MODELLING AND SIMULATION OF MOVEMENTS AND BEHAVIOURS IN LARGE CROWD USING CELLULAR AUTOMATA

By

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Thesis submitted in fulfilment of the requirements for the degree of Master of Science

July 2008

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to my supervisor, Dr. Fazilah Haron for her invaluable help. She provided support, constructive criticism and helpful suggestions during the research. Her support kept me to continue the work until the end.

I am also extremely grateful to my co-supervisor Assoc. Professor Dr. Abdullah Zawawi Hj. Talib. His comments and suggestions helped me very much through the research work and I learned valuable things from him during this period.

I want to thank my wife and my mother for their encouragement and support. My mother has been my teacher in the school. She has continued to be my teacher all these years. I have learned perseverance and hardworking from her.

Finally I would like to express my gratitude to the School of Computer Sciences for making all this possible.

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2. S. Sarmady, F. Haron, M. M. M. Salahudin and A. Z. H. Talib, "Evaluation of Existing Software for Simulating of Crowd at Masjid Al-Haram," Jurnal Pengurusan Jabatan Wakaf Zakat & Haji, vol. 1, no. 1, pp. 83-95, 2007.

3. S. Sarmady, and F. Haron, "Agent-Based Simulation of Pedestrian Movements and Behaviors," in Proceedings of CSPC'07, Universiti Sains Malaysia, 2007.

4. S. Sarmady, F. Haron, and A. Z. H. Talib, "Multi-Agent Simulation of Circular Pedestrian Movements Using Cellular Automata," in Proceedings of Second Asia International Conference on Modelling & Simulation, IEEE Computer Society, Kuala Lumpur, Malaysia, 2008, pp. 654-659.

5. S. Sarmady, F. Haron, and A. Z. H. Talib, "Simulations of Pilgrims' Movements and Actions at the Tawaf Area - Methods and Applications," in the 2nd National Seminar on Hajj Best Practices Through Advances in Science and Technology, Universiti Sains Malaysia, Penang, Malaysia, 2008.

Pemodelan dan Simulasi Pergerakan dan Kelakuan Pejalan Kaki bagi Kumpulan Ramai yang Besar Menggunakan Automata Bersel

ABSTRAK

Kumpulan ramai (crowd) adalah satu daripada fenomena yang lumrah dalam kehidupan kita. Reka bentuk bangunan dan tempat-tempat awam hendaklah menjamin tahap keselamatan minimum yang diperlukan serta keselesaan terhadap kesesakan orang ramai. Ujian keselamatan serta prestasi ke atas sesebuah bangunan dengan menggunakan manusia adalah sesuatu yang sukar, memerlukan masa dan kadang kala membahayakan. Pemodelan dan simulasi kumpulan ramai membolehkan pelbagai jenis ujian dijalankan, contohnya pengongsian (evacuation) dan prestasi dapat dijalankan dengan lebih mudah pada sesuatu reka bentuk. Ujian yang dilakukan secara berulang akan membantu memperbaiki reka bentuk.

Di tempat yang sibuk, pejalan kaki bergerak dalam arah yang berlainan dengan cara tindakan yang juga berbeza untuk mencapai matlamat masing-masing. Dalam usaha memodelkan cara tindakan dan pergerakan pejalan kaki, dalam tesis ini, kami mencadangkan model empat lapisan daripada proses pergerakan manusia. Dua daripada lapisan tersebut ialah ‘lapisan tujuan’ dan ‘lapisan tindakan’, menjadi model kelakuan atau perlakuan pejalan kaki. Dua lapisan lagi, menjadi model perlakuan pergerakan skala besar (pergerakan makroskopik) dan pergerakan setempat skala kecil (pergerakan mikroskopik).

Kami mencadangkan rangka kerja simulasi kumpulan ramai yang menggunakan kaedah simulasi peristiwa diskret berserta dengan dua lapisan atas daripada ‘model proses pergerakan asas’ untuk merangsang tindakan pejalan kaki. Rangka kerja menggunakan suatu model automata bersel bagi pergerakan skala kecil. Kami mencadangkan dua model automata bersel yang berbeza untuk pergerakan terus dan gerakan membulat. Model pergerakan membulat digunakan untuk kajian kes utama kami yang mensimulasi pergerakan tawaf yang membulat di sekeliling Kaabah di Masjid Al-Haram, masjid suci umat Islam.

Kami membina platform simulasi berdasarkan rangka kerja yang dibentang dan digunakan untuk mensimulasi kesesakan orang ramai dalam dua kajian kes yang berasingan. Kajian kes pertama, sebagaimana yang dinyatakan, mensimulasi pergerakan dan perlakuan kumpulan ramai dalam kawasan Masjidil Haram (tempat tawaf). Kajian kes kedua mensimulasi kesesakan orang ramai di sebuah pasaraya yang sibuk di Pulau Pinang. Keputusan terperinci tentang simulasi di samping analisis serta kesahan (validation) algoritma dan model turut dibentangkan.

MODELLING AND SIMULATION OF MOVEMENTS AND BEHAVIOURS IN LARGE CROWD USING CELLULAR AUTOMATA

ABSTRACT

Crowds are one of the ubiquitous phenomena in our life. Design of buildings and public places should therefore guarantee a minimum level of safety, comfort and throughput for the crowd. Testing the safety and performance of buildings using real humans are difficult, time consuming and sometimes dangerous. Modelling and simulation of crowd allow different types of test such as evacuation and performance to be carried out on a design. Repeated tests help in improving the design.

In busy places pedestrians move toward different directions and follow different actions to achieve their goals. In order to model actions and movements of the pedestrians, in this thesis, we propose a basic four layer model of human movement process. Two of the layers, namely "intentions layer" and "actions layer", model the behaviours of pedestrians. Two other layers model the large scale navigational behaviours (macroscopic movements) and small scale local movements (microscopic movements).

We propose a crowd simulation framework which uses discrete event simulation methods along with the two top layers of our "basic movement process model" to simulate actions of pedestrians. The framework uses a cellular automata model for the small scale movements. We propose two different cellular automata models, one for direct line and one for circular movements. The circular movement model is used for our main case study which simulates the circular Tawaf movements around the Kaabah in Masjid Al-Haram, the Muslim holy mosque.

We build a simulation platform based on the presented framework and use it to simulate the crowd in two separate case studies. The first case study, as mentioned, simulated the

movements and behaviours of the crowd in the court area of Masjid Al-Haram (where the Tawaf is performed). The second case study simulates the crowd in a section of a busy supermarket in Penang. Detailed results of the simulation along with the analysis and validation of the algorithms and models are presented.

CHAPTER 1
Introduction

1.1 Background

Crowd can be defined as a group of pedestrians gathered in a place for similar or sometimes different purposes. Crowds are present in most of the places and they have become an inseparable part of our daily life. The study of crowd has therefore become the focus of research in several fields including transport, psychology, safety, cognitive science, artificial intelligence and computer graphics. Even though the study of crowd is possible by observing it, experimenting with the crowd is difficult because of the time, cost and dangers involved. Using a crowd simulation tool would therefore be very convenient. The benefits of using crowd simulation tools have attracted interests to this field in recent years. These tools are created with different purposes in mind which include:

- **Crowd safety and comfort studies:** This category of crowd simulation software can itself be divided into 2 main categories:

    - **Evacuation safety:** This category of crowd simulation software are used to predict if a certain building or design is safe for pedestrians in emergency evacuation conditions or not. Safety regulations differ between countries but in general, regulations require buildings to be designed in such a way that the evacuation is completed in a certain amount of time. It is also important to prepare evacuation plans for places like stadiums, large buildings and huge events like the Hajj in Mecca and the World Youth Day to avoid any catastrophic situations. Preparing plans and improving buildings for safe evacuation will be easier if done with the help of simulation software as it is almost impossible to test the scenarios using real population.

- **Crowd comfort and design efficiency:** This category of software is used to study crowd movements in normal scenarios. This kind of software can be used to investigate if a design can handle a specific amount of pedestrian effectively. If investigations show that the capacity of some of the corridors for example is not sufficient to handle the pedestrians living in the building, engineers will be able to modify and improve their design.

- **Animations:** Software like MASSiVE (Multiple Agent Simulation System in Virtual Environment) [1] are developed to create animation and film scenes. Though movements in these simulations seem smooth and realistic, complete accordance of the results to reality is not a requirement. Therefore these software are not used in serious crowd studies.

- **Entertainment:** In recent years a series of entertainment software has been created which simulate both behaviours and movements of humans. “The Sims” [2] is one of the most famous available products. This software has extensive capabilities. It is possible to extend behaviours of the characters using add-in packages.

Our research is mostly involved with the first category. Our ultimate goal of the research in this field is to build a modern and scalable crowd simulation platform which can simulate different scenarios realistically and with acceptable accuracy. Different companies and researchers have worked toward this goal in recent decade but we are yet far from a platform which can provide such capabilities for every scenario and also crowds with different traits and sizes.

1.1.1 Examples of Crowd

Big gatherings of pedestrians can be observed in covered areas like buildings and stadiums as well as open areas like walkways and parks. The purpose of the gatherings has important effect on the large scale properties and behaviours of the crowd. In a shopping mall for example, people are keen to look at shop windows and enjoy their shopping. In contrast, pedestrians in a street might like to reach their destination faster and therefore the average movement speed could be higher than a shopping mall. Size and density are other important specifications of crowd. Larger crowds (e.g. religious functions) are harder to manage and because of the collective forces of the pedestrians in such a crowd, dangerous incidents are more likely to happen. Pedestrians feel less comfortable in denser crowds and excessive densities are dangerous and should be avoided. It is suggested that the density of 4 pedestrians per square meter is the maximum permitted for safety [3]. The following sub-sections present two specific examples of crowd. We first look at the large crowd in a Muslim mosque in Saudi Arabia where millions of people gather to perform their pilgrimage. We then look at the smaller crowd in a typical supermarket.

1.1.1.1 Crowd at Masjid Al-Haram

Annually more than two million Muslims attend Hajj pilgrimage in Saudi Arabia. Pilgrims gather in the "Masjid Al-Haram", the most important mosque for the Muslims, to perform a series of rituals. Specifically Hajj rituals start from the 9th until 13th Dhu Al-Hijjah (12th Islamic month). Hence during this period congestion occurs at the places of rituals. In the court area or the centre of the mosque starting from the 10th Dhu Al-Hijjah for example, tens of thousands of pilgrims circle around the Kaabah building while some perform prayers. This anti-clockwise motion around Kaabah is called Tawaf. Pilgrims perform another important ritual inside the mosque next to the court area called "Saie". They walk seven times between the hills of Safa and Marwah to complete Saie. In addition to the mosque, some of the Hajj rituals happen in places other than Masjid Al-Haram. In another ritual, "Stoning the Devil" which happens in the valley of Mina, the huge crowd of pilgrims passes over the Jamarat bridge. Pilgrims throw stones at pillars which symbolize the devil.

Most of the Hajj rituals must be completed within a specific period of time. The time limit causes pilgrims to sometimes rush to these places. In the past, several tragedies have occurred during Hajj due to the huge size of the crowd. For example in 1990, 1426 pilgrims died in a Tunnel in Mina due to a stampede. In another case, 270 pilgrims died in Jamarat Bridge in 1994 and the same problem in the same place caused the death of another 244 pilgrims in 2004.

Being able to simulate the behaviour of the crowd could help in managing this important event and to avoid more dangerous cases. Simulation may also help the authorities to smooth out the crowd flow within and outside the Masjid Al-Haram by modifying the design and arrangements in places where congestion takes place. After the 2004 incident, the authorities consulted several crowd research scientists including G.K. Still in order to improve the bridge design. The bridge (including the pillars, exits and entries) was remodelled and several safety improvements were proposed. The improvements include reshaping of the pillars from circle to elliptical form which would cause less resistance against the crowd flow. The simulation model also helped in increasing the awareness of the authorities about crowd dynamics. As a result Hajj of 2005 completed without any incident. However in January 2006 another incident happened at the entry of the bridge which caused the death of 363 pilgrims. Based on Still's assessment [4] the authorities ignored a report which include the results of computer simulation highlighting the high risk areas and they failed to take necessary measures to avoid the problem and this could be the reason of the new incident. After the new incidents, the authorities have decided to immediately start the construction of a multi-level bridge in place of the old single-level bridge. The new bridge design was started well before the new incident. In the design process of the new bridge, crowd simulation software and consultations of several crowd research scientists were used to produce a more effective design which would provide higher safety and capacity at the same time [5]. After the Hajj in January 2006, the old bridge was demolished and construction of the new bridge started. The ground and first levels of the bridge were ready for the Hajj of the next lunar Muslim year and the Hajj of December 2006 was performed without any incidents. The bridge construction was scheduled to be completed by the end of 2007. Fortunately, there has been no major incident after the opening of the new bridge.

As mentioned before one of the places where a huge crowd gathers during the Hajj and other periods of the year (like Ramadan), is the court of Masjid Al-Haram. Even though several studies on the area have been performed in the past, little work has been done on the simulation of the crowd in this area. The court of the Masjid Al-Haram and the Tawaf movement are one of the main focuses of this thesis. A simulation model of the area will help us to understand behaviours and movements of pilgrims in this area better. We will also be able to experiment with the model and suggest measures which can increase the throughput of the Tawaf system and make the area safer.

1.1.1.2 Crowd at a Supermarket

Public places like train stations, parks and supermarkets are visited regularly by most of the people. Design efficiency and safety of these places are therefore very important. Supermarket buildings normally contain sections for food court, drinks, smaller kiosks and shops rented to private sellers. People with different interests visit the building for different purposes. Specific products and services might draw people to some areas of the supermarket and cause congestion while other areas might remain less crowded. The important point in such a place is that products and services determine where people will visit most. Observing video snapshots or using statistical data gathered on the customers can give valuable information about behaviours of the customers. Predicting the utilization of different sections and identifying possible problems can be achieved using a computational model which has been adjusted using the above mentioned data.

1.1.2 Crowd Simulation Methods

Various methods have been used to model movements of crowd. Physics-based models like fluid and particle dynamics methods [6], force-based models [7-9], matrix-based models[10-17] and rule-based models [18, 19] 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 or similar methods to model movements of the entity within cells.

Human behaviour is complex and this makes it difficult to build an ideal model of the crowd. Basic models consider pedestrians similar to each other or with little differences. However, adding more details to available models may help to achieve more realistic simulations. In recent years, more complex models are being used which consider different parameters such as psychological and social traits of pedestrians, communications between agents, roles of leaders, leading to more realistic simulation results. Researchers have attempted to simulate behaviours specific to dense crowds such as pushing, falling, trampling and stampede. These works have been able to achieve different levels of success but more time and work is needed to build models with realistic results which can at the same time reproduce behaviours of crowds in different situations and scenarios.

1.2 Research Objectives and Scope

The objectives of this research are:

- To create a framework for simulating behaviours, actions and movements of pedestrians in a large crowd. In order to simulate the movements we first need to simulate behaviours of the crowd including intentions and actions and then simulate the movements resulting from those actions. We propose a general model of pedestrian behaviours and movements as a basis for our framework.

- To adopt or propose a pedestrian movements model suitable for simulating a large crowd. As one of the case studies in this research, namely "the Tawaf area of Masjid Al-Haram" requires us to simulate both normal direct line movement and circular Tawaf movement; we need models for both types of movement. The movement model should also include way finding behaviours.

- To develop a platform based on the proposed framework. The platform should have a flexible architecture to accommodate new pluggable models in all of the simulation layers for the purpose of testing new research ideas. It should also be possible to create simulation scenarios for different places and situations without changing the software itself.

- To show the usefulness and effectiveness of the platform using case studies. One of the case studies will deal with a very large crowd (specifically the Tawaf area of the Muslim holly mosque). Analysis of the results and different reports will be used for this purpose and to show the validity of the simulations.

1.3 Methodology

As mentioned in the objectives of the research, in this thesis we first propose a general model of crowd behaviours and movements. Our four layer model considers both behaviours and movements of individual pedestrians and it is used along with a multi-agent simulation framework to simulate the emergent behaviour of the crowd out of the movements of individual pedestrians.

With the help of the readings from literature review, we will decide on the general direction of the research in each of the four layers and select a suitable model for each of them. We then integrate separate layers to build a full crowd simulation framework. In our four layer model, two higher layers focus on intentions, decisions and actions of a pedestrian. Two lower layers focus on large scale way finding movements and small scale microscopic movements.

We compare available models for small scale microscopic movements based on our requirement of simulating large crowds. We select cellular automata method as the most suitable one for this layer. For our way finding macroscopic movements layer, we select a model which meets our purpose.

For intentions and actions layer, again different possibilities exist. We first identify our requirements (i.e. a big crowd with actions and intentions limited to a specific set) and then based on the requirements; we select and propose a model. We have chosen "discrete event simulation" methods along with an action and intentions framework for these two layers.

We need a flexible architecture for our simulation platforms so that we are able to test different ideas and models. We design a platform with a flexible architecture in such a way that we can plug in new models for each of the layers later and see the results. For example we can replace our currently used cellular automata microscopic layer with a social force model without affecting the whole structure of the platform.

We use the developed platform to simulate two scenarios to show the generality of the design and its capabilities to simulate different situations and cases. Our first case study is the crowd in the Tawaf area of the Muslim Holly Mosque in Mecca. In the case of Tawaf we have a specific circular form of crowd movement around Kaabah, a building in the middle of the Tawaf area. We build our specific cellular automata movement model for this circular movement type. For normal pedestrian movements we also create and use our basic cellular automata movement model which is based on the least effort concept.

Intention and action layers of the software work based on the statistical data gathered from the real situation and place. We use the available data gathered in [20] to simulate actions and movements of the people inside the Tawaf area. We apply as much rules as we can (rules which exist in the real world) to reproduce the phenomenon observed in reality in the simulation. Applying these rules helps us to have a reasonable simulation of the scenario. After reaching an almost near and acceptable simulation we are able to use more detailed statistical data to calibrate the system and reach more accurate results.

In addition to our main scenario, we have also presented another (less detailed) experiment which depicts a typical crowd simulation scenario. In this scenario we have simulated movements and behaviours of pedestrians in a section of Tesco Extra Supermarket in Penang, Malaysia. This scenario has been presented to show that it is possible to use the framework and the platform to simulate crowd in different situations and places.

We performed a detailed analysis on the results obtained from the two simulation scenarios. First, we analysed the effectiveness and validity of the framework and second, we presented how the results of the simulation can be useful. Results and analysis being provided mostly focused on our first case study, however brief analysis was also provided for the second simulation case, the supermarket.

1.4 Contributions

Contributions of the thesis can be listed as follows:

- A cellular automata model for circular movements.

- A framework which integrates "discrete event simulation methods" into a layered model of intentions, actions and movements of individual pedestrians to simulate emergent movements and behaviours of a large crowd.

- A simulation platform with a flexible architecture as a test bed for crowd simulation research which can readily be used for different simulation scenarios and places without having to change the platform itself.

1.5 Outline of the Thesis

The organisation of the thesis is as follows; Chapter 1 (current chapter) provides an overview of the content and directions of the thesis. Chapter 2 reviews the existing related work on modelling and simulation of crowds. Various crowd simulation models are studied and compared in this chapter. This chapter also provides a short survey on a few of the available software in the market. In Chapter 3, layered model of pedestrian movement process, details of integration of discrete event methods into the model to simulate intentions and actions, way finding algorithm, cellular automata algorithm for circular movements and the basic least effort normal movements model are discussed. In Chapter 4 we present the architecture of the platform that we have designed. We provide details on the implementation of the platform and a short description on the process of preparing and running a simulation scenario. In Chapter 5 we present the output results of our two scenarios and also the analysis of the results. In Chapter 6, we conclude the thesis and present the future directions of the research.

CHAPTER 2
Related Work

2.1 Introduction

Crowd simulation study has been carried out from different aspects including psychological, sociological and physical aspects. Computational models have been mostly focused on simulating movements and behaviours of the crowd in emergency and normal situations.

Models in general, split complicated phenomena into smaller layers, sections, features and behaviours to make them easier to understand. Crowd models in the same way, differentiate between different types of behaviours and features and describe them in separate layers and sub-models. Microscopic movement behaviours in these models refer to small scale behaviours like collision avoidance inside a room and selecting the shortest path to the target. Macroscopic behaviours on the other hand refer to navigation between different areas.

One should differentiate "macroscopic and microscopic behaviours of pedestrians" with "macroscopic and microscopic categories of crowd simulation models". Macroscopic simulations deal only with the general properties of the whole crowd such as flow, density etc. and do not consider interactions of individual pedestrians with the environment and other pedestrians. Macroscopic models use the relation of density to walking speed and flow to calculate overall movements of the crowd. An example of these models is presented in [21] (referenced in [10]). These models are relatively simple and require less computing power because they do not deal with the behaviours and movements of thousands of the individual pedestrians in the crowd.

On the other hand microscopic models simulate the emerging behaviour of the crowd by simulating behaviours and movements of individual pedestrians. These models enable users to investigate interactions of individuals in a crowd to the building details, emergencies, crowd density, actions of other pedestrians and much more details than macroscopic simulations could be provided. New and powerful computers in recent years have made it possible to simulate crowds with thousands of pedestrians and considerable details. Various types of methods have been used to simulate movements and behaviours of crowd. Physics-based models like fluid and particle dynamics methods, force-based models, matrix-based models and rule-based models are among the most commonly used methods. In [22], Lovas uses a discrete-event queuing network method to model movements of individuals in a network consisting of nodes (rooms) and links (doorways). By comparing the capacity of corridors and doorways to the simulated flow, it is possible to predict queuing and congestion status in different parts of the building. This model considers way selection of individuals but it does not simulate small scale movements of them in the physical environment and does not model interaction of pedestrians with the building design details and other pedestrians. In this thesis we focus on microscopic type of models for simulation of movements.

2.2 Models for Microscopic Movement Behaviours

Microscopic movement behaviours (i.e. local motions inside a room or area) of individual pedestrians as mentioned earlier result in emerging behaviours of the whole crowd. Three main approaches have been used to model such behaviours. Particle, fluid and gas dynamics methods such as social forces model [7-9], magnetic forces model [23, 24] and forces based model in [25] use physics based models to simulate movements of pedestrians. Matrix-based systems like cellular automata [10-16, 26] approach and distance maps [27, 28] on the other hand divide environments into cells and use cellular automata or similar methods to model movements of the pedestrians within cells. Rule based models [18, 19] are also among the main model types being used in crowd simulations. The method in [29] is also an example of the variations of the above mentioned methods. We will discuss these three approaches in more detail in the following sub-sections.

2.2.1 Social Forces Model

Social forces model describes the microscopic behaviour of a person in a crowd by the social fields. In this model, the motions of moving pedestrians are described as if they are subject to external "social forces". These forces are a measure for internal motivations (collision avoidance etc.) of the individuals [7].

The repelling forces between people (describing collision avoidance), the repelling forces between people and walls, and attraction forces between pedestrians and their targets result into a force which moves pedestrians in the crowd. Examples of the resulting motion patterns are lane formation when pedestrians are moving in opposite directions, arc formation at doors and oscillatory changes of the walking direction at narrow passages [8].

Social forces model is defined by the equation below:

$$F_{social\,force_i} = m_i a_i = m_i \frac{dv_i}{dt} = m_i \frac{v_i^0(t) e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_w f_{iw} \quad (2\text{-}1)$$

In this equation, m_i is the mass of each pedestrian, v_i^0 is the desired velocity of a pedestrian with which pedestrian is comfortable to move in the absence of interactions, e_i^0 is a vector toward the desired target, f_{ij} is the repulsive force between pedestrian i and other pedestrians which models the collision avoidance between agents, f_{iw} is the repulsive force between pedestrian i and obstacles (walls etc.), τ_i is the relaxation time (which is the time taken for pedestrian i to reach its comfortable speed), and v_i is the actual velocity of the pedestrian at any given moment.

The social forces 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 [8], however it does not always produce realistic results.

This is because the model considers people as particles and describes the interaction of the people as if they are particles which behave based on physical laws. As G.K. Still mentions in his thesis, human do not completely follow the laws of physics, they decide, start and stop at will [3]. Human beings behave based on their thoughts and cognitive processes happening in their mind. Helbing et al. themselves mention that expressing the rules of pedestrian behaviours using equations is possible when we want to simulate automatic reactions and well predictable behaviours happening in standard situations. In other cases Helbing et al. suggest using some probabilistic models [8].

2.2.2 Cellular Automata Models

As mentioned earlier in cellular automata models the simulation space is divided into a grid of cells. In this kind of models, transition of pedestrians among cells happens based on relatively simple rules. Each cell holds a single pedestrian and the state of each cell is computed as a function of its previous state and the states of the adjacent cells. Though the rules are simple in nature they are able to simulate the complex emergent behaviour of a crowd. Since the simulation is being performed for each individual pedestrian and because the movements are flexible, it is easily possible to integrate a higher level artificial intelligence or cognitive model to control the larger scale movements of pedestrians (i.e. way-finding etc.).

Gipps and Marksjö's work [30] (referenced in [31]) is one of the first attempts to use cellular automata to model pedestrian flows. The cellular automata was then used to simulate vehicle movements by Biham [32] and Nagel-Schreckenberg [33, 34]. The models were again later used for modelling pedestrian movements by Blue and Adler [10-12], Dijkstra [14, 15], Burstedde, Schadschneider and Kirchner in [13, 16, 26, 35, 36].

In the next sub-sections we will review two of the most important cellular automata models namely Blue-Adler and Burstedde-Schadschneider's model.

2.2.2.1 Blue and Adler Cellular Automata Models

One of the important CA models being used in crowd simulation has been proposed by Blue and Adler. Blue and Adler [10] describe a CA algorithm which uses lane selection and speed determination to simulate a crowd which moves toward a single direction in a walkway. In this algorithm, pedestrians try to choose a lane which allows them to reach their maximum desired speed more freely (Figure 2-1).

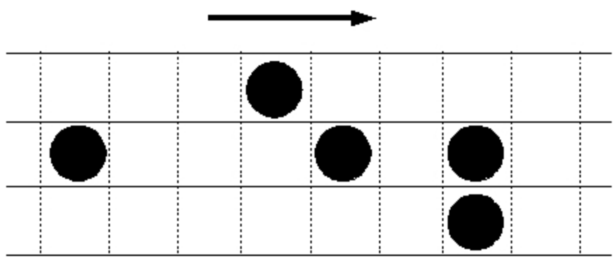

Figure 2-1: Blue and Adler Model Movements of Pedestrians in a Walkway

- In the first step each pedestrian looks to see if its adjacent cells are free and are not selected by a neighbouring pedestrian.

- In the second step pedestrian selects one of the free lanes (either the current one or one of the adjacent lanes) based on which lane provides more free space for the pedestrian to reach its maximum desired speed. If both the current lane and the two adjacent lanes provide enough space to reach the maximum speed, the pedestrian will prefer its current lane with a probability of 80% (10% for each adjacent lane). Selection probabilities can be changed though.

- In the third step the number of moves in a time unit is identified and the pedestrian performs its move. The number of cells in a move is determined by the pedestrian's maximum speed and also the free available space. For example if a pedestrian's desired speed is 4 cells per second and there are 4 or more empty cells in front of it, the pedestrian will move 4 cells forward. If the free space is only 3 cells, pedestrian will move only 3 cells forward.

The results of this model are evaluated with the "Highway Capacity Manual" which includes empirical data on density and speed relations in walkways.

In Blue and Adler's first paper a one directional movement has been discussed while in next papers two [11] and four directional [12] movements are studied. These models study pedestrian movements in very limited scenarios. Simulating movements of pedestrians in a free space in which movement directions are not limited and people do not move in lanes cannot be achieved using these models.

2.2.2.2 Burstedde-Schadschneider Model

Schadschneider, Kirchner, Nishinari and Burstedde have proposed cellular automata models for pedestrian movements in [13, 16, 26, 35, 36]. In their earlier papers basic forms of their cellular automata model were presented while more improved models were described in the later papers. We will therefore take a look at one of these works.

In [13], Burstedde et al. have proposed a multi directional model for pedestrian movement. In this model each pedestrian can move into one of its 8 neighbouring cells in each time step. However, the authors have used minimum amount of intelligence for the pedestrians to make the model simple. Selection of the cell is based on a 3 x 3 matrix of preference (Figure 2-2).

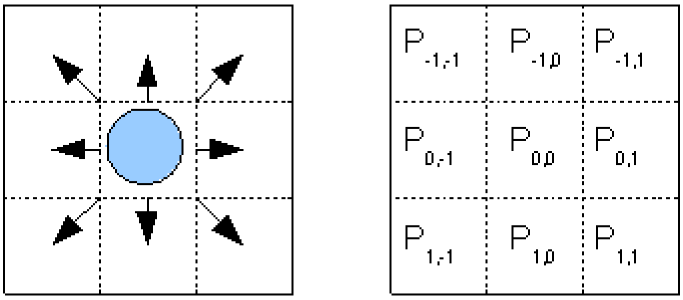

Figure 2-2: Movement Preference Matrix

A preference level is calculated for each cell and the pedestrian selects the cell which is preferred more for its next move. They describe that they have used a model with V_{max} = 1 cell/time-step for all pedestrians (i.e. only transitions to neighbours are allowed) due to the sharply peaked velocity distribution of pedestrians (to a value around 1.3-1.4 m/s). They mentioned that a greater maximum velocity would be harder to implement in 2 dimensions. The number of possible target cells increases quadratically with the interaction range. In addition it will be necessary to check whether the path is blocked by other pedestrians and this will make it more ambiguous for diagonal motion and crossing trajectories to be performed. A few main ideas are being used to move pedestrians in CA cells such as:

- Each cell can be occupied just by one pedestrian. Before the pedestrians move, Cell selection process happens for all of the pedestrians. If two pedestrians select the same cell as their next cell, the one with a higher preference will move in and the other one will stay where it is.

- Each pedestrian when passing from a cell leaves a trace in the cell. This is similar to Chemo-taxis effect. Each pedestrian prefers to move into cells with higher concentration of traces. The trace put in a cell will diffuse into neighbouring cells and decay with time. Traces of pedestrians will vanish finally, if no other pedestrian passes through the same path for some time. This whole idea is used to convert the effect of long range interactions into a local interaction which is easier to handle using local CA cell selection methods. The traces are stored in something called dynamic field. In discrete form of dynamic field, there is a matrix which stores dynamic field value for each CA cell. When a pedestrian moves into a cell, the value of related cell in dynamic field will be increased by 1.

- In addition to dynamic field a static field is also used in this model. The static field as its name suggests, does not change during time. This specific type of field is considered to model the effect of interactions of pedestrians to specific areas of buildings (for example attraction points like doors or specific objects). Transition probability affected by static field causes the pedestrian to move in the direction of larger fields.

In this model transition probability P_{ij} in the direction (i,j) is given by:

$$P_{ij} = NM_{ij}D_{ij}S_{ij}(1 - n_{ij}) \tag{2-2}$$

D_{ij} is the dynamic field value in the cell and S_{ij} is the static field value in the cell. M_{ij} is a matrix of preference which identifies the direction which pedestrian prefers to move. n_{ij} identifies if the cell is already occupied by a pedestrian or not. If a cell is already occupied then n_{ij} will be 1 and ($1-n_{ij}$) will become 0. Multiplication with a 0 will result in a probability of 0 of moving into this specific occupied cell (collision avoidance). N is a normalising parameter which causes the sum of probability of moving into neighbouring cells to become 1.

Other researchers have tried to improve this model. Kirchner et al. have added friction effects to model clogging and its effect in evacuation rate from doors where a lot of people compete to enter into cells [16]. Henein [37] has added pushing forces to Kirchner's model [36] to simulate the effects on evacuation speed and pedestrian injuries due to excessive force.

2.2.3 Rule Based Models

Rule based models [18, 19] introduced specific behaviour based rules for simulating the movements and interactions of simple creatures like birds, fishes and animals in the form of a flock. This model was later used to simulate movements of pedestrians. In this model creatures interact based on their perception of the environment. These behavioural rules include collision avoidance (creatures avoid collision with the others in the flock), velocity matching (match velocity with nearby creatures in the flock) and flock centring (stay close to nearby creatures in the flock).

2.2.4 Dense Crowd Specific Behaviours

Pedestrians show somehow different behaviours 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.

N. Pelechano et al. created a HiDAC system (High Density Autonomous Crowds) based on social forces to simulate very dense crowds. They introduced braking and repulsion forces in small distances to simulate pushing effect and collision avoidance [38, 39]. As a result they were able to simulate injuries, falling and trampling of pedestrians due to the excessive pushing forces in the crowd. Simulations of dangerous and emergency situations are carried out more realistically in their system.

In [37], a method to simulate such effects with cellular automata type of movement models has been reported. In this thesis we have worked on dense and large crowds but we have not yet modelled pushing and falling effects. These effects might be considered in case we would like to extend the work to simulate emergency situation.

2.2.5 Comparison of Available Microscopic Models

In previous sections we reviewed most important available models for the simulation of microscopic pedestrian movements. Every model has its own weaknesses and advantages. Based on specific requirements and simulation scenario a model can be more suitable than the others. In this section we briefly compare limitations and advantages of the reviewed models.

- **Social Forces Model:** The relatively complex nature of the nonlinearly coupled Langevin differential equations being used in this model makes it difficult to apply changes to the model to match it with different scenarios. For example for circular movements the equations cannot be used directly (as in our case study on circular Tawaf motions which will be discussed later). It is also difficult to introduce new features and functionalities to the model as changes in the equations and therefore numerical methods being used to solve it will be required. Such amount of changes to the software might be undesirable. Due to the computational complexity of the model, simulations based on this model require high processing power. If the number of pedestrians is large it will be practically impossible to use this method unless we incorporate parallel processing technique or grid computing technology. Quinn was able to simulate a single simulation cycle of 10,000 agents in 1/50 seconds with 11 CPUs [40].

Social forces model is able to simulate low and high-density crowds but it does not deliver a realistic model by itself. Because of the continuous nature of this model, simulation results are smoother in comparison to grid based models. However simulation resulted from these models appear like movements of particles rather than people and in close distances reveals the shaking effects [39]. In the previous section we gave a brief overview of Pelechano's work on a modified social forces model (HiDAC) which is able to simulate pushing, falling and trampling of pedestrians in a dense crowd and at the same time produces more realistic results.

- **Cellular Automata (CA) Models:** As mentioned earlier, models based on CA are not able to simulate dense crowds realistically. This is because the simulation space has been divided into cells of a grid. Movements of pedestrians happen in discrete fixed size distances. Speed of pedestrians can have discrete values (1,2,3 … cells in a time unit). As a result, movements of pedestrians appear like board games. CA models better suit for small to medium density crowds [13] but if the focus of the simulation is not on the very small scale behaviours of the crowd (rather on larger scale behaviours) this kind of models can be used with higher density crowds. Due to their simple algorithmic steps, these methods are very fast and it can be used for simulation of very large crowds. Meyer-Konig was able to run a simulation cycle consisting tens of thousands of agents in 1/30 second on a single CPU [18]. We also previously mentioned that integration of a higher layer behavioural model into these models is quite easy.

- **Rule Based Model:** In low-density crowds, these models can deliver realistic results and smooth movements but unlikely to produce acceptable results for dense crowds. This is because the models employ waiting rules to avoid collisions and they do not consider pushes 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]. Table 2-1 summarises comparison results.

Table 2-1: A Summary of the Comparison on Microscopic Movement Models

Model	**Social Forces**	**CA**	**Rule Based**	**HiDAC**
Continuous / Discrete	Continuous	Discrete	Continuous	Continuous
Realistic for Sparse Crowds	No	No	Yes	Yes
Realistic for Dense Crowds	No	No	No	Yes
CPU Usage (Ability to Simulate Large Crowds)	High (No)	Low (Yes)	Low (Yes)	Very High(No)
Modelling of Push/Falling/Trampling	No	No *	No	Yes
Ease of modifying the model	Difficult	Easy	Medium	Difficult

* In Henein [37] this modelling has been considered

2.3 Models for Macroscopic Movements

For macroscopic movements, different approaches have been studied. 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 behaviour, abilities and stress level in a specific moment. Other ideas such as exploring, learning and communicating with other agents [1] have also been investigated. In this approach, each agent will have a mental map, which expands as an agent explores environment or learns by communicating with others. This map contains geometry of places in a graph form.

As discussed earlier macroscopic behaviour is the navigation between rooms and areas in a simulated environment. This behaviour 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 behaviour because of the knowledge transfer which occurs among them. Small numbers of pedestrians, who know the environment, help others to find their way better [1], [2]. Therefore, in a busy place, finding the way is relatively easier because these people may become a "guide" in finding a way out.

2.4 Combining Movement Models with Behavioural Models

In real life, people move toward different goals and perform different actions in an environment. Not considering these different goals and actions will result in a less realistic simulation. For this reason recently researchers have started to build behavioural models on top of the movement models to achieve better simulations.

Pelechano et al. integrate an additional PMFserv human behaviour model unit on top of their MACES crowd simulation system which could influence the decision making of agents at the micro and macro movement levels in order to allow more individualistic behaviour and therefore more realistic crowd simulation[41]. PMFServ (Performance Moderator Function Server) models different human behaviours like abilities, stress, emotions, and decisions. In this system decision making happens based on emotions, stress level and physiology. This model is a very extensive human model for general use (not specifically for crowd simulation) which has been under development for several years by Silverman et al. Because of the complex model being used, the size of the simulation has been limited to several hundred agents [42-44].

McKenzie et al. in VMASC (Virginia Modeling, Analysis and Simulation Center) work on a project aimed at building a cognitive human model which can be used for military simulations and general applications like crowd simulation [45]. In this model, a list of available stimuli and behaviours are selected. Stimuli and other effective parameters determine cognitive state for crowd, group and individuals. Behaviour selection (from the list of available behaviours) is affected by the cognitive states of those entities.

In [46] Musse and Thalmann describe their hierarchical model for simulating human crowds. In their work they propose a hierarchy which includes virtual crowds, groups and individuals. They provide 3 methods to control the identities including: innate and scripted behaviours, defining behavioural rules and by external control in real time.

2.4.1 Group Effects

In addition to the individual pedestrian parameters and actions, interactions between pedestrians have important effects on collective behaviours of a crowd. One of the interactions happening between pedestrians is the grouping effect. Members of a family, a group of friends or colleagues could form a group of agents which are attached to each other, move and stop with each other or try to maintain a minimum distance to each other. Big groups move slower and may act as obstacles to movement of other pedestrians. They will also communicate and transfer information concerning path and emergency.

Group effects have been studied from different aspects. In [47] Musse et al., propose a crowd model based on sociological interactions of virtual humans (like common goals and interests) to form the emergent behaviours of crowd. However this model mostly focuses on relatively sparse crowds. In [48], Pelechano et al. discuss and model the rule of trained leaders and people with knowledge of the environment the evacuation and way finding speed. In [49], Musse et al., present a framework which considers group intelligence, group emotions and group actions in addition to actions of individuals.

To increase the accuracy of the simulation, we might consider this effect. However in a very dense crowd (in which people are forced to stay near to each other and freedom of movement is limited), the effect of grouping might be different in comparison to less dense situations. We have not included this effect in our model in this thesis, however it is possible to attach pedestrians to groups and then force them to maintain a small distance to each other and study the results.