for crowd management in Masjid-Al-Haram," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 141–152.

[241] A. Al-Mshat, N. Al-Baqmi, I. Al-Bedawi, and M. Kamel, "The design and implementation of guidance and control of large numbers of pilgrims in the holy land. Study," in *Proc. Custodian Two Holy Mosques Inst. Hajj Umrah Res.*, 2004.

[242] H. J. Alshalani, N. I. Alnaghaimshi, and S. M. Eljack, "ICT system for crowd management: Hajj as a case study," in *Proc. Int. Conf. Comput. Inf. Technol. (ICCIT)*, Sep. 2020, pp. 1–5.

[243] 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.

[244] 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.

[245] F. Khan and O. Gazzaz, "Communication intervention strategy for crowd management at Masha'er," in *Proc. 14th Sci. Symp. Hajj, Umrah Madinah Visit*, 2014, pp. 139–158.

[246] Y. Jiang, Y. Miao, B. Alzahrani, A. Barnawi, R. Alotaibi, and L. Hu, "Ultra large-scale crowd monitoring system architecture and design issues," *IEEE Internet Things J.*, vol. 8, no. 13, pp. 10356–10366, Jul. 2021.

[247] Y. Miao, Y. Tang, B. A. Alzahrani, A. Barnawi, T. Alafif, and L. Hu, "Airborne LiDAR assisted obstacle recognition and intrusion detection towards unmanned aerial vehicle: Architecture, modeling and evaluation," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 7, pp. 4531–4540, Jul. 2021.

[248] B. E. Moore, S. Ali, R. Mehran, and M. Shah, "Visual crowd surveillance through a hydrodynamics lens," *Commun. ACM*, vol. 54, no. 12, pp. 64–73, Dec. 2011, doi: 10.1145/2043174.2043192.

[249] K. Haase, H. Z. A. 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.

[250] 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.

[251] 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, doi: 10.1145/1618452.1618468.

[252] R. Narain, A. Golas, S. Curtis, and M. C. Lin, "Aggregate dynamics for dense crowd simulation," in *Proc. ACM SIGGRAPH Asia Papers*. New York, NY, USA: Assoc. Comput. Machinery, 2009, doi: 10.1145/1661412.1618468.

[253] M. C. Lin, S. Guy, R. Narain, J. Sewall, S. Patil, J. Chhugani, and A. Golas, "Interactive modeling, simulation and control of large-scale crowds and traffic," in *Proc. Int. Workshop Motion Games*. Berlin, Germany: Springer, 2009, pp. 94–103.

[254] 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.

[255] 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)*, Aug. 2015, pp. 65–70.

[256] 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.

[257] A. Ahmad, "Analyses and systems of receiving hajjis, (using computer simulation model) for the year 1409 h," in *Proc. Custodian Two Holy Mosques Inst. Hajj Umrah Res.*, 1989.

[258] M. Al-Zahrani, "Study using computer simulation of the procedures to receive pilgrims at the Islamic port of Jeddah: (Hajj 1410 h)," in *Proc. Custodian Two Holy Mosques Inst. Hajj Umrah Res.*, 1991.

[259] 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 Simulation*. New York, NY, USA: Assoc. Comput. Machinery, May 2017, pp. 231–240, doi: 10.1145/3064911.3064924.

[260] 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.

[261] E. Felemban, F. U. Rehman, A. Ahmad, and M. Felemban, "A modelling and scheduling tool for crowd movement in complex network," *Intell. Autom. Soft Comput.*, vol. 31, no. 3, pp. 1361–1375, 2022. [Online]. Available: http://www.techscience.com/iasc/v31n3/44839

[262] R. Alqurashi and T. Altman, "Multi-level multi-stage agent-based simulation model of crowd dynamics in last floor of Al-Haram Al-Sharif," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 159–167.

[263] M. Yassin, M. Elgamal, and M. Shambor, "Crowd movement analysis in Al-Masjed Al-Nabawy using modelling and simulation," in *Proc. 18th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2018, pp. 4–13.

[264] A. Golas, R. Narain, and M. Lin, "A continuum model for simulating crowd turbulence," in *Proc. ACM SIGGRAPH Talks*. New York, NY, USA: Assoc. Comput. Machinery, 2014, doi: 10.1145/2614106.2614163.

[265] H. A. M. Malik, F. Abid, A. R. Gilal, and A. S. Raja, "Use of cloud computing in Hajj crowed management and complex systems," in *Proc. 4th IEEE Int. Conf. Eng. Technol. Appl. Sci. (ICETAS)*, Nov. 2017, pp. 1–5.

[266] R. Zhao, Q. Hu, Q. Liu, C. Li, D. Dong, and Y. Ma, "Panic propagation dynamics of high-density crowd based on information entropy and Aw-Rascle model," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 10, pp. 4425–4434, Oct. 2020.

[267] R. Zhao, Q. Liu, Q. Hu, D. Dong, C. Li, and Y. Ma, "Lyapunov-based crowd stability analysis for asymmetric pedestrian merging layout at T-shaped street junction," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 11, pp. 6833–6842, Nov. 2021.

[268] G. Vizzari and L. Manenti, "An agent-based model for pedestrian and group dynamics: Experimental and real-world scenarios," in *Proc. 11th Int. Conf. Auto. Agents Multiagent Syst.*, vol. 3, 2012, pp. 1341–1342.

[269] S. Manzoni, G. Vizzari, K. Ohtsuka, and K. Shimura, "Towards an agent-based proxemic model for pedestrian and group dynamics: Motivations and first experiments," in *Proc. 10th Int. Conf. Auto. Agents Multiagent Syst.*, vol. 3, 2011, pp. 1223–1224.

[270] H. Kurdi, A. Alzuhair, D. Alotaibi, H. Alsweed, N. Almoqayyad, R. Albaqami, A. Althnian, N. Alnabhan, and A. B. M. A. A. Islam, "Crowd evacuation in Hajj stoning area: Planning through modeling and simulation," *Sustainability*, vol. 14, no. 4, p. 2278, Feb. 2022. [Online]. Available: https://www.mdpi.com/2071-1050/14/4/2278

[271] E. Felemban, F. U. Rehman, A. A. Biabani, A. Naseer, and U. Alabdulwahab, "Towards building an interactive platform for analyzing movement of buses in Hajj," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2019, pp. 3775–3778.

[272] E. Felemban, F. Rehman, R. Nnouh, and O. Hussain, "An interactive and scalable platform for analyzing and visualizing movement of buses using modeling and simulation in Hajj," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 141–155.

[273] M. A. R. Abdeen, I. A. Nemer, and T. R. Sheltami, "A balanced algorithm for in-city parking allocation: A case study of al Madinah city," *Sensors*, vol. 21, no. 9, p. 3148, May 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/9/3148

[274] S. M. Al-Shariff, M. S. Alam, Z. Ahmad, and F. Ahmad, "Smart transportation system: Mobility solution for smart cities," in *Proc. 2nd Smart Cities Symp. (SCS)*, 2019, pp. 1–6.

[275] O. Tayan, Y. M. Alginahi, M. N. Kabir, and A. M. A. Binali, "Analysis of a transportation system with correlated network intersections: A case study for a central urban city with high seasonal fluctuation trends," *IEEE Access*, vol. 5, pp. 7619–7635, 2017.

[276] 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, p. 325, 2013.

[277] M. Jassas, A. Qasem, and M. K. Shambour, "IoT-based remote road traffic prediction and management for smart cities," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 113–123.
[278] S. Misbahuddin, J. A. Zubairi, A. Saggaf, J. Basuni, S. A. Wadany, and A. Al-Sofi, "IoT based dynamic road traffic management for smart cities," in *Proc. 12th Int. Conf. High-Capacity Opt. Netw. Enabling/Emerging Technol. (HONET)*, Dec. 2015, pp. 1–5.
[279] F. Abdessemed, "An integrated system for tracking and control pilgrims shuttle buses," in *Proc. 14th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2011, pp. 384–389.
[280] I. Ben Dhaou, "Client-server network architecture for safe pilgrim journey in the kingdom of Saudi Arabia," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2010, pp. 1043–1048.
[281] F. Othman, "The development of automatic sorting centers to facilitate the passage of pilgrims' vehicles," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 299–311.
[282] N. Koshak, A. Nour, K. Center, and S. Arabia, "Integrating RFID and GIS to support urban transportation management and planning of Hajj," in *Proc. 13th Int. Conf. Comput. Urban Planning Urban Manage.*, 2013, pp. 1–19.
[283] O. Tayan, A. M. A. 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.
[284] S. A. H. Alhuthali, M. Y. I. Zia, and M. Rashid, "A simplified traffic flow monitoring system using computer vision techniques," in *Proc. 2nd Int. Conf. Comput. Inf. Technol. (ICCIT)*, Jan. 2022, pp. 167–170.
[285] R. M. Elhassan, "Organic waste sorting proposed system in Mecca city," in *Proc. Int. Conf. Sustain. Energy Future Electr. Transp. (SEFET)*, Jan. 2021, pp. 1–6.
[286] A. Basalamah, "Sensing the crowds using Bluetooth low energy tags," *IEEE Access*, vol. 4, pp. 4225–4233, 2016.
[287] M. A. Rahman, G. Loukas, S. M. Abdullah, A. Abdu, S. S. Rahman, E. Hassanain, and Y. Arafa, "Blockchain and IoT-based secure multimedia retrieval system for a massive crowd: Sharing economy perspective," in *Proc. Int. Conf. Multimedia Retr.* New York, NY, USA: Assoc. Comput. Machinery, Jun. 2019, pp. 404–407, doi: 10.1145/3323873.3326924.
[288] A. Mandourah and M. Yamin, "Using blockchain technology to manage Hajj and Umrah," in *Proc. 9th Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, Mar. 2022, pp. 870–875.
[289] D. Radain, S. Almalki, S. A. Almarghalani, and S. Elhag, "Towards achieving the 2030 vision, the case study of automating the food production services during the Hajj season and quality control using the blockchain technology," in *Proc. 5th Int. Conf. Future Netw. Distrib. Syst.* New York, NY, USA: Assoc. Comput. Machinery, Dec. 2021, pp. 144–154.
[290] H. M. Fardoun, A. S. Mashat, and A. P. Ciprés, "Mecca access and security control system," in *Proc. 13th Int. Conf. Interacción Persona-Ordenador*. New York, NY, USA: Assoc. Comput. Machinery, 2012, pp. 1–7, doi: 10.1145/2379636.2379665.
[291] 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.
[292] S. S. Alwakeel, B. Alhalabi, and M. M. Alwakeel, "Perspectives on system of systems for pilgrimage ritual guidance and management," in *Proc. IEEE Int. Syst. Conf.*, Mar. 2014, pp. 425–430.
[293] H. Samkari and A. Gutub, "Protecting medical records against cybercrimes within Hajj period by 3-layer security," *Recent Trends Inf. Technol. Appl.*, vol. 2, no. 3, pp. 1–21, 2019.
[294] A. Gutub and N. Alharthi, "Improving Hajj and Umrah services utilizing exploratory data visualization techniques," in *Proc. 16th Sci. Symp. Hajj, Umrah Madinah Visit*, 2016, pp. 561–572.
[295] M. M. Almutairi, D. Apostolopoulou, G. Halikias, A. A. A. Sen, and M. Yamin, "Enhancing privacy and security in crowds using fog computing," in *Proc. 9th Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, Mar. 2022, pp. 57–62.
[296] N. A. Nawaz, A. Waqas, Z. M. Yusof, and A. Shah, "A framework for smart estimation of demand-supply for crowdsource management using WSN," in *Proc. 2nd Int. Conf. Internet things, Data Cloud Comput.* New York, NY, USA: Assoc. Comput. Machinery, Mar. 2017, doi: 10.1145/3018896.3025140.
[297] M. Murad, M. Y. I. Zia, and I. A. Tasadduq, "Monitoring pollution and air quality of pedestrian and automotive tunnels in the city of Makkah," in *Proc. Ind. Syst. Eng. Conf. (ISEC)*, Jul. 2020, pp. 1–5.
[298] M. Yasein, E. Khan, and M. Shambour, "Towards smart camps in Mina holy place: Exploiting IoT technologies," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 123–132.
[299] A. Almadah, H. Hammami, B. Zafar, and Y. Ali, "Smart Hajj platform," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 335–347.
[300] M. W. Aziz, A. A. Sheikh, and E. A. Felemban, "Requirement engineering technique for smart spaces," in *Proc. Int. Conf. Internet things Cloud Comput.* New York, NY, USA: Assoc. Comput. Machinery, Mar. 2016, doi: 10.1145/2896387.2896439.
[301] A. Morgan, M. Yasein, and K. Khayyat, "Towards smart monitoring of holy places: A minimalcost maximal-coverage sensor placement methodology," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 167–175.
[302] M. A. Mojamed, "Smart Mina: LoRaWAN technology for smart fire detection application for Hajj pilgrimage," *Comput. Syst. Sci. Eng.*, vol. 40, no. 1, pp. 259–272, 2022.
[303] S. Ahmmed, M. A. A. Khan, M. K. Hasan, A. Y. Saber, M. N. Huda, and M. Z. Rahman, "STLF using neural networks and fuzzy for anomalous load scenarios—A case study for Hajj," in *Proc. Int. Conf. Electr. Comput. Eng. (ICECE)*, Dec. 2010, pp. 722–725.
[304] M. Baz, J. Alamri, M. Alshamrani, M. Alzain, and N. Alharthi, "A developed decision support system for pilgrims housing in Makkah using artificial intelligence algorithms," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 124–133.
[305] M. Shambor, B. Bitainah, M. El-Shamrani, and M. Yassin, "Forecasting the quantities of electricity and water needs required for the Makkah region during the next ramadan seasons," in *Proc. 19th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2019, pp. 304–311.
[306] M. Elgamal, "Predicting the number of pilgrims in ramadan using the deep learning technique and comparing them with other methods," in *Proc. 20th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2021, pp. 104–112.
[307] S. A. E. Mohamed and M. T. Parvez, "Crowd modeling based auto activated barriers for management of pilgrims in Mataf," in *Proc. Int. Conf. Innov. Trends Comput. Eng. (ITCE)*, Feb. 2019, pp. 260–265.
[308] 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.
[309] S. Al-Ahmadi, M. O. Aljurbua, and A. Alabdulhafez, "A novel risk-based access control framework for dynamic environments," in *Proc. Int. Conf. Comput. Inf. Technol. (ICCIT)*, Sep. 2020, pp. 1–10.
[310] A. Sawalmeh, N. S. Othman, H. Shakhatreh, and A. Khreishah, "Providing wireless coverage in massively crowded events using UAVs," in *Proc. IEEE 13th Malaysia Int. Conf. Commun. (MICC)*, Nov. 2017, pp. 158–163.
[311] M. Shambour, E. Khan, and A. Alsalebi, "Optimal distribution of tents in Mina area," in *Proc. 17th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2017, pp. 720–726.
[312] 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.
[313] M. Deriche and M. Mohandes, "A hybrid RFID-LPR system for vehicle access control during pilgrimage season in Saudi Arabia," in *Proc. Int. Multi-Conf. Syst., Signals Devices*, Mar. 2012, pp. 1–6.
[314] M. Naser, M. Rafie, R. Budiarto, and W. Alsalihy, "Security considerations in embedding RFID in 'Hajj' system," *Eur. J. Sci. Res.*, vol. 42, no. 1, pp. 133–138, 2010.
[315] F. U. 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.
[316] A. Ahmad, M. A. Rahman, I. Afyouni, F. Ur 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.
[317] L. Alabdulkarim, W. Alrajhi, and E. Aloboud, "Urban analytics in crowd management in the context of Hajj," in *Social Computing and Social Media*, G. Meiselwitz, Ed. Cham, Switzerland: Springer, 2016, pp. 249–257.
[318] G. K. Kostopoulos, "E-government in the Arabian Gulf: A vision toward reality," in *Proc. Annu. Nat. Conf. Digit. Government Res.*, 2003, pp. 1–7.

[319] H. S. Alotaibi, R. Mahjoub, and M. Faezipour, "An intelligent system to control the operation of tunnels and subways: Application in Makkah and Madina traffic and pedestrian tunnels," in *Proc. Annu. Connecticut Conf. Ind. Electron., Technol. Autom. (CT-IETA)*, Oct. 2016, pp. 1–5.
[320] N. Alharthi and A. Gutub, "Data visualization to explore improving decision-making within Hajj services," *Sci. Model. Res.*, vol. 2, no. 1, pp. 9–18, 2017.
[321] A. Morgan and K. Khayyat, "Optimal distribution of service points in holy places," in *Proc. 18th Sci. Forum Hajj, Umrah Madinah Visit Res.*, 2018, pp. 14–24.
[322] S. Barhamain, "Makkah and Madinah are smart cities planning perspective," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, 2015, pp. 282–298.
[323] T. F. Himdi and R. S. Sandhu, "Lattice-based models for controlled sharing of confidential information in the Saudi Hajj system," in *Proc. 13th Annu. Comput. Secur. Appl. Conf.*, 1997, pp. 164–174.
[324] M. Shambour and A. Gutub, "Personal privacy evaluation of smart devices applications serving Hajj and Umrah rituals," *J. Eng. Res.*, pp. 1–22, Sep. 2021.
[325] (2017). *Vision 2030, Kingdom of Saudi Arabia*. [Online]. Available: http://vision2030.gov.sa/en
[326] M. Sehli, P. Sarkar, and L. Young, "The development of e-Hajj: Influence of diversity issues," in *Proc. 20th Pacific Asia Conf. Inf. Syst. (PACIS)*, 2016, p. 340.
[327] M. T. Parvez and S. A. Mahmoud, "Offline Arabic handwritten text recognition: A survey," *ACM Comput. Surv.*, vol. 45, no. 2, pp. 1–35, Mar. 2013, doi: 10.1145/2431211.2431222.
[328] A. Hassan, *Technology Application in Tourism Fairs, Festivals and Events in Asia*. Springer, 2022. [Online]. Available: https://link.springer.com/content/pdf/10.1007/978-981-16-8070-0.pdf
[329] D. A.-S. Nizami, M. Rehan, I. Ismail, T. Almeelbi, and O. Ouda, "Waste biorefinery in Makkah: A solution to convert waste produced during Hajj and Umrah seasons into wealth," in *Proc. 15th Sci. Symp. Hajj, Umrah Madinah Visit*, May 2015, pp. 1–12.
[330] M. Yamin, "Secure and healthy Hajj management: A technological overview," *Amer. Academic Scholarly Res. J.*, vol. 7, no. 3, pp. 1–8, May 2015.

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