Agent-based Simulation of Crowd at the Tawaf Area

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Abstract – *Every year during the Hajj season there is a concentration of more than two million people within the vicinity of the Masjid Al-Haram. Congested areas, such as the Tawaf, may reach beyond a safe level of four people per square meter during this peak period. The Tawaf area together with the Ottoman construction is able to accommodate up to 72,000 people (in a praying position). Simulation of the movement and behavior of such a huge crowd can be useful in managing this important event. One of the recent trends in modeling and simulation is the agent technology which has been used to model and simulate various phenomenon such as the study of land use, infectious disease modeling, economic and business study, urban dynamic and also pedestrian modeling. In this paper we use multi-agent based method to simulate the crowd at the Tawaf area. We present the architecture of the software platform which implements our proposed model and briefly report our early experience in using Repast J which is an agent-based simulation toolkit to model the crowd at the area.*

Keywords: Crowd modeling, simulation, cellular automata, multi-agent, pedestrian.

1 Introduction

More than two million people attend Hajj each year. Thousands of these pilgrims are present in each section of the Masjid Al-Haram at any one time. In the Tawaf area tens of thousands of pilgrims circle around the Kaabah and some perform prayers. Understanding the behavior and the dynamic of such a huge crowd may help in managing this important event. Furthermore, such effort may help the authorities to smooth out the crowd flow within and outside the mosque. Management of evacuation is another application of crowd simulation and this does not exclude the Masjid Al-Haram.

There are various methods in modeling the movements of crowd reported in the literature. Physics-based models like particle and fluid dynamics methods, force-based models, matrix-based models and rule-based models are among the most commonly used methods. Fluid and gas dynamics methods use physical models to simulate movements. Matrix-based systems on the other hand divide environments into cells and make use of cellular automata to model movements of the entity within each cell.

In recent years, more complex models are being used which consider more parameters such as psychological and social specifications of pedestrians, communications between agents, roles of leaders, leading to more realistic simulation results [1]. Highly dense and panic crowd may lead to behaviors such as pushing, falling, trampling and stampede. Human behavior is complex and this makes it difficult to build an ideal model of the crowd. However, adding more details to available models may help us to achieve more realistic simulations.

The organization of the paper is as follows; section 2 reviews the existing related work on modeling and simulation of crowds. Social forces model, cellular automata models and rule based model are discussed. In section 3 we first suggest a basic layered model of pedestrian movement process and then apply the different layers of the model in our simulation plan. We will also discuss the relation of the proposed model with movements in the Tawaf area. In section 4 we present the architecture of the simulation platform and briefly discuss the agent-based simulation toolkit which we use in this project. Finally, the conclusion is given in section 5.

2 Related work

Microscopic movement behaviors (local motions inside a room or an area) are a very important part of crowd modeling. Generally, three main approaches have been used to model such behaviors. Social forces model [3],[4],[5], cellular automata approach [6],[7],[8] and rule based modeling [9] are being used in most studies. Other methods like magnetic forces model [10], distance maps [11] and the variations of the above mentioned methods [12] have also been introduced but the first three have been used more widely.

2.1 Social forces model

Social forces model describes the microscopic behavior of a person by the social fields. In this model, the motion of a moving person (or a pedestrian) is described as if they are subject to "social forces". These forces are a measure for internal motivations (collision avoidance etc.) of the individuals [3]. Social forces model is able to simulate low and high-density crowds but it does not deliver a realistic model by itself. Simulation resulted from these models appear like movements of particles rather than people and in close distances reveals the shaking effects [13]. Human do not completely follow the laws of physics, they decide, start and stop at will [14]. This model is considerably complex and therefore simulations based on this model require high processing power. M. Quinn [15] was able to simulate a single simulation cycle of 10,000 agents in 1/50 seconds with 11 CPUs.

Nevertheless, this model has been used to simulate many important crowd phenomena successfully such as arch formation at doors, lane formation and oscillatory changes of the walking direction at narrow passages [4].

2.2 Cellular automata models

Cellular Automata (CA) models [6], [7], [8], [16], [17] on the other hand use a uniform grid of cells with local states. Certain rules are being used to compute the state of each cell as a function of its previous state and the states of the adjacent cells. CA models divide the "world" into discrete cells, which typically hold a single pedestrian. Hence, models based on CA are not able to simulate dense crowd realistically – movements appear like board games while the pedestrian appears in an orderly manner. CA models better suit for small to medium density crowds [13]. Due to their simple algorithmic steps, these methods are very fast. Meyer-Konig was able to run a simulation cycle consisting tens of thousands of agents in 1/30 second on a single CPU [18].

2.3 Rule-based models

Rule based models [9] use specific predetermined rules for movements of pedestrians. In low-density crowds, these models can deliver realistic results but unlikely to produce acceptable results for dense crowds. The models employ waiting rules and do not consider collision detection, pushing and repulsion. This type of model is not able to simulate panic and some other specific situations of interest which occur in dense crowds [13].

2.4 Models for macroscopic movements

For macroscopic movements, different approaches have been proposed. Several simulations use a database of way finding information (routes, etc.). Agents will have access to this information and use them depending on their individual behavior, abilities and stress level at a specific moment. Other ideas have been experimented in way finding process such as exploring, learning and communicating with other agents [1]. In this approach, each agent will have a mental map, which expands as an agent explores environment or learns by communicating with one another. This map contains geometry of places in a graph form.

3 Simulation

As highlighted earlier the main purpose of this work is to simulate the crowd movements in the Tawaf area. Our aim is to reproduce the movements of crowd and also model the crowd effects. We have also considered detailed characteristics and behaviors of individual pedestrian agents. Software agents can act autonomously in order to accomplish these tasks. Agents act on behalf of the pedestrians and simulate their individual behaviors. A multi-agent system consists of pedestrian agents which in turn simulate the entire crowd.

In order to simulate movements of human beings using multi-agent methods we need to have a model of human movement process. Complex models of human behaviors (not specifically for crowd simulation) have already been suggested and different multi-agent systems have been built based on the model. Dr. Silverman's PMFserv [19], [20], [21] is one good example of such a model. This system is able to simulate more than 1000 agents at a time [19]. However we anticipate that such models are not suitable for our problem. Hence, a simpler human model is preferred. We shall describe the methods chosen to simulate each layer of the movement process in the following sections.

3.1 Modeling the pedestrian movement process

In this section, we suggest a basic model of human movement process. We will then use this model in the design of our system. Helbing and Molnar discussed a similar process in [4]. They took into account the stimulus, psychological/mental processes and actions as the process leading to the pedestrian behaviors.

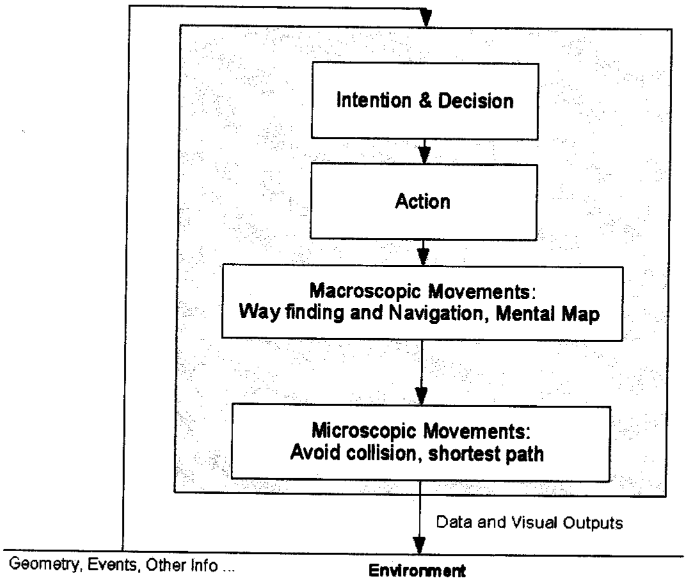

Figure 1: Basic movement process model

Movements of a human normally start because of a specific intentions and decision. As an example, someone decides to visit his mother in another city. This intention results into a decision and a series of actions. These include going to train station, buying a ticket, traveling on a train etc. Going to train station is a macroscopic movement, which needs navigation and way finding behaviors. During macroscopic movements, microscopic local movements like collision avoidance and shortest path selection will take place. In addition, some environmental events and parameters may trigger a new decision and action. In order to create a realistic simulation we need to model all these concepts (intention and decision, action, macroscopic movements and microscopic movements).

Microscopic movements which occur in a particular situation are very important because they can affect the validity of the entire simulation. Consider an agent, which intends to go into a room and exit through another door. From macroscopic point of view, the agent should go from an entrance point to an exit point. From microscopic point of view, however, agents show very different and complex behaviors during transition from one point to the other. Other agents, obstacles and walls may affect "shortest path selection" behavior of the agents. Agents may need to make small changes to their path, for example, stop, before reaching the next point.

3.2 Microscopic movements

As discussed earlier social forces model is able to simulate more realistic microscopic movements but in a sample study, Quinn [15] has been forced to use 11 CPUs to simulate the movements of 10,000 agents. We anticipate that it is least likely for the model to perform reasonably fast on a typical personal computer for the crowd in the Tawaf area (which can be more than 50,000 pedestrians during peak time). The huge number of pedestrians makes it impossible to use this method unless we incorporate parallel processing technique or grid computing technology. As a result, we decided to use a cellular automata model for our initial studies. At a later stage of the work we will decide whether we should move to social forces model.

Social forces model is defined by the equation below:

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0(t) e_i^0(t) - v_i(t)}{\tau_i} + \Sigma_{j(\neq i)} f_{ij} + \Sigma_w f_{iw}$$

In this equation, *m* is the mass of each pedestrian, v_i^0 is the desired velocity with which pedestrian will move in the absence of interactions, e_i^0 is the desired direction (toward attraction points), f_{ij} is the repulsive force between pedestrians which models the collision avoidance between agents, f_{iw} is the repulsive force between pedestrian and obstacles (walls etc.), τ is the time constant and v_i is the actual velocity of the pedestrian at any given moment. We do not use a similar velocity for every pedestrian rather our multi-agent behavior engine will determine this velocity for each agent.

3.3 Macroscopic way finding behaviors

As discussed earlier macroscopic behavior is the navigation between rooms and areas in a simulated environment. This behavior is different when a pedestrian has some knowledge about the place and when it does not know much about the environment. Communication between pedestrians has an important role on this behavior because of the knowledge transfer which occurs among them. Small number of pedestrians, who know the environment, help others to find their way better [1], [2]. Therefore, in a crowded place, finding the way is relatively easier because these people may become a "guide" in finding a way out.

Based on the above assumptions, we can simplify the architecture of the software by using static path tables. We assume that there are limited number of logical and suitable paths between every source and destination rooms or areas. In this method, better routes have lower cost in the path table. Pedestrians will choose one of those routes depending on their knowledge level and parameters coming from the multi-agent behavior engine (which simulates pedestrian behaviors). In some cases, the path may be chosen randomly. As for the Tawaf movement, pedestrians will only try to maintain circular movements around the Kaabah.

3.4 Characteristics of individual agents

Earlier crowd simulation systems used pedestrians with the same characteristics in their simulations or used pedestrians with minor differences. Helbing's basic social forces model adopts this approach. In the real world however, people in a crowd can be different in terms of age, abilities, knowledge etc. These specifications affect the decisions and actions of the pedestrians. Building a complete model of human behavior and considering all effective parameters in simulation of pedestrians is almost impossible due to the high number of parameters and the complexity of the behaviors. Instead, we will build a basic human behavior model to meet our purpose. We will also identify and choose some of the most important effective parameters. For example age, orientation or way finding capabilities, gender, health level, energy, fatigue, desired speed and stress level. As we saw earlier, each parameter may affect one or more layers of the model. The first two top layers of our model determine actions, which will be mapped to movements. These layers therefore affect the parameters of the two lower layers. Choosing the route and desired speed are among the most important parameters of these two layers.

3.5 Dense crowd specific behaviors

Pedestrians show somehow different behaviors in dense crowds, for example, pushing other pedestrians. In low density situation, pedestrians change movement direction to avoid collision. In dense crowds, however, pedestrians are not able to maintain enough distance from others. This makes them feel uncomfortable and they may attempt to open some space for themselves by pushing others. In addition, pedestrians may push others to open their way in entrances and exits in congested path. Each pedestrian prefers to move with a desired speed. If someone is moving slower, others may push him to be able to reach their desired speed. If the amount of the pushing force is high enough this may cause pedestrians to fall, crash into walls and become injured. In fact, other pedestrians may trample the fallen pedestrians. These pedestrians then become obstacle for other pedestrians and slow down the movement of the whole crowd. In order to realistically simulate a dense crowd we must model the above phenomena.

3.6 Simulation of movements in the Tawaf area

The pilgrims typically move with specific intentions such as "go to pray", followed by "go to Tawaf" or "Safa-Marwa for Saie" etc. "Going to Tawaf" is considered as an intention according to our movement procedure model. Each intention may result in a specific series of actions. As an example, to perform Tawaf, the person must go to the Masjid Al-Haram, perform the tawaf, and then perhaps pray behind Maqam Ibrahim and leave the mosque. We should map each intention to a series of actions and map the actions to a series of macroscopic movements – "Going to Masjid Al-Haram", "perform Tawaf", "pray behind Maqam Ibrahim" and "leave the mosque" in this case.

The simulation of the next layer requires us to model the macroscopic movements. Tawaf consists of circling seven times around the Kaabah. We ought to navigate through several points around the Kaabah. With this methodology, we will have to navigate through a series of points to complete an action which requires microscopic movements. An alternative way will be to maintain an approximate radius around the Kaabah. To achieve an intention we may have several alternative lists of actions forming an action graph. In a more general scenario, we may want our multi-agent behavior system to determine the intentions, actions etc.

As highlighted earlier, since cellular automata and social forces model focus on the lower-layer microscopic motions so we need other parameters on top of them to build a more realistic simulation. Adding two additional layers on top of the movement process will help us to achieve this objective.

4 Simulation platform architecture

We are currently working on the simulation platform, which will cover all the layers of our movement process model. We will first use the platform to simulate the Tawaf area of the Masjid Al-Haram. We hope that we could use the same platform to simulate other sections of the mosque. Demographic information and the comparison of the simulation results to the information gathered from the real environment will help us to calibrate our model. The architecture of the proposed simulation platform can be summarized by figure 2. The simulation platform consists of a simulation engine which is responsible for the physical movement (MiCS – Micro-macro Crowd Simulator module) and also the behavior (MABS – Multi-Agent Behavior Simulator module) of the pedestrian. Agent Editor and Geometry Editor are modules that feed the system with the pedestrian and geometry input data. Visualizer module displays the results while the Event Recorder and Event Analyzer helps in producing the reports or evaluation tools. The following sections discussed the different components of our platform.

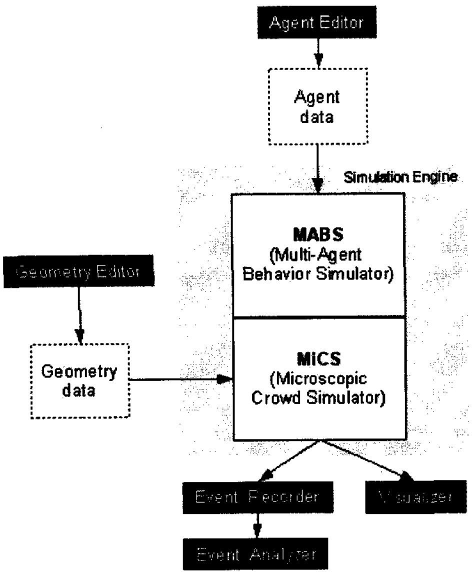

Figure 2: Our proposed architecture of the system

4.1 Micro-macro Crowd Simulator (MiCS)

Simulation of macroscopic and microscopic movements is performed in the crowd simulator module. As described earlier we use a cellular automata model for microscopic movements and static path tables for way finding and macroscopic movements. Microscopic Crowd Simulator (MiCS) module reads geometry information from the geometry data and receives the information on the subsequent action from multi-agent behavior engine. A path is then selected to achieve the action. It then simulates the movement using a cellular automata model and output/results are recorded using event recorder module of the software. Event recorder saves results in a database or file.

4.2 Multi-Agent Behavior Simulator (MABS)

The role of MABS is to generate the crowd behaviors. Users of the system will use an agent editor to build the crowd by specifying the combining agents. Demographic information can be useful for this purpose. Though many agents are copied from a single template, each one will act autonomously. Each agent will decide for its next action. In the later phase of the project, we plan to develop a Multi-Agent Behavior module which consists of a perception module that can be used to understand the environment and events happening in its surrounding area. Behavior module uses a cognition process to determine decisions and actions according to certain rules. For the purpose of this study we chose a relatively simple human behavior model since we anticipate a complex model will consume a lot of computing power and hence the simulation results can not be obtained in real-time (especially on a personal computer).

4.3 Supporting modules

A geometry designer will be used to design the simulated environment and should supports modification for the new geometry design. The modification features is essential to enable us to use the software for other parts of the Masjid Al-Haram and to test new designs of each section. Results of the simulation will be displayed by the visualizer module. An event analyzer module will help us to analyze outputs such as speed, volume, patterns and the statistics of crowd and agent movements.

4.4 Multi-agent simulation toolkits

For the development of our simulation platform we have two options. We could build every single part of the platform ourselves or to use available reusable components. Using existing agent-based simulation libraries and toolkits would reduce the development time. Several such libraries and toolkits are available but a few of them have become popular among the modeling and simulation community. Developers of these toolkits have added several interesting features and have made their toolkits more efficient over time.

These toolkits either use their own scripting languages or rely on a standard programming language. Netlogo as an example uses its own language while Repast, MASON and Swarm rely on standard languages. All the three mentioned toolkits provide libraries for use with Java language. Repast J and MASON are developed in Java language themselves while SWARM is developed using Objective-C and Java.

We use standard Java language and "Repast J" libraries for our current project. This toolkit is a freeware and open source library which provides different features like grids for cellular automata, graphical output, GIS utilities and basic agent and event schedule infrastructures. In comparison, MASON provides better GUI features and also includes components for visualizing of continuous models but lacks some of the components like GIS data integration.

5 Conclusion

In this paper, we have identified an approach, which we believe to be suitable for simulating huge and dense crowd in the Tawaf area and congested places of the Masjid Al-Haram. We have presented our basic movement process model. We have also presented the development of the crowd simulation platform which is based on the model. A multi-agent behavior system will simulate the behaviors of the individual pedestrians in the crowd. Demographic and real world observations can be used to calibrate the multi-agent behavior system. The development of the simulation can be speed up by the use of existing agent-based simulation toolkit.

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