Agent Based Modeling and Simulation of Pedestrian Crowds

In Panic Situations

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ABSTRACT

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The increasing occurrence of panic stampedes during mass events has motivated studying the impact of panic on crowd dynamics and the simulation of pedestrian flows in panic situations. The lack of understanding of panic stampedes still causes hundreds of fatalities each year, not to mention the scarce methodical studies of panic behavior capable of envisaging such crowd dynamics. Under those circumstances, there are thousands of fatalities and twice that many of injuries every year caused by crowd stampede worldwide, despite the tremendous efforts of crowd control and massive numbers of safekeeping forces. Pedestrian crowd dynamics are generally predictable in high-density crowds where pedestrians cannot move freely and thus gives rise to self-propelling interactions between pedestrians. Although every pedestrian has personal preferences, the motion dynamics can be modeled as a social force in such crowds. These forces are representations of internal preferences and objectives to perform certain actions or movements. The corresponding forces can be controlled for each individual to represent a different variety of behaviors that can be associated with panic situations such as escaping danger, clustering, and pushing. In this thesis, we use an agent-based model of pedestrian behavior in panic situations to predict the collective human behavior in such crowd dynamics. The proposed simulations suggest a practical way to alleviate fatalities
and minimize the evacuation time in panic situations. Moreover, we introduce contagious panic and pushing behavior, resulting in a more realistic crowd dynamics model. The proposed methodology describes the intensity and spread of panic for each individual as a function of distances between pedestrians.
ACKNOWLEDGEMENTS

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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>AI- models</td>
<td>Intelligence Based Models</td>
</tr>
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<td>PI</td>
<td>Proportional Integral Controller</td>
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LIST OF SYMBOLS

\( v \) Velocity
\( x \) Position
\( t \) Time
\( a \) Acceleration
\( m \) Mass
\( V_i^0 \) Desired velocity
\( V_i \) Actual velocity
\( \tau_i \) Acceleration time
\( f_{ij} \) Interaction forces between agent \( i \) and \( j \)
\( r_i \) Shoulder width
\( r_{ij} \) Sum of shoulder width for agent \( i \) and \( j \)
\( d_{ij} \) Distance separating the center of the pedestrian's \( i \) and \( j \)
\( K \) & \( k \) Large constants determine the obstruction effects in cases of physical interactions
\( A_i \) Large constants to reproduce the distance kept at normal desired velocities
\( B_i \) Small constants to reproduce the distance kept at normal desired velocities
\( \mathbf{n}_{ij} \) Normalized vector between agent \( i \) and \( j \)
\( t_{ij} \) Represent the tangential direction between agent \( i \) and \( j \)
\( \Delta v_{ji}^t \) The tangential velocity difference between agent \( i \) and \( j \)
\( p_i \) Time-dependent parameter
\( V_{i,\text{max}} \) The maximum desired velocity
\( V_{ave i} \) The average speed in the desired direction of motion
\( u_i \) Output signal for PI controller
\( e_i \) Error signal for PI controller
\( k_{pi} \) Proportional constants for PI controller
\( k_{iI} \) Integral constants for PI controller
\( P_i \) Panic parameter
\( f(P_i) \) Function with exponential growth mapping the panic parameter to value ranging from zero to one
\( \mathbf{v}_i^0(t) \) Normal vector, represent agent-wanted direction
\( r_{pi} \) Surrounding proxemics area radius
\( r_{vi} \) Field of vision radius
\( r_{si} \) Surrounding area for panic spreading radius
\( c_i \) Constant weight the environment affect versus the social contagious influence
\( z_i \) Constant represents personal confidence
\(w_j\) Constant used to weight the panic influence caused by the agents in the surrounding area of agent \(i\)

\(Q_i\) Constant representing sources of fear in the surrounding environment

\(S_{a_i}\) Constant saturation level
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Chapter 1

Introduction

Dense crowds happen in many events including concerts, rallies, stadiums, political speeches, and religious sites. With such large density, there is high potential for critical situations and crowd stampedes. Although authorities work on guaranteeing safety in such mass events, critical situations keep recurring. Panic behavior has a significant impact on crowd dynamics, as a specific form of collective behavior emerging in situations of a great degree of complexity. Unfortunately, there are a scarce empirical resources, which inhibits better understanding of such complicated behavior and its influence on crowd dynamics.

Herding behavior is a cause for panic contagion, in which individuals transfer their attitudes to others pedestrians. This leads to a spread of panic among other pedestrians in an uncontrollable manner. In other words, panicking individuals tend to cause social contagion, leading to jamming and life-threatening overcrowding. Moreover, biological studies indicate the role of hormones in the change of human reactions, decision-making, and behaviors in situations of danger and horror [16].

For this reason, panic works as an essential factor in influencing crowd behavior. Motivated by these circumstances, we develop an agent-based model that uses a panic parameter that can be contagious among pedestrians to influence their behaviors. Furthermore, we introduce pushing actions that cause body collisions and stampede. The
model can simulate the motion of pedestrians and reproduce observed features of crowd
dynamics such as lane formation, oscillations at bottlenecks, dynamics at intersections,
and transition to uncoordinated movement due to clogging.

1.1 Motivation

With a successive increase of mass events, ensuring pedestrian safety has become a great
challenge to governments in many countries. The open source for geographic information
system (GIS) Esri shows crowds disaster date around the world classify according to
causes. See table (1) and Figure (1). Entertainment and religious events according to Esri
have the highest number of crowd disaster among the categories.

![Figure 1 World crowd disaster by cause](http://http://yorku.maps.arcgis.com/apps/webappviewer/index.html?id=e7c52856187642e19bd227865393432c)
Table 1: List of some stampedes in the last centuries [17].

<table>
<thead>
<tr>
<th>Estimated Deaths</th>
<th>Date</th>
<th>Name</th>
<th>Nat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>278</td>
<td>December 5, 1876</td>
<td>Brooklyn Theatre fire</td>
<td>USA</td>
</tr>
<tr>
<td>1389</td>
<td>May 18, 1896</td>
<td>Khodynka Tragedy</td>
<td>Russian Empire (Moscow)</td>
</tr>
<tr>
<td>602</td>
<td>December 30, 1903</td>
<td>Iroquois Theatre Fire</td>
<td>USA-Chicago</td>
</tr>
<tr>
<td>1,426</td>
<td>July 2, 1990</td>
<td>Mecca tunnel tragedy</td>
<td>Saudi Arabia-Mina, Mecca</td>
</tr>
<tr>
<td>270</td>
<td>May 23, 1994</td>
<td>unnamed</td>
<td>Saudi Arabia-Jamarat Bridge, Mecca</td>
</tr>
<tr>
<td>53</td>
<td>May 30, 1999</td>
<td>Nyamiha disaster</td>
<td>Belarus</td>
</tr>
<tr>
<td>35</td>
<td>March 5, 2001</td>
<td>unnamed</td>
<td>Saudi Arabia-Mina, Mecca</td>
</tr>
<tr>
<td>100</td>
<td>February 20, 2003</td>
<td>Station nightclub</td>
<td>USA, Rhode Island</td>
</tr>
<tr>
<td>291</td>
<td>January 2005</td>
<td>unnamed</td>
<td>Maharashtra, India</td>
</tr>
<tr>
<td>953</td>
<td>August 31, 2005</td>
<td>a Baghdad bridge stampede</td>
<td>Iraq</td>
</tr>
<tr>
<td>115</td>
<td>October 13, 2013</td>
<td>Ratangarh Mata Temple disaster</td>
<td>India-Datia</td>
</tr>
<tr>
<td>2,262</td>
<td>September 24, 2015</td>
<td>unnamed</td>
<td>Saudi Arabia-Mina, Mecca</td>
</tr>
</tbody>
</table>

The Hajj is an annual pilgrimage to Mecca, Kingdom of Saudi Arabia, prescribed as a duty for Muslims to undertake at least once in their lifetime if they can afford to do so physically and financially. In the past ten years, Mecca hosted 24.8 million pilgrims from all across the world. Over two million pilgrims come to Mecca each year, creating a great challenge to the government of Saudi Arabia to organize such massive gathering event. Moreover, the extraordinary growth of pilgrim numbers in the last years was due to the advancement in transportation means and excellent resolution by the Saudi government to expand infrastructure facilities in the pilgrimage facilities [18].
After the unfortunate stampede incident in July 1990 causing 1426 fatalities, the Saudi government has invested more than $120 billion (SR567 billion) over the years to improve pilgrimage sites and infrastructure development for Hajj and crowd safety control [18]. However, on 24 September 2015, an unfortunate incident occurred in Mina at the junction of streets 204 and 223 leading to Jamara Bridge. In that unfortunate accident, 769 people reported killed, 934 others injured despite the crowd control plan and huge numbers of safekeeping forces [17]. With an ambitious plan, Saudi Arabia hopes to increase the number of pilgrims in the upcoming years to nearly 3 million pilgrims each year, allowing larger number of Muslims to perform the Hajj.

The need for better understanding of crowd dynamics is essential for implementing this ambitious plan safely. In particular, there is a need for a simulation module that considers the psychological condition of crowds.

1.2 Objectives and Contributions

The global scale of this problem and the great demand for a solution motivates this thesis. The proposed agent-based model for pedestrian dynamics is based on existing approaches using a social force model. The main contribution of our model is its ability to combine both the physical condition and mental state of pedestrians into a simple and very practical and applicable model.
The proposed model takes into consideration the following objectives:

- **Psychology**: Modeling the psychological state of the crowd.
- **Fidelity**: Predicting the motion of pedestrians realistically while maintaining tractability.
- **Variety**: Representing various pedestrian characteristics. Every individual pedestrian has somatic properties such as weight, shoulders width, and psychological characteristics, such as lack of patience and the response to the sources of danger.

In this work, we use an agent-based model to simulate crowd dynamics. In particular, we introduce contagious panic and pushing behaviors, resulting in a more realistic model. Furthermore, our model helps to anticipate cases of panic stampede during mass events. In doing so, it also provides a better understanding of the psychological impact on the crowd dynamic. It improves on the old model that represent pedestrians as a fearless particle that does not take into the account the psychological state of the crowd.
Chapter 2

Background

The empirical study of pedestrian crowds started four decades ago. Direct observation, photographs, and time-lapse were popular methods of data gathering back then, where the goal was to design pedestrian facilities and elementary crowd control plans. Nevertheless, these methods were unable to predict pedestrian movement especially in critical conditions such as evacuation. Therefore, many different models have since been proposed. An overview of the most popular models for crowd simulation is presented next.

2.1 Related work

Many different models have been proposed for crowd dynamics. For instance, transition matrix models [19], queueing models [20], and stochastic models [21]. These models work in a similar way. They use expected arrival times of pedestrians and the expected times of service such as boarding, buying a ticket, and the time to get the food at the restaurant, in addition to finite capacity arrivals, or limited resources.

A study by Henderson suggests that crowd dynamics are similar to gasses and fluids dynamics [22]. The difference in interactions between gasses or fluids and interactions pedestrians question the accuracy of this model. Although, gas-kinetic or fluid-dynamic
theory can be modified to behave similarly to pedestrian dynamics, they still cannot provide individual pedestrian motions.

The interests of the research community has shifted toward agent-based or microsimulation modeling of pedestrian crowds such as cellular automata models for crowd dynamics [23] and artificial intelligence-based models (AI- models) [24].

Microsimulation models uniquely allow one to consider the uncoordinated movement of pedestrians and self-organized pedestrian dynamics, making them consistent with observations. With this in mind, a social force model was been developed. These socio-psychological forces represent behavioral preferences or internal desires and objectives to perform certain actions or movements, as opposed to be physical forces such as acceleration or friction between pedestrians.

2.1.1 Dirk Helbing social force model

The Helbing model uses a blend of physical forces and socio-psychological to simulate crowd dynamics [1], with the goal of investigating the features of escape panic. According to Helbing, in panic stations pedestrians have tendencies to act noticeably quicker than normal, and start pushing each other. The dynamics through a bottleneck converts to uncoordinated movements, and at the exits, arching and clogging are observed, and jams build up.
The Helbing model introduces acceleration equation:

$$m_i \frac{dV_i(t)}{dt} = m_i \frac{V_i^0(t) - V_i(t)}{\tau_i} + \sum_{j \neq i} f_{ij} + \sum_w f_{iw} \quad (1)$$

Each of $N$ pedestrians, $i$, has a desired speed and direction vector $V_i^0(t)$ and actual velocity vector $V_i(t)$. A pedestrian tends to adapt the actual speed and direction with a definite individual time, $\tau_i$. Characteristic mass $m_i$ and shoulders width $2r_i$ are pedestrian parameters. Moreover, pedestrian, $i$, tries to keep a separating distance from other pedestrian's, $j$, and walls, $w$. This behavior can be expressed by using the interaction forces $f_{ij}$ and $f_{iw}$, respectively.

The repulsive interaction forces $f_{ij}$ are described as:

$$f_{ij} = \left\{ A_i \exp \left[ \frac{r_{ij} - d_{ij}}{B_i} \right] + K g(r_{ij} - d_{ij}) \right\} n_{ij} + k g(r_{ij} - d_{ij}) \Delta v_i^t t_{ij} \quad (2)$$

The corresponding repulsive forces with the wall are described as:

$$f_{iw} = \left\{ A_i \exp \left[ \frac{r_i - d_{iw}}{B_i} \right] + K g(r_i - d_{iw}) \right\} n_{iw} - k g(r_i - d_{iw}) (v_i \cdot t_{iw}) t_{iw} \quad (3)$$

Here $V_i(t) = \frac{dx_i}{dt}$ and $d_{ij} = \|x_i - x_j\|$, represent the distance separating the center of the pedestrians $i$ & $j$. The normalized vector $n_{ij} = (n_{ij}^1, n_{ij}^2)$ is defined as $(x_i - x_j)/d_{ij}$.

If the distance $d_{ij}$ is less than $r_{ij} = r_i + r_j$, where $2r_i$ is the shoulders width and $r_i$ is the radius of pedestrian $i$, then, pedestrians $i$ & $j$ touch each other. The function $g(y)$ is equal to the argument $y$ if $i$ & $j$ touch each other ($d_{ij} < r_{ij}$) and zero otherwise. Here
\( t_{ij} = (-n_{ij}^2, n_{ij}^1) \) represent the tangential direction and \( \Delta v_{ji}^t = (v_j - v_i) \cdot t_{ij} \), the tangential velocity difference. Constants \( K, k \) and \( A_i \) are large, and \( B_i \) is small constant.

The model uses \( K g(r_{ij} - d_{ij}) \) to represent body force, which corresponds to body compression, and \( k g(r_{ij} - d_{ij}) \Delta v_{ji}^t t_{ij} \) to represent sliding friction force, encumber relative tangential motion, when pedestrians \( i \) & \( j \) touch each other. Moreover, it uses self-propelling interactions between pedestrians, \( A_i \exp \left[ \frac{r_i - d_{iw}}{B_i} \right] \), to keep a separating distance from others and similarly from the wall.

In addition, Helbing introduced pushing behavior. This behavior may be described by increasing the desired velocity according to:

\[
| V_i^0(t) | = (1 - p_i(t)) | V_i^0(0) | + p_i(t) V_{i, max} \tag{4}
\]

Where \( V_i^0(0) \) is the initial, and \( V_{i, max} \) the maximum desired velocity. The time-dependent parameter \( p_i(t) \) is \( 1 - \frac{V_{ave}(t)}{| V_i^0(0) |} \), where \( V_{ave}(t) \) denotes the average speed in the desired direction of motion which is a measure of impatience.

The Helbing model describes observed features of crowd dynamics in both a panic situation and normal ones. One example is lane formation, where pedestrian with same desired walking direction will form lanes \([3]\), (see Figure (2)). Another is uncoordinated movement due to congestion in bottlenecks or exits as the desired velocities increase and people rush for the exit \([3]\), (see Figure (3)).
Although this may be the best microsimulation model available for describing the crowd dynamic in panic or normal situations, it does not represent realistic pushing behavior. The simulation result of Helbing model shows the pedestrian in the back (the furthest from the door) are not touching the pedestrian in the front of him or her, (see Figure (4)). If a pedestrian is not making contact with another pedestrian, there is no desire of pushing or fighting to pass through. Comparison of Helbing pushing behavior and the new proposed method will be discussed in detail in Chapter 4.
Moreover, the model shows no relation between the panic and the desired velocities or pushing behavior. Furthermore, the lack of contagious panic makes the model less realistic and inconsistent with biological studies. Our goal is to propose a methodology that describes the intensity and spread of panic for each individual in addition to pushing behavior, resulting in a more realistic crowd dynamics model.

Figure 4 Simulation of pedestrians moving towards the 1m-wide exit of a room of size 15m X 15m showing no desire of pushing or fighting to pass through [1].
Chapter 3

Theory and Approach

In this chapter, the proposed model will be presented as an extension of the work that had been done by Helbing [1]. The model is for an individual who is part of a crowd and lives in a virtual world. This individual, which will be referred to as an agent from now on, is the element that will encapsulate the intelligence of the system. Therefore, this approach is based on the collective behavior of individual intelligent agents, rather than any global mechanism, from whose interactions a group behavior and self-organized agent dynamics will arise.

3.1 Proposed Agent-Based Model

This work builds on an existing microsimulation model by Helbing [1]. It uses a blend of physical forces and socio-psychological to simulate crowd dynamics. Our goal will be to introduce i) a panic parameter that impacts agent behaviors, ii) a contagion mechanism for panic spread in crowds, and iii) auxiliary states to model pushing behaviors, as not exhibited by the Helbing model [1].

This equation consists of two parts planning given by:

\[ m_i \frac{dv_i(t)}{dt} = m_i \frac{v_{i0}(t) - v_i(t)}{\tau_i} + f_i \]  \hspace{1cm} (5)

\[ u_i(t) = m_i \frac{e_i(t)}{\tau_i} \]  \hspace{1cm} (6)
Here $u_i(t)$ is the control output and $m_i$ and $\tau_i$ are the agent mass and time constant, respectively. Interaction forces are given by:

$$f_i = \sum_{j(\neq i)} f_{ij} + \sum_w f_{iw} \tag{7}$$

Here $e_i(t) = V_i^0(t) - V_i(t)$ represents the error between the desired velocity $V_i^0(t)$, and actual velocity, $V_i(t)$. From eq. (6), we can see that Helbing planning equation is representation of proportional control.

### 3.1.1 Pushing Model Formulation

Pushing behavior is where an agent tries to force a path through a crowd. This will require changing the modeling of the planning equation. In order to allow an agent to push, the planning part needs to overcome interaction forces. To achieve this effect, we add an integrator to the planning part, resulting in a new acceleration equation that can be represented as proportional integral control (see Figure (5)):

$$\frac{dV_i(t)}{dt} = u_i(t) + \frac{1}{m_i} f_i \tag{8}$$

$$u_i(t) = k_{pi} e_i(t) + f(P_i) \cdot k_{li} \int_0^t e_i(t) \, dt \tag{9}$$

$$f_i = \sum_{j(\neq i)} f_{ij} + \sum_w f_{iw} \tag{10}$$

$$e_i(t) = V_i^0(t) - V_i(t) \tag{11}$$

$$V_i^0(t) = (f(P_i) V_{i max} + (1 - f(P_i)) |V_i^0(0)|) \cdot \overrightarrow{V_i^0(t)} \tag{12}$$
Here $V_{\text{max}}$ is a scalar that represents the maximum speed that an agent can reach, and $|V_i^0(0)|$ represents the initial speed (before panicking) or the agent's speed in relaxed situations. Furthermore, $\overrightarrow{V_i^0(t)}$ is a normal vector that represents the agent's desired direction. Also introduced is the panic parameter $P_i \in [0,1]$. Note that the integrator is active only if $f(P_i)$ is not zero. The increase of $f(P_i)$ leads to the increase in the desire to push and to cross the crowd. The function $f(P_i)$ has exponential growth, mapping the panic parameter to a value ranging from zero to one, for example suitable function:

$$f(P_i) = \frac{1-\exp(-P_i)}{1-\exp(-1)}$$

(13)

The parameter $k_{pl}$ & $k_{il}$ are proportional and integrator constants, respectively. The proportional and integrator constants reflect the strength of the agent. In other words, they represent how fast an agent change its status the bigger the constant, the faster the change. However, the interaction forces will be kept unchanged as it was described in Helbing model in the previous chapter. The repulsive forces will be only active if the agent $j$ was in the surrounding area of agent $i$, where the surrounding proxemics area for the force $f_{ij}$ are defined by a circle centered at the position of the agent $i$ with radius $r_{pi}$. In addition there is a field of vision, defined by a circle centered at the position of the agent $i$ with radius $r_{vi}$ and used to activate $f_{iw}$ in a similar way. The field of vision mostly covers a big area except in a situation like smoking room, in which case the area will shrink.
3.2 Panic Contagion

Herding behavior is an essential reason to model panic contagion, in which individuals transfer their behavior to other agents. This leads to spread of panic among other agents. In other words, panicking individuals tend to cause social contagion leading to jamming and life-threatening overcrowding. Every agent has $P_i$ as a panic parameter, value ranging from zero to one. The initial value for the panic parameter is always zero, but it increases due to the sources of fear in the surrounding environment or it could be inherited from the surrounding agent. As far as spreading is concerned, we use a model of consensus or diffusion dynamics with external input [42], [2]. Our model depends on the number of agents in the surrounding area and their level of fear. The surrounding area is defined by a circle centered at the position of the agent with radius $r_{si}$. Panic contagion also depends on their relative distances. An agent will be affected more by surrounding agents with less distance. These factors result in the model:

$$P_i = c_i \left( z_i P_i + \sum_{j \in r_{si}} P_j w_j \right) + (1 - c_i) Q_i$$

(14)
\[ \sum_{j \in r_{si}} w_j + z_i = 1, \quad w_j = \frac{(1-z_i)/d_{ij}}{\sum_{k \in r_{si}} 1/d_{ik}} \]  

(15)

Here \( c_i \) is a constant, which is used to weight the environment effect versus the social contagious influence. In the same way, \( w_j \) is a constant used to weight the panic influence caused by the agents in the surrounding area of agent \( i \). The constant \( z_i \) represents personal confidence in agent own judgment of the situation. In other words, \( 1 - z_i \) represents the amount of influence by the other agent in the surrounding area of agent \( i \). In addition to \( Q_i \) constant representing sources of fear in the surrounding environment such as fire or fire smoke, life-threatening overcrowding and power outage in crowded public site. The result of modeling panic contagion will be discussed in detail in the next chapter.

3.3 Anti Windup

For agents, the allowable values of the control output \( u(t) \) is limited. A saturation level \( Sa_i \) is used such that \(|u(t)| < Sa_i \). Windup occurs if agent is stuck in the crowd pushing...
to open a way for himself, resulting in accumulation on the integral terms. This behavior is called windup. In other words, this occurs when the controller's output can no longer affect the controlled variable (saturation) resulting in accumulation of significant error during this time on the integral terms. When the error $e(t)$ tends to zero the control output $u(t)$ of the PI is equal to the integral terms. Due to the windup, undesirable behavior started to immersion. To resolve the problem, an anti-windup technique was used, involving the integrator being turned off for periods of time until the response falls back into an acceptable range. In our model, the integrator will be turned off if the control output $u(t)$ saturates, (see Figure (6)) which resembles a limit to the agent capability of pushing.

### 3.4 Implementation

In order to implement the proposed Model in MATLAB, we chose to discretize the continuous model, resulting in the next model:

$$V_i(t + 1) = V_i(t) + h(u_i(t) + \frac{f_i}{m_i})$$  \hspace{1cm} (16)

$$u_i(t) = k_{pi} e_i(t) + f(P_i) \cdot k_{li} y_i(t)$$  \hspace{1cm} (17)

$$y_i(t) = y_i(t - 1) + \frac{h}{2} (e_i(t) - e_i(t - 1))$$  \hspace{1cm} (18)

One-sided differencing methods were used to approximate the derivative numerically:

$$\frac{dV_i(t+1)}{dt} \approx \frac{V_i(t+1) - V_i(t)}{h}$$, and a trapezoidal rule was used for approximating the integral

$$\int_0^t e_i(t) \, dt \approx y(t) = y_i(t - 1) + \frac{h}{2} (e_i(t) - e_i(t - 1)).$$
Chapter 4

Results and Analysis

In this chapter, we will go over the spreading panic model, panic effect on the velocity, pushing behavior, and a windup effect on the agent behavior.

The following parameters are used as default for all simulation results shown in this chapter, and any changes will be mentioned accordingly:

Repulsive forces parameters:
\[ B_i = 0.08 \, m \, , A_i = 2 \times 10^3 \, N \, , K = 1.2 \times 10^5 \, kg \, s^{-2} \, , k = 2.4 \times 10^5 \, kg \, m^{-1} s^{-1} \]

Agent specifications parameters:
\[ m_i = 80 \, kg \, , 2r_i = \text{uniformly randomly distributed in the interval } [0.5 \, m, 0.7 \, m] \]
\[ V_{max} = 10 \, m \, s^{-1} \, , \, V_i^0(0) = 0.8 \, m \, s^{-1} \, , \, r_{pi} = 5 \, m \, , r_{vi} = 400 \, m \, , r_{si} = 1.5 \, m \]

PI control parameters:
\[ k_{pi} = 2 \, , \, k_{li} = 0.7 \, , \, Sa_i = 6 \]

Spreading panic parameters:
\[ c_i = 0.9999 \, , \, z_i = 0.99 \]
4.1 Spreading Panic

The panic behavior has a significant impact on crowd dynamics. As simulation of 200 agents in a closed room was performed in order to explore the effect of panic in the crowd dynamics. Targeting the spread of panic among agents, one agent is used as a source of panic, with it's panicking parameter fixed to one. Panic set to zero as an initial value for the other agent. The environmental source of panic parameter $Q_i$ is fixed to zero for all agents. The simulation result shows panic spreading over the crowd, see Figure (7). Video of the simulation is available at [26].

Figure 7 Panic spreading over the crowd where the color represents the panic parameter.

In another experiment, the simulation starts with panicking parameters randomly distributed in the interval from zero to one for all agents. The environmental source of panic parameter $Q_i$ is fixed to zero for all agents. The simulation results shows how panic
is distributed over the crowd then decreases with time until it goes to zero, (see Figure (8)). Video of the simulation is available at [27].

Figure 8 The uniform distribution of panic over the crowd.

4.1.1 Relationship between Panic and Velocity

In panic situations, agents tend to increase their speed in order to run away from the source of panic. The relation between desired velocity and panic depends on the function of panic $f(P_i)$. For this reason, it has to be an increasing function. In our case, the function of panic is defined as $f(P_i) = \frac{1 - \exp(-P_i)}{1 - \exp(-1)}$, see Figure (9). Targeting the change of desired velocity as a response of panic, $Q_i$ is used as a function of position where it starts incrementing with small value if the agent is the farthest from the room exit. It mimics that agent does not want to be the last. The simulation results show agents rushing to the
door if they feel been left behind, and that is a response to the environmental panic parameter $Q_i$, (see Figure (10)). Video of the simulation is available at [28].

Figure 9 The function of panic defined as $f(P) = \frac{(1 - \exp(-P))}{(1 - \exp(-1))}$

Figure 10 Simulation showing change of wanted velocity as response of panic.
4.1.2 Relationship between Panic and Pushing

Panicking agents tend to push other agents to increase their chance of survival or to open ways among the crowd. In this section, comparison of pushing behavior between the Helbing model and the proposed model will be discussed. To explore the effect of panic on the agent's pushing behavior, a simulation of 50 agents in a closed room was simulated. For the sake of comparison, one agent (we will refer to it as agent-red) will be used to push the other agents in its way in order to cross thru the crowd,(see Figure (11)). The other 49 agents will try to maintain their positions. Moreover, all the initial parameters for the simulation are the same.

![Simulation to test pushing behavior.](image)

For The Helbing model, pushing behavior is described by increasing the desired velocity. Therefore, a maximum desired velocity of 10 m/s was given to agent-red. The time-
dependent panic parameter is fixed as \( p(t) = 0 \). Giving agent-red the maximum speed possible all the time resamples the worst situation. The first problem with this method is the lack of a relation between panic and pushing. Instead, the function depends on time, which resamples a lack of patient behavior more than pushing behavior. The second problem is that the simulation shows that agent-red was unable to cross the crowd, although the other agents are not pushing, (see Figure (12)). Our proposed model was able to show a relation between panic and pushing by introducing the panic parameter. In addition, for the same simulation agent-red with panic parameter fixed equal to one was able to cross the crowd, although it was given a desired velocity of only 5 m/s, (see Figure (13)). It is worth mentioning that the environmental source of panic parameter \( Q_i \) is fixed to zero for all agents, as well as \( c_i \) for all the agents. The simulation results are available as video at [29] for the Helbing model and [30] for the proposed model.

Figure 12 The simulation of the Helbing model shows that agent-red was unable to cross the crowd, although the other agent are not pushing.
Figure 13 The simulation of the proposed model shows that agent-red was able to cross the crowd, although it was given desired velocity of only 5 m/s.

4.2 Pushing with Anti Windup

During our testing for pushing behavior in the proposed model, an unwanted behavior was discovered, which could be seen as drifting in an undesirable direction. An agent starts to drift after reaching its targeted location. When an agent reaches its targeted location, the error tends to zero and the control output $u(t)$ of the PI controller will be equal to the integral terms causing this drifting away from the targeted location. To explore the effect of windup on the agent's behavior, the same simulation used in section (4.1.2) to test the relationship between panic and pushing have been used with a change
in the initial location of agent-red (see Figure (14)). Here agent-red is trying to reach the location [0, 0].

Figure 14 Simulation to test the effect of windup on the agent's behavior.

Before using anti-windup, the simulation shows agent-red drifting away from the targeted location [0, 0] after reaching there (see Figure (15)). The simulation result is available as video at [31]. On the other hand, the simulation with anti-windup method showed no drifting for agent-red (see Figure (16)). The simulation result is available as video at [32].

Figure 15 Agent-red drifting away from the targeted location after reaching there.
Figure 16 After using anti-windup method, agent-red doesn’t drift away from the targeted location after reaching there.

Figure 17 In black, agent-red location in the Y-axis. In blue, the control output $u(t)$. On the top is before using anti-windup, it shows the oscillation in the control output $u(t)$. As a result, we see drifting in the location of agent-red to the negative part of the Y-axis. Where agent-red targeted location is zero in the Y-axis. On the bottom is after using anti-windup, it shows less oscillation in the control output $u(t)$. As a result, we see less drifting in the location of agent-red to the negative part of y-axis.
4.3 Improving Bottlenecks

In [1] a method to improve bottlenecks has introduced by smoothing the corners and using a funnel-shaped corridor (see Figure (18)). In addition, that work has pointed out that boundaries influenced pedestrian flows in a crucial way. Moreover, it was suggested that planning buildings and facilities can be improved by using computer simulation and change the boundaries in order to methodically configure the shapes of facilities to improve the pedestrian flows, see Figure (19).

Figure 18 Conventional (left) and improved (right) bottlenecks.

Figure 19 Different phases in the evolutionary optimization of a bottleneck.
Based on our model, we also investigated the optimal angle of the funnel-shaped. The corridor evacuation simulation of 200 agent was used with different angles each time ranging from zero to thirty-five, to determine an optimal angle, (see Figures (20,21,23)).

![Simulation images](image_url)

**Figure 20** The colors represent pressure on the agent. The simulation has shown that pressure localization depends on corridor angle. As the angle increases, the centralize pressure move from the entrance of the corridor to the exit. For the corridor with zero angle, we can see the pressure on the agent in the entrance of the corridor is high. In the other hand, for the corridor with the angle of thirty we can see the pressure on the agent in the exit of the corridor is very high.

Analysis of the results of this simulation showed a significant improvement in the time of the evacuation and reduce the pressure on the agent can be achieved by using corridor angle of 10 degrees. As a result, the flow of agents will be improved as result of agent densities spreading in the corridor (see Figure (23)). The simulation result for corridor angle are available as video at [33-40].
Figure 21 leaving time of agents, shows incoordination of exiting the room and the required time for evacuation 200 agents through 1 m door for each angle.

Figure 22 Box plot, shows medians and agents leaving time distribution for the different angles. where the first form the left is zero angle and the least on the right is angle of thirty-five.
Chapter 5

Future Work and Conclusions

This chapter summarizes the thesis and outlines directions for future research.

The proposed model was able to combine physical conditions and mental state of the agent into a simple, very practical, and applicable model. However, still many extensions of this research deserve further consideration.

5.1 Future Work

The results of this thesis point to several interesting directions for future work:

- Calibration: The model has many parameters that need calibration in order to reproduce observed features of crowd dynamics. It is important to realize that empirical data of crowd dynamics are needed. Another key factor is panic, which cannot be observed with a monitoring camera. Rather, panic needs to be inferred using possibly biometric data assimilation that will be collected using wearable technology.

- Communication: In a crowd, agents can communicate with each other. This communication is not necessarily vocal but could be hand gestures or any other form of communication. Agents may not use the same language but yelling, screaming and calling for help are universal and understood by all. The ability of
communication between agents and what it causes in crowd dynamics is interesting to incorporate into the model.

- **Wave:** One of the most interesting collective behavior is crowd waves. In high-density crowds agents start to lose control of their motion and waves start to emerge in a situation of great complexity (see video at [41]). To the best of our knowledge, none of the agent-based models is able to reproduce this behavior [25].

- **Rising:** In high density crowds, the pressure increase can cause lifting agents up at certain local area to the point that they lose contact with the ground. That causes panic among agents and a high chance for crowd stampede. It is important to realize that this behavior will need a three-dimensional model.

Hoping to address some of these issues in the near future, we are looking to contact the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research Umm Al-Qura University for empirical data that will be used to calibrate the model and test the reproduction of the empirical data.

### 5.2 Conclusion

In this work, we addressed the problem of crowd stampede. Panic behavior has a significant impact on crowd dynamics. A discussion of different crowd simulation models was provided. In general, these different types of crowd simulation models do not take in the psychology study of the crowd into account. The focus of our work was on introducing a contagious panic parameter that influences agents behavior. A modified version of
Helbing’s social force model results in the significant improvement of a pushing behavior and its relationship with panic parameter, together with a simulation of evasion and spreading of panic. Finally, another contribution relies on single panic parameter that can represent crowd dynamics in normal and panic situations. The simplicity of the proposed model is inherent in its conceivable interactions, making it robust with respect to parameter variations. Consequently, it is suitable for studying crowd dynamics in different situations and testing pedestrian sites for their suitability in emergencies. However, the proposed model parameters are still uncalibrated or available data on crowd flows. In addition to many developments of this model deserve further consideration.


[26] Panic spreading over the crowd where the color represents the panic parameter https://drive.google.com/open?id=0B7qp-MR75XWidEwzV3VaNndSNnc.

[27] The uniform distribution of panic over the crowd https://drive.google.com/open?id=0B7qp-MR75XWidEwzV3VaNndSNnc.

[28] Simulation showing change of wanted velocity as response of panic https://drive.google.com/open?id=0B7qp-MR75XWiaGFqaVFfSTFQUG8.

[29] The simulation of the Helbing model shows that agent-red was unable to cross the crowd, although the other agent are not pushing https://drive.google.com/open?id=0B7qp-MR75XWiTEtLMU9nNU5VMIU.

[30] The simulation of the proposed model shows that agent-red was able to cross the crowd, although it was given desired velocity of only 5 m/s https://drive.google.com/open?id=0B7qp-MR75XWibDRyREt2Um1faVU.

[31] Agent-red drifting away from the targeted location after reaching there https://drive.google.com/open?id=0B7qp-MR75XWiOWNPS1o2RWFscVE.

[32] After using anti-windup method, agent-red doesn't drift away from the targeted location after reaching there https://drive.google.com/open?id=0B7qp-MR75XWiYnJaa0R5NWR1RU0.

[33] The simulation result for corridor angle of zero are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiUm1wSTZ0MEpQYIk.

[34] The simulation result for corridor angle of Five are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiRzRtZ1dVZkVjenM.

[35] The simulation result for corridor angle of Ten are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiQVpETFzWC10aVk.

[36] The simulation result for corridor angle of Fifteen are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiMmxpRUJGMUppaFE.

[37] The simulation result for corridor angle of Twenty are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiTGM4aWdzQks1MDQ.

[38] The simulation result for corridor angle of Twenty-five are available as video at https://drive.google.com/open?id=0B7qp-MR75XWibHVoUDY1Sjh0TEk.
[39] The simulation result for corridor angle of Thirty are available as video at https://drive.google.com/open?id=0B7qp-MR75XWi1RJMEtQaDV5MEk.

[40] The simulation result for corridor angle of Thirty-five are available as video at https://drive.google.com/open?id=0B7qp-MR75XWiTnFGR0kxUVd1WIU.

[41] Crowd waves https://drive.google.com/open?id=0B7qp-MR75XWiWmVCVU1QTEY2Tjg.