A MODIFIED SOCIAL FORCE MODEL FOR CROWD DYNAMICS

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by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

LKF	Lakoba, Kaup, Finkelstein
MATLAB	A numerical computing environment that allows matrix manipulations, plotting of functions and data, implementation of algorithms
MPSM	Microscopic Pedestrian Simulation Model
SFM	Social Force Model
SimWalk	A computer simulation software which simulates pedestrians' movement

SUATU MODEL DAYA SOSIAL YANG DIUBAHSUAI UNTUK DINAMIK KERUMUNAN

ABSTRAK

Model daya sosial merupakan model pejalan kaki yang banyak digunakan dalam perisian simulasi komputer kerana ciri-ciri model ini yang lebih realistik. Banyak pengubahsuaian telah dibuat untuk mengimprovasi model daya sosial ini. Salah satu daripada pengubahsuaian tersebut ialah pengenalan kepada mekanisme penghentian sendiri di mana suatu faktor hormat digunakan untuk mencetuskan mekanisme ini. Faktor hormat ini menentukan suatu kawasan untuk seorang pejalan kaki berjalan dengan kelajuan yang diingini. Dalam penyelidikan ini, nilai faktor hormat yang tetap ini akan diubahsuai untuk memperoleh gambar rajah asas yang lebih tepat. Faktor hormat dinamik yang diperoleh ini akan digunakan untuk mengkaji pelbagai situasi dalam simulasi pejalan kaki. Salah satu situasi yang dikaji melibatkan pejalan kaki berumur yang berjalan lebih perlahan dan memerlukan kawasan yang lebih besar untuk berjalan. Modifikasi lain melibatkan faktor hormat dinamik dalam simulasi pejalan kaki bagi pelbagai arah. Tindakan pejalan kaki yang saling menghormati akan dimasukkan dalam modifikasi ini. Visual simulasi akan dianalisa untuk mengkaji kecekapannya. Faktor usia dan jantina akan dimasukkan ke dalam simulasi pejalan kaki pelbagai arah untuk menghasilkan simulasi yang realistik. Aplikasi model daya sosial biasa dalam suatu perisian komputer komersial, SimWalk akan dibincang. Salah satu ritual keagamaan di Makkah iaitu mengelilingi Ka'aba (Tawaf) akan dijadikan kes kajian. Lazimnya, jemaah-jemaah menghadapi dua masalah utama ketika menunaikan Tawaf. Masalah pertama ialah kebanjiran jemaah semasa musim Haji. Seterusnya, pintu masuk ke kawasan Tawaf yang tidak

dikawal menyebabkan jemaah-jemaah masuk dari pelbagai arah. Kajian ini memberi beberapa cadangan untuk mengatasi masalah ini. Pelbagai reka bentuk pintu masuk akan direka menggunakan SimWalk dan masa yang diambil oleh para jemaah untuk menyempurnakan Tawaf akan dibandingkan.

A MODIFIED SOCIAL FORCE MODEL FOR CROWD DYNAMICS

ABSTRACT

The Social Force Model (SFM) is the most recent form of pedestrian model which is widely used in computer simulation software, as this model is more realistic. Many modifications have been done to improvise the SFM. One of them is a self-stopping mechanism introduced by earlier researchers where a respect factor is used to determine the self-stopping mechanism. The respect factor determines the respect area which is the area for pedestrians to walk at their own preferred speed. In this thesis, the constant respect factor is modified to obtain a better fundamental diagram. Also, the new dynamic respect factor is used to investigate different situations in simulating pedestrians. One of the situations involves elderly pedestrians who walk at a slower speed needs wider walking space. Another modification in the dynamic respect factor is to simulate pedestrians walking in multi-directions. The action of “respect” between pedestrians is incorporated into this modification. The visual simulations are analyzed to study its efficiency. The characteristic of age and gender factor is incorporated into the multi-directional walkway to produce a simulation which is close to the real-life crowd. The application of the normal Social Force Model in computer simulation models is also discussed here. The pedestrian simulation computer software, SimWalk, is used to study the simulation of pedestrian flow. The study of circumambulation of the Ka’aba is taken as an illustrative example, where performing Tawaf is one of the rituals when performing the Hajj. The pilgrims face two main problems in this situation. The first is the overflowing of the pilgrims during the Hajj season. Secondly, entry into the Tawaf area is not controlled which causes pilgrims to move in from various directions concurrently. This study suggests various mitigation measures to alleviate the problems associated to circumambulation of the Ka'aba. The entrances and exits of the Tawaf area are modified using SimWalk to compare the differences of the time taken to complete the Tawaf ritual. The various locations and designs of barriers at the exits and its effect on the time taken for the pilgrims to exit the Tawaf area are also discussed.

CHAPTER 1

INTRODUCTION

1.1 Microscopic Pedestrian Studies

Microscopic crowd dynamics play an important role in designing walkways to promote good pedestrian flow and minimize discomfort in large crowds. Areas such as zebra crossings, bus and train stations and shopping malls are prone to huge volumes of moving pedestrians and require proper and thorough architectural planning.

The behaviour of pedestrians may be described as a hierarchical view as introduced by Hoogendoorn (2001). The operational level describes an instantaneous physical motion of pedestrians. This level consists of the general gait of pedestrians. Next is the tactical level where pedestrians who are at the decision making level such as choosing the optimal path from one activity location to another. On the strategical level, long term decisions such as the sequences in which the activities will be accomplished are made.

It is therefore viable to simulate crowds on the computer. Microscopic pedestrian models in the form of differential equations are essential to produce crowd simulations. A good model should be able to produce realistic displacement changes of the pedestrians i.e. the way the pedestrian walks toward the destination. The pedestrian should be able avoid another pedestrian and navigate through obstacles.

One of the most popular microscopic pedestrian models is the Social Force Model (SFM) proposed by Helbing and Molnar (1995). SFM is favored for computer simulations by many researchers since it produces realistic pedestrian movements. SimWalk, commercial software for microscopic pedestrian simulation, is a result of research simulations using SFM.

Another pedestrian model, which is somewhat similar to the SFM, is the Multi-Agents Pedestrian Model proposed by Teknomo (2002). Teknomo proposed this model to tackle some of the issues that yield certain unrealistic results of SFM. Teknomo has created his simulation program, Micro Pedsim, which is based on his multi-agents model.

These models consist of the forces exerted by the pedestrian (hence the term social force) that can influence the path of the affected pedestrian. These models also have parameters that can have their values changed to manipulate the walking path of the pedestrian. These parameters are used to calibrate their respective force components and are crucial to adjust the behaviour of the crowd to be as realistic as possible in a hypothetical environment.

A successful simulation is where the individual pedestrian's movement is realistic. The behaviour of the crowd produces useful macroscopic values such as pedestrian traffic flow, average walking speed and discomfort.

Pedestrian simulation is extremely important in areas where the safety of people could be jeopardized; in instances of extreme density of pedestrians. Instances such as emergencies and panic escape situations, improper planning of exit can lead to disaster, where people are "clogged up" in narrow hallways and exits and injured or killed. Figures 1.1 and 1.2 are graphical examples of emergencies that can lead to stampedes in narrow walkways.

Figure 1.1: Pedestrians squeezes through a door (Sheffield)

Figure 1.2: Pedestrians leaving through a door (Guatemala)
Pictures courtesy of Panic : A Qualitative Analysis (www.panics.org/)

1.2 Research Problems

Many researchers have modified the Social Force Model to produce a more realistic model where the modifications involve the repulsion force and general behaviour of pedestrians (Helbing et.al.,2000a; Helbing et.al, 2000b; Helbing et.al., 2001; Helbing et.al., 2002; Lakoba et.al., 2005; Seyfried et.al.,2006). There are several problems that have not been analyzed by other researchers regarding the SFM.

1- The basic SFM model does not involve the self-stopping mechanism which allows a gradual stop to pedestrians' movements as they approach each other. Parisi et. al. (2009) discussed this problem where the self-stopping mechanism was included into the SFM by defining a respect factor for pedestrians. This respect factor defines a respect area which is the comfortable walking zone of a pedestrian. However, this study uses a constant respect factor for pedestrians walking in any density of crowd. The effect of various densities towards the size of the respect area has not been dealt with.

2- As previous studies have only discussed the self-stopping mechanism in a uni-directional crowd, the efficiency of the mechanism has not been studied for a realistic crowd which is a multi-directional crowd.

3- According to the studies by LaPlante et. al.(2007) , pedestrians vary in age and gender. These factors have not been incorporated simultaneously into a single simulation to study the movements of pedestrians. The lack of these parameters restricts the simulations to a standard crowd with similar speed and repulsive forces.

1.3 Research Objectives

The main objective of this thesis is to improve the simulation of pedestrians' movement by incorporating suitable pedestrian characteristics into the Social Force Model. The specific objectives of this study are:

1) To identify various types of Microscopic Pedestrian Simulation Models.

2) To identify the modifications that has been done to improvise the Social Force Model

3) To modify the constant respect factor in the self-stopping mechanism in order to reproduce the fundamental diagram that is more suitable to the fundamental diagram by Weidmann

4) To incorporate the age factor into the SFM by modifying the respect factor.

5) To incorporate the self-stopping mechanism, age and gender factor in a multi-directional crowd to create a realistic simulation

1.4 Importance and Significance of the Research

The growth of the number of pedestrians has provided the need for proper and safe walking pathways. Without proper planning to create safe walking areas, congestion will be a major problem that would lead to many crowd disasters should an emergency occur. Thus, the simulation of pedestrians' movements has to be incorporated into designing the architecture plan of a building to ensure the building is designed to accommodate an adequate amount of pedestrians.

To develop a proper simulator, it is essential that the developers understand the pedestrians' behaviour and incorporate them into the mathematical model that simulates the movements of the pedestrians. By doing this, the simulation will be more realistic when compared with the real-life situations.

This research might help the architects to design safe buildings, such as shopping complexes, sport stadiums and ritual areas. The main focus of this research is on the behaviour of pedestrians in general, and the flow rate of pedestrian moving out of the room. The other part of the research also focuses on the design of a safer Tawaf area exit.

1.5 Research Scope

The main objective of this study is incorporating simple pedestrian behaviours into the microscopic pedestrian simulation model in normal situations. The environment of the study is aimed for the uni-directional movement as well as multi-directional movement. The other part of the research also aims on the designs of exits in Tawaf area based on a chosen simulator. Moreover, certain parameters which will be introduced in this study are estimated by performing repeated simulations.

1.6 Research Methodology

The microscopic pedestrian model focuses on simulation based on individual movements. Thus, understanding certain aspect of pedestrians' behaviours helps to develop a suitable simulator that conforms to the real-life crowd. This thesis focuses mainly on the tactical level of pedestrian behaviour where the decision to choose a route is made. Simple behaviours and characteristics of pedestrians are incorporated into the chosen microscopic pedestrian model which is the Social Force Model. The modification to incorporate these parameters is introduced into the preferred force in the model. The values of the parameters chosen are estimated from the curve-fitting method which helps to reproduce the fundamental diagram.

1.7 Organization of Thesis

This thesis consists of five chapters as explained below:

a) In chapter 1, the microscopic pedestrian study is introduced and the research problems are identified. This chapter also elaborates the objective and the significance of this research.

b) The subject matter in chapter 2 discusses the various kinds of Microscopic Pedestrian Simulation Models. This chapter also gives in detail the main model adapted in this thesis (the Social Force Model) as well as the modifications that have been done to the model by previous researchers.

c) In chapter 3, the behaviour of pedestrian who is described as the self-stopping mechanism is discussed. The problems regarding the available mechanism by using a constant respect factor is explained and a dynamic respect factor is introduced to the self-stopping mechanism in uni-directional pathway to produce a more realistic fundamental diagram.

The developed dynamic respect factor, different aspects of pedestrians' characteristics is provided. The dynamic respect factor is modified to suit elderly pedestrians who tend to walk slowly and prefer more space.

The walking behaviour of normal pedestrians is also incorporated into the self-stopping mechanism in the Social Force Model. The pedestrians walking in a crowd tend to respect each other in certain ways. This behaviour is analyzed and incorporated into the self-stopping mechanism. Simulations are done to obtain experimental result such as pedestrian flow and speed of walking to compare the results obtained with other studies and real-life situations. Visual simulations are also performed to inspect the walking patterns of pedestrians.

d) In chapter 4, a commercial simulator is chosen to study one of the ritual of Hajj, Tawaf. The study specifically deals with the design of the exits that would reduce the problem of congestion at the Tawaf area.

e) The final chapter is the conclusion where all the contribution of the thesis would be summarized.

CHAPTER 2

MICROSCOPIC PEDESTRIAN SIMULATION MODEL

2.1 Introduction

The growing number of pedestrians in the world today has created the need to design safer pedestrian walking facilities. Microscopic Pedestrian Simulation Model (MPSM) is a computer simulation model used to determine the pedestrians' movement (Hoogendoorn, 2001). In MPSM, pedestrians are treated as individual particles. The forces act on pedestrians as individuals and not as group particles. There are a few types of MPSM namely the Benefit Cost Cellular Model, the Cellular Automata Model, the Magnetic Force Model, the Multi-Agents Pedestrian Model (MAPM), and the Social Force Model (SFM).

2.2 Background of the Microscopic Pedestrian Simulation Model

2.2 (a) The Benefit Cost Cellular Model

The Benefit Cost Cellular Model was developed by Gipps and Marksjo (Hoogendoorn, 2001). In this model, an area is divided into 0.5 by 0.5 m^2 cells. Pedestrians will occupy one cell. Calculation will be done to find the net benefit in each cell around the pedestrian including the cell where the pedestrian is standing. A pedestrian will move to the cell that has the maximum net benefit. If the maximum net benefit is on the cell where the pedestrian is standing, then the pedestrian remains stationary.

The net benefit,

$$B = S - P(\sigma_i) \tag{2.1}$$

where, S is the repulsive effect of the score and $P(\sigma_i)$ is the gain score or motivation force for a pedestrian to move to his destination.

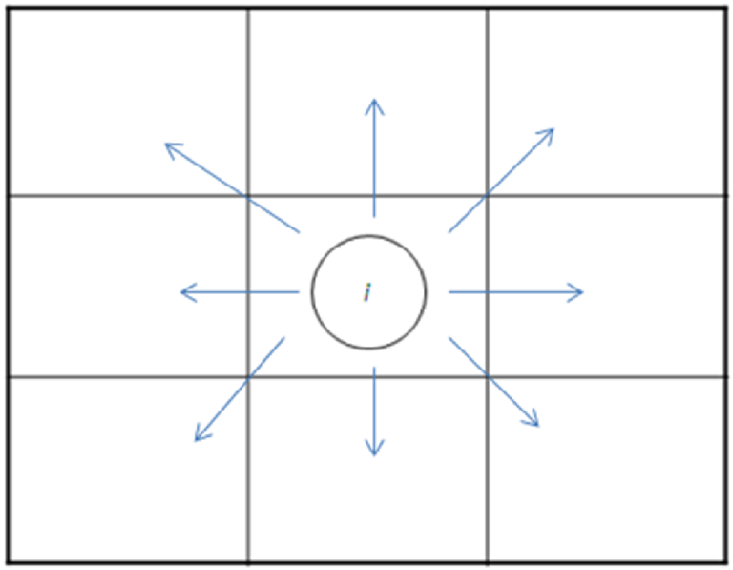

Figure 2.1: The representation of a pedestrian in a benefit cost cellular model

2.2 (b) The Cellular Automata Model

The Cellular Automata Model is similar to the Benefit Cost Cellular Model. This model is widely used in the simulation of traffic. However, this model is also used in simulating pedestrians.

2.2 (c) The Magnetic Force Model

The Magnetic Force Model was developed by Okazaki(1979), Matsushita and Okazaki (1981) and Okazaki and Yamamoto (1993). This model is based on the magnetic field where the pedestrian is assumed to have a positive pole while the destination is the negative pole. Obstacles such as walls have positive pole too. Thus, a pedestrian is attracted to his destination while repelling other obstacles. Calculation for this model is based on the Coulomb's Law to calculate the force from a pole and acceleration force to avoid collision with other pedestrians or obstacles.

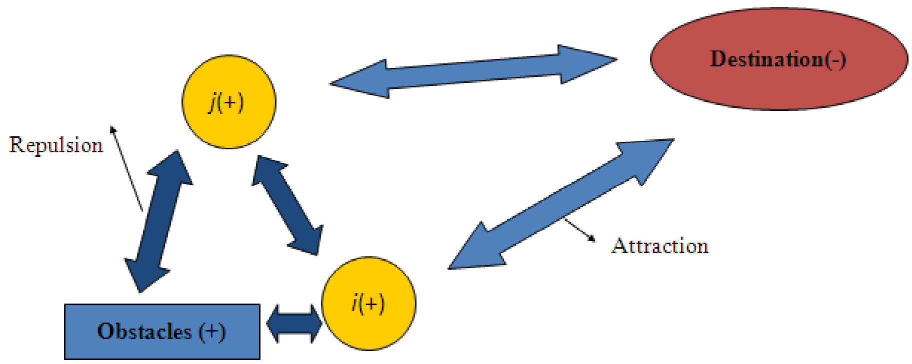

Figure 2.2: The forces that acts on pedestrians in the magnetic force model

2.2(d) The Multi-Agents Pedestrian Model

In the Multi-Agents Pedestrian Model (MAPM) that was developed by Teknomo (2002), individual pedestrians are seen to have certain behaviours. They tend to avoid other passengers as they prefer to move away and overtake each other to maintain their speed. Each pedestrian agent will be developed to have his/ her own unique characteristics and dynamic emotional level. Collectively, the pedestrians will tend to walk together and able to self-organize into lane-formations.

In building the MAPM, the pedestrians are modeled as autonomous agents with non-linear system Differential Equation. Here, the building of the model is based on a set of non-linear dynamical system that represents positive and negative feedback loop. Positive effects promote the changes in the system while the negative effects may cause fluctuation in the system. This model consists of driving velocity and two types of repulsive forces which are the overtaking force and avoiding collision force.

The driving velocity which directs a pedestrian to the destination is defined as

$$\mathbf{v}_d^i(t) = \frac{\mu_{\max}}{\alpha}\left(\mathbf{e}_i^0(t)\right) \tag{2.2}$$

where

$\mathbf{e}_i^0(t) = \frac{\mathbf{x}_i^0(t) - \mathbf{x}_i(t)}{\left\|\mathbf{x}_i^0(t) - \mathbf{x}_i(t)\right\|}$ is the direction of motion of the pedestrian

$\mathbf{x}_i^0(t)$ is the destination point

$\mathbf{x}_i(t)$ is the current location of the pedestrian

α is dimensionless positive parameter to generalize the model

$\mu_{\max}$ is the maximum walking speed of a pedestrian.

The term

$$\mathbf{v}_{ov}^n(t) = \mu_{\max}\frac{(2r - \mathbf{y}(t))}{\chi d(t)} \tag{2.3}$$

denotes the first repulsive intended velocity that models the overtaking and meeting behavior of pedestrians where

$d(t) = \left\|\mathbf{x}_j(t) - \mathbf{x}_i(t)\right\|$ represents the distance between pedestrians.

$\mathbf{y}(t)$ and r represents the intrusion of the closest pedestrian in sight and influence radius respectively (Teknomo, 2002).

$\mu_{\max}$ is the maximum walking speed of a pedestrian within a path.

χ is a nondimensional constant used as a constant calibration and validation of the model.

$\frac{\mu_{\max}}{\chi d(t)}$ is known as the smoothing factor to maintain the walking speed of the pedestrian.

The overtaking force, f_{ov} that acts on pedestrian *i* is shown as below

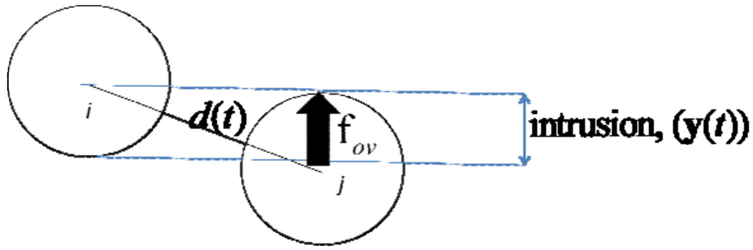

Figure 2.3: The overtaking force that acts on a pedestrian *i*

$\mathbf{v}_{ov}^{n}(t)$ however only works when another pedestrian is within the sight distance of the acting pedestrian and the nearest pedestrian will be considered if there are many pedestrians present. Only one other pedestrian is considered in determining the pedestrian's first repulsive intended velocity. If many pedestrians are considered, the acting pedestrian's movement becomes erratic. This model also does not guarantee that the pedestrian will collide with another pedestrian provided that there is not enough space to overtake.

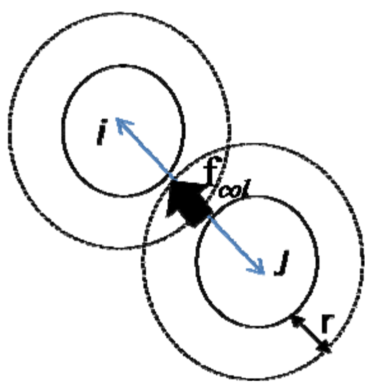

Figure 2.4: The avoiding collision force that acts on a pedestrian *i*

The term

$$\mathbf{v}_{col}^{i} = \frac{\mu_{\max}}{\beta} \sum_{j} \left(\frac{2r}{\left\| \mathbf{x}_{j}(t) - \mathbf{x}_{i}(t) \right\|} - 1 \right) \left(\mathbf{e}_{j}^{i}(t) \right) \tag{2.4}$$

denotes the second repulsive intended velocity to avoid collision with another pedestrian.

$\mathbf{e}^i_j(t) = \dfrac{\mathbf{x}_j(t) - \mathbf{x}_i(t)}{\left\|\mathbf{x}_j(t) - \mathbf{x}_i(t)\right\|}$ represents the unit direction of pedestrian *j* from *i*.

β is a parameter used as constant calibration and validation of the model.

This repulsive velocity is generated when both pedestrians' influence radii r overlap (the pedestrians are close to each other). Intended velocity increases nonlinearly with the distance between the pedestrians. In this model, an acting pedestrian *i* is able to overtake another pedestrian, slow down when another pedestrian is close by and can avoid physical contact with another pedestrian in order to reach a certain destination as the radius is taken into account. This model was calibrated and validated using real world data. Although the influence radius manage to overcome collision among pedestrians it is not realistic to include the radius in the repulsive force as in real world situation pedestrian do not have an invisible force around him that stops him from colliding with another pedestrian.

Since $\mathbf{v}(t) = \dfrac{d\mathbf{x}_i(t)}{dt}$ and $\mathbf{a}(t) = \dfrac{d\mathbf{v}(t)}{dt} = \dfrac{d^2\mathbf{x}_i(t)}{dt^2}$ where $\mathbf{x}_i(t)$ represents the current location of a pedestrian *i*,

$$m\frac{d^2\mathbf{x}_i(t)}{dt^2} + \frac{d\mathbf{x}_i(t)}{dt} =$$
$$\mu_{\max}\left\{\left(\frac{\mathbf{e}_i(t)}{\alpha}\right) + \frac{(2r - \mathbf{y}(t))}{\chi d(t)} + \sum_j\left(\frac{2r}{\left\|\mathbf{x}_j(t) - \mathbf{x}_i(t)\right\|} - 1\right)\left(\mathbf{e}^i_j(t)\right)\right\} \tag{2.5}$$

Equation 2.5 is a non-linear second order differential equation that can be solved using numerical method. This equation of pedestrian's position is dependent on the position, speed and acceleration of a pedestrian.

2.2(e) The Social Force Model

The Social Force Model (SFM) was developed by Helbing and Molnar (1995). Initially, this model was considered for the case of normal, non-panicking behavior. Many modifications have been done to improve the model (Helbing et.al.,2000a; Helbing et.al, 2000b; Helbing et.al., 2001; Helbing et.al., 2002; Lakoba et.al., 2005; Seyfried et.al.,2006;). The modified SFM which is called the Helbing-Molnar-Farkas-Vicsek (HMFV) was developed by Helbing et.al.(2000a).

The equations of the model are based on second order differential equations which can be solved using standard numerical methods. In SFM, the pedestrians act as individuals and are affected by external and internal forces. Internal force is the force within pedestrian that motivates him to walk towards his direction. External forces are forces from other pedestrians and obstacles that affect the pedestrian's walking path.

The Social Force is defined as:

$$\mathrm{f}_i(t) = m_i \frac{\mathrm{dv}_i(t)}{\mathrm{d}t} = m_i \, \mathrm{a}_i(t)$$

$$= \mathrm{f}_i^d(t) + \sum_{j\neq 1} \mathrm{f}_{ij}^{sr}(t) + \sum_{j\neq 1} \mathrm{f}_{ij}^{g}(t) + \sum_{j\neq 1} \mathrm{f}_{iw}^{sr}(t) + \sum_{w} \mathrm{f}_{iw}^{g}(t) + \sum_{a} \mathrm{f}_{ia}(t) + \sum_{g} \mathrm{f}_{ig}(t) + \xi_i(t) \tag{2.6}$$

where $\mathrm{f}_i(t)$ is the sum of all the forces acting on the pedestrians

$\mathrm{f}_i^d(t)$ is the driving force that is exerted within the pedestrian as a motivation for him to move towards his destination.

$\mathrm{f}_{ij}^{sr}(t)$ is the social repulsion force exerted from pedestrian *j* to pedestrian *i* who repulses the pedestrian *j* from pedestrian *i* so that no collision occurs between both pedestrians.

$\sum_{j\neq 1} \mathrm{f}_{ij}^{g}(t)$ is the granular force that is exerted in a case where contact occurs between the two pedestrians. This force includes a friction force which occurs in the tangential direction as a sliding force between two pedestrians and a pushing force which occurs to the normal of a pedestrian to push the another pedestrian away from him in the case of contact between two pedestrians.

$\sum_{j\neq 1} \mathrm{f}_{iw}^{sr}(t)$ and $\sum_{w} \mathrm{f}_{iw}^{g}(t)$ represents the social repulsion force and granular respectively; the force between a pedestrian and other obstacles

$\mathrm{f}_{ia}(t)$ and $\mathrm{f}_{ig}(t)$ represent the attraction force; the force that attracts pedestrians to form a crowd in a particular area.

Without loss of generality, attraction forces can be omitted from the equation.

This results in the reduced SFM as follows:

$$\mathrm{f}_i(t) = \mathrm{f}_i^{d}(t) + \sum_{j\neq 1} \mathrm{f}_{ij}^{sr}(t) + \sum_{j\neq 1} \mathrm{f}_{ij}^{g}(t) + \sum_{j\neq 1} \mathrm{f}_{iw}^{sr}(t) + \sum_{w} \mathrm{f}_{iw}^{g}(t)$$
$$= m_i \frac{v_i^d \mathbf{e}_i(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j=1, j\neq i}^{N_p} A_i \exp\left(\frac{\psi_{ij}}{B_i}\right)\mathbf{n}_{ij}(t) + \sum_{j=1, j\neq i}^{N_p} \left(kg(\psi_{ij})\mathbf{n}_{ij}(t) + \kappa g(\psi_{ij})\mathbf{t}_{ij}(t)\right) + \xi_i(t) \qquad (2.7)$$

where,

v_i^d is the desired speed of pedestrian i

$\mathbf{e}_i(t) = \left(\dfrac{\mathbf{x}_i^o - \mathbf{x}_i(t)}{\left\|\mathbf{x}_i^o - \mathbf{x}_i(t)\right\|}\right)$ is the unit vector directing to the desired destination.

τ_i is the relaxation time (time needed to accelerate from current speed to desired speed.)

$\mathbf{v}_i(t)$ is the velocity of pedestrian at time ,t

A_i is the interaction intensity which is the impact of external forces on the pedestrian.

B_i is interaction distance, which is the impact of distance between pedestrians on potential exerted by pedestrian *i* to pedestrian *j*.

$\psi_{ij}(t) = r_{ij} - d_{ij}(t)$; r_{ij} is the sum of radius of pedestrian *i* and *j*, $d_{ij}(t)$ is the distance between pedestrians' centre of mass.

k and κ represents the normal and tangential elastic parameters respectively.

$\mathbf{n}_{ij}(t) = \dfrac{\mathbf{x}_j(t) - \mathbf{x}_i(t)}{\left\| \mathbf{x}_j(t) - \mathbf{x}_i(t) \right\|}$ is the normalized unit vector pointing from *j* to *i*.

$\mathbf{t}_{ij}(t)$ is the tangential unit vector orthogonal to $\mathbf{n}_{ij}(t)$ and represents the direction of the friction force.

The velocity at time $t + \Delta T$ for the reduced SFM is defined as

$$\mathrm{v}_i(t + \Delta T) = \mathbf{v}_i(t) + \mathbf{a}_i(t)\Delta T \qquad (2.8)$$

and the final position of pedestrian *i* is

$$\mathrm{r}_i(t + \Delta T) = \mathrm{r}_i(t) + \mathrm{v}_i(t)\Delta T \qquad (2.9)$$

The repulsion forces that acts on pedestrian *i* is represented in the figure below.

Figure 2.5: Representation of the repulsion forces that acts on a pedestrian *i*

To date, there are many modifications done to improve the Social Force Model. Some of the modifications would be discussed in Section 2.4 below.

2.3 Advantages and disadvantages of the Microscopic Pedestrian Simulation Model

Table 2.1: The comparison between various kinds of microscopic pedestrian simulation models (based on Teknomo(2002)) .

	Model	**Advantages**	**Disadvantages**
1	Benefit Cost Cellular Model	Simple and fast	Arbitrary scoring of the cells and pedestrian makes the model difficult to be calibrated in the real world
2	Cellular Automata Model	Simple	Heuristic approach of updating rules is undesirable
3	Magnetic Force Model	Has force to avoid collision	The validation can only be done by visual inspection
4	Queuing Network Model	Evacuation concept	Behavior not clearly shown, collisions are possible

Table 2.1 shows the comparison between various kinds of microscopic pedestrian simulation models. The greatest advantage of the SFM which distinguishes it from other MPSMs is its ability to represent the interactions among the pedestrians in a more realistic way. The SFM has introduced all aspects of pedestrian flow perfectly (Seyfried et. al., 2006). For this distinction, the SFM has been considered by a majority of researchers (Weidmann, 1993; Hoogendoorn et.al., 2001; Kretz et. al., 2006; Seyfried et.al., 2006) as the representative model for the environmental phenomena which are caused by the interaction between pedestrians such as congestion.

2.4 Modifications to the Social Force Model

2.4.1 The LKF model by Lakoba, Kaup and Finkelstein

Lakoba et. al (2005) proposed some modifications to the model to obtain more realistic behaviour for a certain number of pedestrians. The modifications include introducing an overlap-eliminating algorithm to eliminate the occurrence of overlapping between pedestrian. The modifications also include some realistic parameters to the model. They modified the SFM with some new effects which includes density effects and memory effects. These modifications allow the model to react in the Tactical and Strategical level.

2.4.2 Reproducing the Fundamental Diagram in One-Dimensional System

Seyfried et. al. discussed the fundamental diagram in 1-D system in (Seyfried et.al, 2005). There are a few ways to quantify the capacity of pedestrian facilities which are relationship between density, ρ , and velocity, v and relationship between density, ρ and flow, *f*. The flow of the pedestrian is defined as the number of pedestrians crossing a particular area during a specified period of time.

Fundamental Diagram is defined as the relationship between velocity and density. The Fundamental diagram differs for various situations such as ramps and bottleneck and also differs between uni and bidirectional stream(Seyfried et.al., 2006; 2007).

2.4.2(a)Fundamental Diagram for the Simplest System.

The simplest system in the fundamental diagram by Weidmann (1993) as explained by Seyfried(2005) is a unidirectional stream in a plane without bottleneck in a non-pushy and non-panic situation. As density increases, velocity decreases.

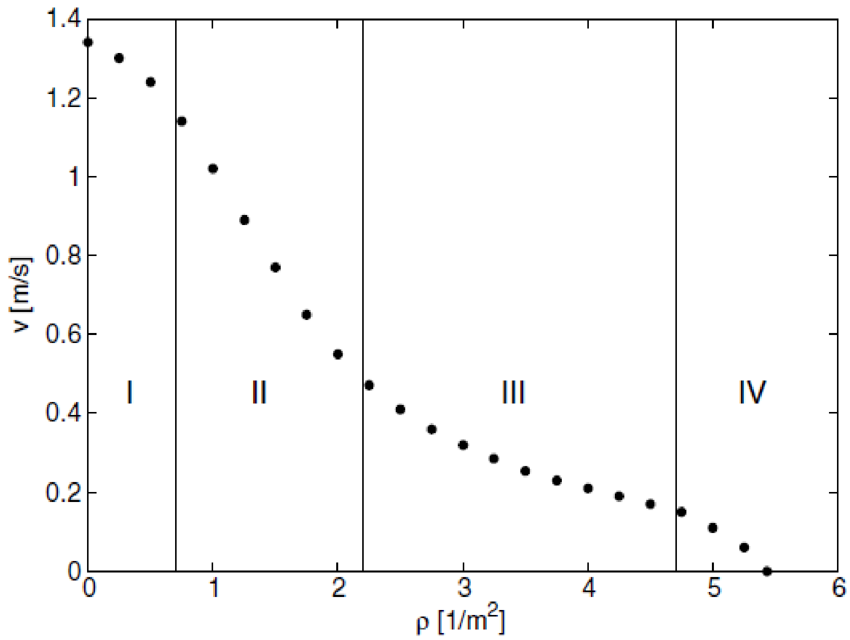

Figure 2.6: The empirical relation between density and velocity according to Weidmann(1993) – as explained in Seyfried (2005)

Domain (I) - $\rho < 0.7$

In a low-density situation, the velocity decreases slowly. In this domain, most of velocity is individual free velocity of pedestrian. Pedestrians still can keep their desired speed. The decrease was caused by passing manoeuvres.

Domain(II)- $0.7 \leq \rho < 2.3$

In this domain, the decrease of velocity is almost linear with increase of density. The possibility of the pedestrian to choose his desired velocity is restricted, due to reduction of space. However, the contact among pedestrians is still less in this domain.

Domain(III)- $2.3 \leq \rho < 4.7$

The linear decrease of the velocity ends. The contact among pedestrians becomes clearer causing the internal friction to increase.

Domain (IV)- $\rho \geq 4.7$

The velocity decreases rapidly, causing the space available for pedestrians, movement to be totally restricted. In this domain, the internal factor determines the velocity of the pedestrian; where pedestrians are not allowed to move at their desired speed.

In the paper by Seyfried (2005), some real-life experiments for one-dimensional system were constructed and the results of the experiment were compared to the results produced by Weidmann (1993).The experiments were done to test if microscopic model can produce empirical relation between velocity and density in a simple system. The results obtained in this experiment agrees with the literature data of Weidmann(1993). The results obtained are shown in the diagram below.

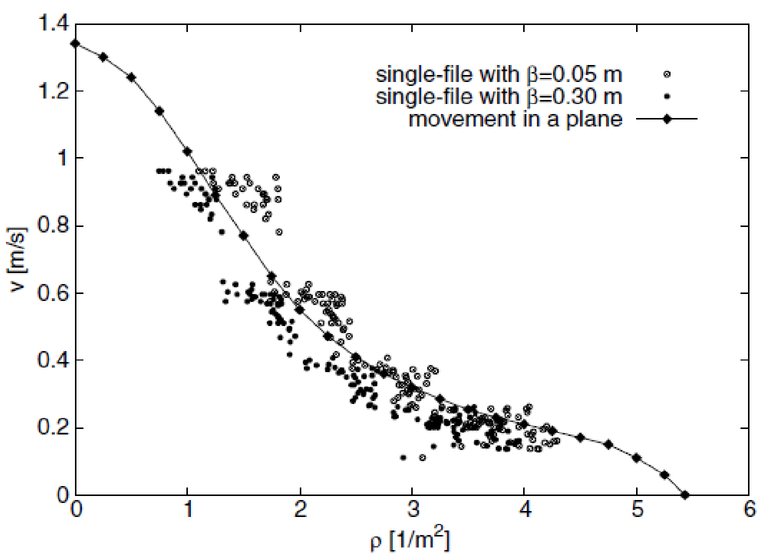

Figure 2.7: The comparison of the velocity–density relation for the one-dimensional movement with the movement in a plane according to Weidmann (1993)- Diagram obtained from Seyfried et.al.(2005)

2.4.2(a)Modifications by Seyfried et.al.

The modifications by Seyfried et. al.(2006) were based on Helbing et.al. (2000b). However Seyfried et.al (2006) introduced a one-dimensional social force model. In this model, the driving force is defined to be the same as the SFM. However the repulsion force has some difference where the force is defined from Helbing et.al. (2000b)

$$\mathrm{f}_i^r = \sum_{j\neq i} -\nabla A_i \left(\frac{1}{\left\| \mathbf{x}_i - \mathbf{x}_j \right\| - d_i} \right)^{B_i} \tag{2.10}$$

where the hardcore $d_i = a + bv_i$ with $a = 0.36m$ and $b = 1.06s$ (Seyfried et.al., 2005) is the required length by pedestrian i or the size of pedestrian *i* acting with remote force on other pedestrians as explained by Helbing et.al. (2000b). The required length increases as velocity increases (Seyfried et.al., 2005). Seyfried et.al.(2006) investigated the impact of remote action on repulsive force. For simplicity, the authors set the desired velocity, $v_d(\mathrm{t})\mathbf{e}_i(t)>0$ and $m_i = 1$. Also, $\mathbf{x}_j - \mathbf{x}_i>0$ which means the position of pedestrian *j* is always in front of pedestrian *i*.

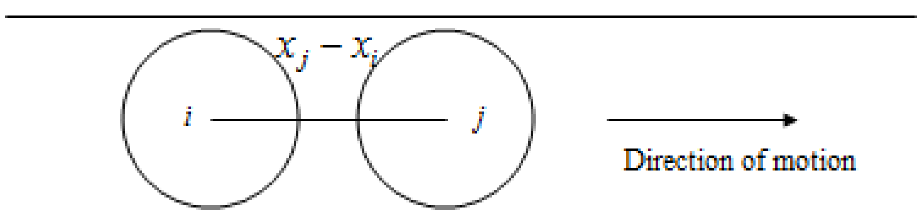

Figure 2.8: The position of pedestrian *j* has to be in front of pedestrian *i* and the required length d_i

Hard bodies without remote action (Seyfried et.al, 2006)

$$\mathbf{f}_i(t) = \begin{cases} \dfrac{v_d(\mathrm{t})\mathbf{e}_i(t) - \mathbf{v}_i(t)}{\tau_i} & : \ \mathbf{x}_j(t) - \mathbf{x}_i(t) > d_i(t) \\ -\alpha(t)\mathbf{v}_i(t) & : \ \mathbf{x}_j(t) - \mathbf{x}_i(t) \le d_i(t) \end{cases} \tag{2.11}$$

From the term above, as long as pedestrian *j* is not within the required length in the direction of $\mathbf{e}_i$, the pedestrian walks with his driving force. When the position of pedestrian *j* falls within the required length, the pedestrian i immediately stop ($\mathbf{v}_i(t) = 0$)

Hard bodies with remote action (Seyfried et.al, 2006)

$$\mathrm{f}_i(t) = \begin{cases} \mathrm{g}_i(t) & : \ v_i(t) > 0 \\ \max(0, \mathrm{g}_i(t)) & : \ v_i(t) \le 0 \end{cases}$$

with

$$\mathrm{g}_i(t) = \frac{v_d(\mathrm{t})\mathbf{e}_i(t) - v_i(t)}{\tau_i} - A_i \left(\frac{1}{\left\| \mathbf{x}_i - \mathbf{x}_j \right\| - d_i} \right)^{B_i} \tag{2.12}$$

The range of repulsive force is a function of the velocity v_i with respect to the required length, d_i. The equation above guarantees that the pedestrian *i* will stop if the force leads to negative velocity. By the proper choice of parameters of A_i, B_i and small time steps, the condition gets active during relaxation time.

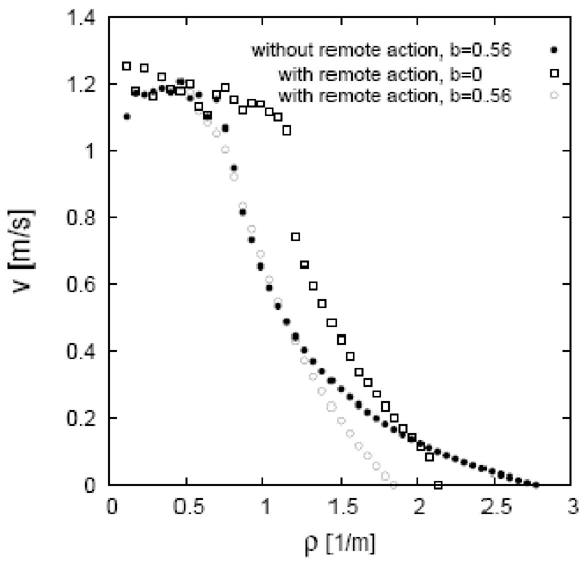

Figure 2.9: The velocity-density relation for one-dimensional movement

Seyfried et.al., (2006) compared the modification done to the result without the effect of remote action to the hard core bodies with remote action from Helbing et.al.(2000b). From this investigation, it was found that with proper adjustment to the model parameter b , the required length for moving with a particular velocity is a function of the current velocity. When the required length is independent of the velocity (i.e b =0), then the distinct density wave occurs where a velocity gap is observed in the fundamental diagram. An optimal value of $b = 0.56s$ is set to obtain a velocity-density relation agrees with the fundamental diagram in Weidmann (1993).

However, in Seyfried et.al. (2005) the optimal value is determined as $b = 1.06s$ with respect to the same fundamental diagram. This inconsistency is explained by the 'short-sightedness' of the model (Seyfried et.al., 2006) where in actual world, the speed of a pedestrian is not only affected by the pedestrian in front but also to others around him. This study refers only to the simplest system in