A Review on Tawaf Crowd Simulation: State-of-the-Art

S. Mohamad, M. S. Sunar and R. M. Hanifa

Abstract—Crowd simulations have many benefits over real-life research. Managing the uncertainties that arise in disasters can be very challenging since crowd behavior in emergency situations requires the exposure of real people to the actual environment, and in some serious cases, might endanger or harm them if they actually perform the actions. As an alternative, many researchers use simulation. Currently, there are many simulation models in research and development that deal with crowd evacuation. Thus, the aim of this paper is to explore the various models relating to crowd evacuation and focusing particularly on tawaf crowd simulation.

Index Terms—Cellular Automata, Crowd Simulation, Intelligent Agent, Tawaf

1 Introduction

MASJID Al-Haram in Saudi Arabia is one of the most crowded pilgrimage locations in the world. The large crowd of pilgrims in Mecca during Hajj (pilgrimage) and Umrah (spiritual enhancement visit), posed one of the most significant and complicated existing crowd management challenges. The number of pilgrims and visitors has increased over the years.

Every sections of the mosque can host up to several thousands of pilgrims at any one time. During peak periods, such as during Hajj and the last ten days of Ramadhan [1], tens of thousands of pilgrims circumambulate around the Ka'aba (the most sacred site for Muslims) seven times in the counterclockwise direction known as tawaf, while others are performing prayers in the main court. Hajj and Umrah crowd management and evacuation procedures during emergency situations deserve particular attention as these events occur continuously throughout the year. Poor management and evacuation plan may not only result in anxiety and stress but also at worse result in crushing, injury and even death.

Tawaf ritual at Masjid Al-Haram involves large number of people at any one time especially during Hajj and Umrah season. Every Muslim aspires to visit Mecca at least once in his/her life to perform Hajj. The number of pilgrims and visitors has increased over the years and due to the large scale gathering, it is important to understand and model the behavior and movement of the crowd so as to improve crowd management techniques and ensure the safety of the pilgrims.

Curtis et al. [2] highlighted that tawaf has several properties, such as heterogeneous population, high density, varying velocities and complex motion flows, which make simulating it particularly challenging. Heterogeneous population means different pilgrims may move with different purposes. For example, some of the pilgrims enter or exit the Mataf area, while others circle the Ka'aba or stand still to pray. In terms of high density, the crowds in certain parts of the Mataf area are denser than others. According to Zafar [3], the density near the Ka'aba can become as high as eight pilgrims per square meter. This is extremely high and restricts the movement of the pilgrims. Complexity of motion flows refers to variants of crowd flows that have been observed during the tawaf. Besides circumambulating, pilgrims will simultaneously try to stand still to kiss the Black Stone at the corner of the Ka'aba. There are also pilgrims who attempts to move inwards orthogonally to the circular flow, towards the Ka'aba, while others move outwards towards the exit. Therefore, the circular flow is interrupted resulting in congestion at the corner of the Ka'aba near the Black Stone.

In the following subsections, the simulation related to tawaf will be presented. Comparisons with each of these simulations will be made to highlight the strengths and weaknesses of each technique.

2 Crowd Simulation Techniques

Modeling and simulating crowd under emergency condition is important as it could be used as one of the tool to analyze and assess safety precautions. The following subtopics review prior studies on tawaf crowd simulation.

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2.1 Cellular Automata

Samardy, Haron and Talib [4] presented a cellular automata model for the simulation of the pilgrims in a circular tawaf movement. In their paper, they claimed that most of the available software are unable to simulate circular movements in tawaf area with enough accuracy and details and furthermore can only handle relatively small crowds. However, their proposed circular model was able to simulate very large crowd of hundreds of thousands of pedestrians on a single personal computer with considerable amount of details. Their focus was mostly on the movement in the main court of the mosque and the tawaf area. They presented a basic framework for the actions and movements of pedestrians carrying out the tawaf movement using statistical discrete event approach to simulate the pedestrians' actions, and they use a model based on cellular automata to simulate pedestrians' movements. Two separate cellular automata models were used; one specifically for circular movements while the other simulates free walks between a source and a destination point. The simulation of actions and movements of individual pedestrians provides insights into the emergent behaviors of the crowd. They proposed a simple and basic model that focuses on human movements as shown in Fig. 1.

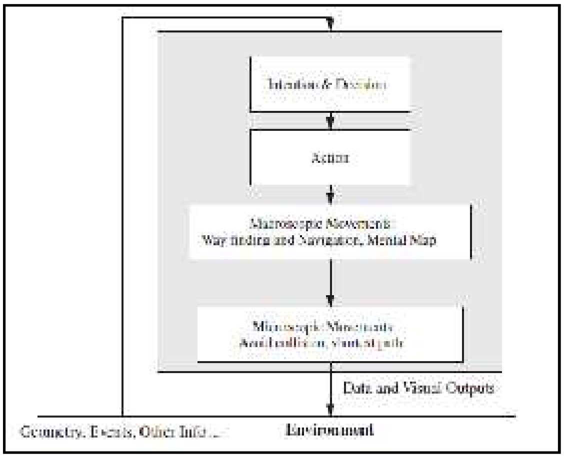

Fig. 1. Basic movement process model

The resulting software proved that the proposed model is capable of simulating very large crowd that is equivalent to 22,000-23,000 agents in real time (1s of simulation time using 1s of computing time). They compared the speed-density graphs obtained from empirical observations as well as compared simulation snapshots with photos taken at the actual place (refer to figure 2).

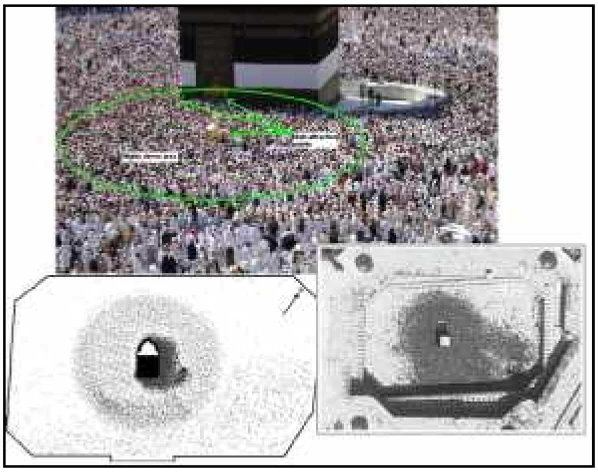

Fig. 2. Real-world congested area (top), simulation snapshot (bottom left) and satellite photo (bottom right)

The proposed circular cellular automata model includes new rules, higher accuracy and flexibility. Their model also considered the details of tawaf movement and integrated a discrete-event actions model into the crowd simulation architecture to simulate very large crowds. The software was used to predict whether changes to the area or to the operation of the place would create a significant gain in the throughput of the system. However, a limitation in their research is that they failed to consider specific actions such as pushing, falling and grouping of individuals.

2.2 Intelligent Agents

Mulyana and Gunawan [5] used the concept of intelligent agent in simulating crowd behavior of individual pilgrims. Their Hajj crowd simulation was able to demonstrate more realistic pilgrims' behavior for three Hajj rituals, i.e. tawaf, sa'i (the devotional act of walking seven times between the hillocks of Safa and Marwah which are located some distance from the Ka'aba inside Masjid Al-Haram) and jumrah (the throwing of seven stones). The intelligent agent design is shown in Table 1.

The simulation was developed to provide illusion of Hajj crowd. Hajj is a ritual activity which is not only bound to time but also to the place. Therefore, the agent needs to know the current location so that it can determine appropriate behavior according to the condition of the location. Agent was placed in different virtual environment and did specific activities according to the environment or location. In designing the layout for specific movements, significant places around the Ka'aba, such as the hajar-al-aswad, maqam Ibrahim and hijr Ismail, were taken into account. The specific rituals like prayer and kissing the hajar-al-aswad are also modeled in the form of finite state machine. Replicative validity was used to find out whether their model matches data already acquired from the real system. Screenshots from simulation was compared to the actual Hajj activities in the real world (refer to figure 3).

TABLE 1. AGENT DESIGN

Agent type	Hajj activities
percepts	▪ *body sensors* (front, left, and right): used for collision detection with environment (other agents or buildings) ▪ *avoid sensor*, used to detect other agent so it can avoid collision ▪ *agent view*, used to detect other agents ▪ *agent action*, agent need to know its own action so that it can determine next action ▪ *environment layout*: used by agent to recognize its environment so that it can determine appropriate hajj activities
actions	▪ idle ▪ walk ▪ brisk walk ▪ stoning ▪ kiss the black stone (*hajar aswad*) ▪ wave hand to the black stone
goals	Do hajj activities according to *sunnah* [1]
environment	▪ floor (walking path) ▪ obstacles (other agents and buildings) ▪ vector field, which will determine agent's movement ▪ specific ritual area/object, such as *thawaf*, *sa'i* dan *jumrah* area

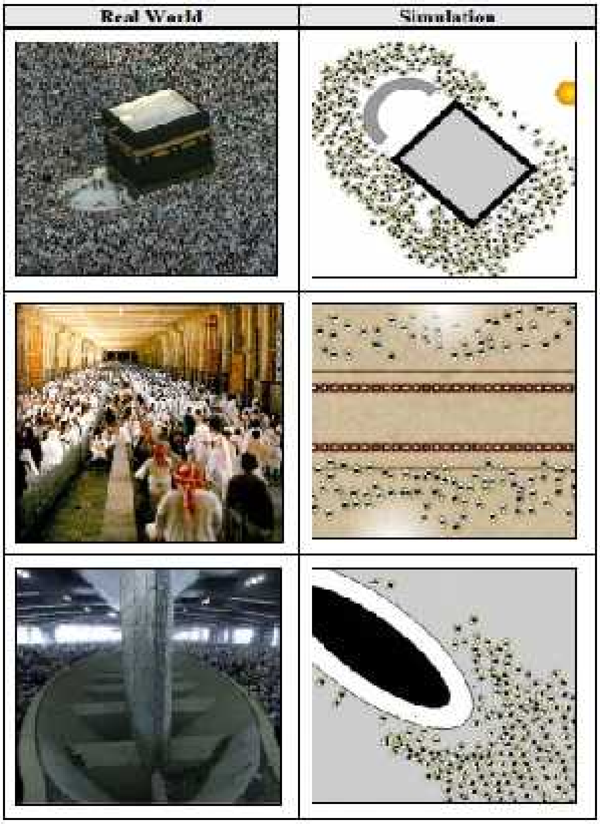

Fig. 3. Replicative validation result

Due to computer processing limitations, not more than 300 agents were used for this purpose compared to two million people in the actual case. To subjectively evaluate the implemented system, questionnaire survey was conducted. Ten people participated in the survey (six male and four female) of which four have performed their hajj, while the remaining six have not. Given the small sample size of respondents compared to the real situation, the accuracy of the model is questionable.

Siddiqui and Gwynne [6] investigated the relationship between simulating individual agent actions and generating reliable emergent conditions (e.g. congestion). They presented a simple framework for categorizing real-world observations and then translating these observations into simulated environment as shown in figure 4. Their research focused on the analysis of pedestrian behavior which is also equally applicable for the analysis of evacuee behavior. Their analysis of pedestrian behavior involved estimating pedestrian experiences/comfort levels and identifying where problems may arise that need to be addressed (i.e. to ensure comfort and prevent an incident). Their analysis of evacuee behavior involved the identification of conditions that may delay the time for an evacuating population to reach safety based on the scenario faced. Three scenarios were considered in identifying the relationship between the individual-level actions/factors simulated and the conditions that emerge:

1. Using the model's default movement parameters;
2. Using modified movement parameters to reflect the observed travel speeds; and
3. As 2, with the inclusion of a sub-set of the procedural activities observed represented as tasks inserted to reflect individual-level actions.

These scenarios were conducted using the building EXODUS model for a single agent and on a population of 15,000 to examine the impact of agent interaction upon the condition produced. The model is able to represent simple itineraries based on the recombination of basic behavioral tasks such as movement, delay in movement associated with specific actions, change of direction, and change of speed. As such, the model was able to discriminate between the impact of different individual-level factors and their impact upon the outcome of an event. However, there are still hypothetical and real scenarios relationships that have not yet been adequately represented such as tawaf crowd evacuation.

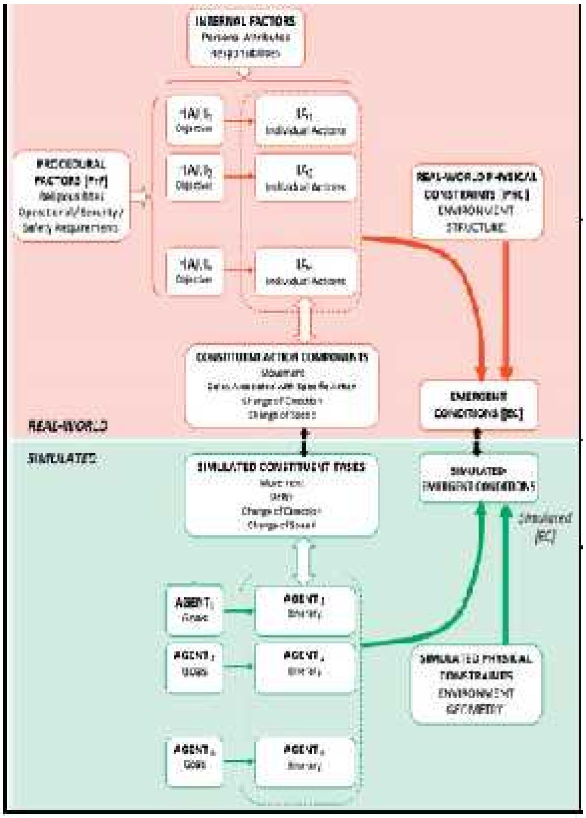

Fig. 4. Analytical Framework

2.3 Physical-based in Multi-agent Simulations

Kim, Guy and Manocha [7] presented an interactive algorithm to model physics-based interactions in multi-agent simulations. Their approach is capable of modeling both physical forces and interactions between agents and obstacles. Besides, their approach allows the agents to anticipate and avoid collisions for local navigation. They combined velocity-based collision-avoidance algorithms with external physical forces. The overall formulation can approximately simulate various physical effects, including collisions, pushing, deceleration and resistive forces. They integrated their approach with the multi-agent tawaf simulation from Curtis et al. [2]. The system overview is shown in figure 5.

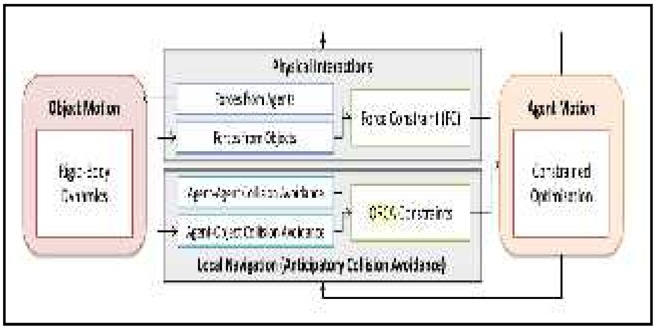

Fig. 5. System overview

Agents are assumed to travel with its preferred velocity if there were no collisions. An agent will compute a new velocity to satisfy the velocity constraints and will update its position based on the preferred velocity. The following are the two types of constraints imposed on an agent's velocity:

1. Optimal Reciprocal Collision Avoidance (ORCA) constraints guide the collision avoidance by specifying the space of velocities which are guaranteed to remain collision-free for a given period of time.
2. Force constraints account for forces which arise through physical interactions with other agents and objects.

Their simulation included about 35,000 agents whose behavior was modeled using finite-state machines (FSM). As the agents in the FSM state of moving to the Black Stone come closer to the Ka'aba, they allowed them to physically push nearby neighbours with additional forces in order to reach the Black Stone (refer to figure 6). Upon completing the circle, they measured the average speed and density of the agents for their simulation.

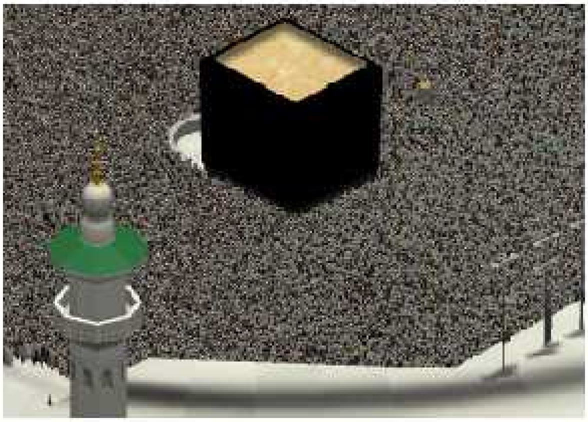

Fig. 6. Simulation of tawaf with 35K agent circling around the *Ka'aba*

Although they claimed that their newly developed simulation was successful, there are still a few drawbacks in their simulation. Firstly, the result generated is only an approximation and may not be physically accurate. Next, they assumed that agents are constrained to move along a 2D plane, and they used the projected positions of 3D dynamic objects to compute the interactions. Lastly, they used simple approximation for each agent i.e. they cannot accurately simulate physical interactions with human-like articulated models and 3D objects.

2.4 Agent in Spiral Movement

Shuaibu et al. [8] modeled the pedestrian agent performing tawaf using the concept of parameterization of spiral. The agents are set at defined velocities on spiral trajectory, moving counter clockwise mode inward and outward to increase and decrease the radii. They presented a new trajectory path planning that simulates the movement of individual agents performing tawaf. Figure 7 shows a new method of performing tawaf simulation based on analogy of logarithmetic spiral phenomena that occurs in nature.

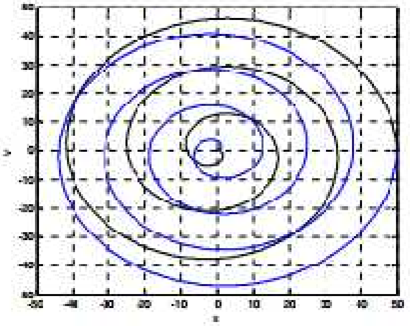

Fig. 7. Spiral trajectory for varying path radius

Their aim was to simulate complex scenario involving multiple agents interacting with each other and avoiding collision within a defined path. To do so, they have generated a population of 1,000 pedestrian agents with 50% male and 50% female including, 5% handicap agents. Level of Service (LoS), which is the density that determines the tendency of free flow or break flow of individual agents, was assigned consistent with the observed crowd at tawaf. Figure 8 shows the simulation outcomes of their algorithms.

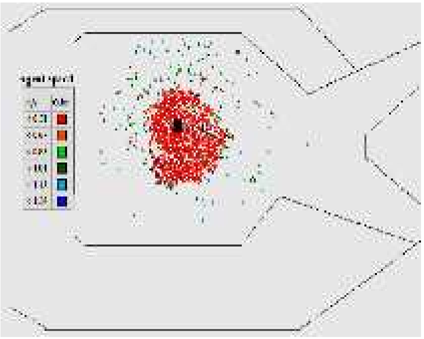

Fig. 8. Simulation of pedestrian agents performing tawaf on spiral path

Several simulations were run and the average density of the crowd, average velocity of individual agents and duration to complete the tawaf were calculated. Table 2 shows the summary of their simulation outcomes.

TABLE 2. SUMMARY OF THE SIMULATION OUTCOMES

Methods	Duration (min)	Average Density (P/m^2)	Level of Service (LoS)
Spiral movement (4_inward, 3_outward)	38.0	4.2	C
Circular pattern (Undirected situation)	60.1	3.3	B

One of the limitations with this situation is that it only focuses on spiral path without considering the high population (more than 1000 agents) and agents that stop for other purposes during *tawaf*.

2.5 Augmented Reality

Shahidan, Sunar and Khader [9] proposed an alternative way to simulate crowd using the Augmented Reality (AR). Their idea came from the study made by Zhen and Li [10] that has categorized three classes for their markers: object-markers to represent the virtual objects, operator-markers to adjust the properties of virtual group, and control-markers to control the simulation process. Figure 9 shows the example of the work by Zheng and Li.

Fig. 9. Controlling crowd characteristics using Markers

The key problem with the research made by Zheng and Li is that the work has been made for general crowd situation and does not take into account a specific real environment situation. Thus, Shahidan et al. [9] proposed to integrate the crowd simulation into an augmented reality based environment. They believe this integration would open for further potential in Hajj crowd simulation such as interaction approaches, visual approaches, realism factors, application effectiveness as well as the usability for training, crowd management and planning.

3 Conclusion

Previous sections have shown that agent-based simulations have been widely used to simulate large crowds at the tawaf area. Many algorithms based on behavior modeling, social forces, cellular automata, and velocity-based formulation have been proposed for multi-agent simulation [7]. To best model the crowd, intelligent agent can be utilized as it enables each character in the crowd to have different goals and different behaviors which reflects the real world. To realistically model the real world, the agent model must not only have the capability to make decisions, but also must have location specific capability [5]. Kim et al. [7] stated that individual or a group of pilgrims can be implemented as agents which have the capabilities to sense, think, and act. These capabilities will enable more realistic human behavior and crowd model. Continued research is needed in using augmented reality as an alternative to simulate crowd especially at the tawaf area. However, studies on crowd simulation in AR are limited and they have only been implemented in 3D virtual environment with 2D interaction using mouse and keyboard.

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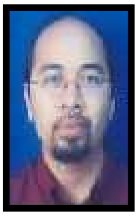

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