Group Social Force and Interactive Opinion Dynamics

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In order to investigate how individuals interact and form the collective pattern of crowd, microscopic models have been developed in recent decades, in which an individual's behavioral/psychological status can be modeled and simulated. A well-known model is called social-force model based on Newtonian dynamics. Inspired by the social-force model, this paper presents a new model to characterize group behavior in crowd dynamics. We essentially introduce a new form of group social force to characterize social relationship among individuals, and opinion dynamics is further integrated in the model to study how self-organized phenomena emerges from interaction of individuals. The cognition and behavior of individuals are further modeled with environmental stimuli to form a closed-loop process. This method has been partly tested in FDS+Evac, and the testing results justifies certain pre-evacuation phenomena observed in egress research.

I. INTRODUCTION

How individual behavior leads to emergence of group-level organization is a fascinating research topic, and it is commonly deemed as an inter-discipline involving complex systems, physics, computer science and nonlinear systems. Various models have been proposed to investigate such a system, such as cellular automaton, lattice gas model, and so forth. Around 2000 an innovative pedestrian model was introduced by physical scientists (Helbing and Molnar, 1995; Helbing, Farkas and Vicsek, 2000; Helbing et al., 2002), and it was named by social-force model. This model has been widely accepted and mainly used in simulation of crowd evacuation in the past decade, and it has been incorporated into several advanced egress simulators, such as Fire Dynamics Simulator with Evacuation (Korhonen et. al., 2008, Korhonen, 2017), Pedsim, SimWalk, MassMotion (Oasys, 2018), VisWalk, Maces (Pelechano and Badler, 2006) and Menge.

Very interestingly, certain psychological factors are characterized in the model such as "desired velocity" and "social force," and to some extent, these concepts are not physical entities because they reflect people's opinions and exist in human mind. Thus, the model is not typically within the scope of physics study, but in an interdisciplinary domain. In fact, the psychological concept of stress contributes to investigating a pedestrian's response and adaption to the environment, and the social-force model is hereby extended to characterize the interplay between individuals and their surroundings. In this report we will focus on how an individual interacts with the surrounding individuals, and group dynamics will be discussed in detail. We will introduce a new form of group force which contributes to form groups in pedestrian motion. The force is an extension of the traditional social-force, and it describes the social relationship among individuals.

The rest of the paper is organized as below. Section 2 briefly reviews the mathematical formula of the social force model. In Section 3 group social force is presented in an exponential form by extending the traditional social force, and Section 4 focuses on how group dynamics is formed by using the group social force. The herding effect and interactive opinion dynamics are essentially discussed in Section 5. In Section 6 the group dynamics is jointly used with opinion dynamics to investigate the crowd response in pre-evacuation stage. The concluding remarks are presented in Section 7.

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II. About the Social-Force Model

The social-force model presents psychological forces that drive pedestrians to move as well as keep a proper distance with others. In this model an individual's motion is motivated by a self-driving force $\boldsymbol{f}_i^{drv}$ and resistances come from surrounding individuals and facilities (e.g., walls). Especially, the model describes the social-psychological tendency of two individuals to keep proper interpersonal distance (as called the social-force) in collective motion, and if people have physical contact with each other, physical forces are also taken into account. Let $\boldsymbol{f}_{ij}$ denote the interaction from individual j to individual i, and $\boldsymbol{f}_{iw}$ denote the force from walls or other facilities to individual i. The change of the instantaneous velocity $\boldsymbol{v}_i(t)$ of individual i is given by the Newton Second Law:

$$m_i \frac{d\,\boldsymbol{v}_i(t)}{dt} = \boldsymbol{f}_i^{drv} + \sum_{j(\neq i)} (\boldsymbol{f}_{ij}^{soc} + \boldsymbol{f}_{ij}^{phy}) + \sum_w (\boldsymbol{f}_{iw}^{soc} + \boldsymbol{f}_{iw}^{phy})$$

$$m_i \frac{d\,\boldsymbol{v}_i(t)}{dt} = \boldsymbol{f}_i^{drv} + \sum_{j(\neq i)} \boldsymbol{f}_{ij} + \sum_w \boldsymbol{f}_{iw} + \boldsymbol{\xi}_i \quad (1)$$

where m_i is the mass of individual i, and $\boldsymbol{\xi}_i$ is a small fluctuation force. Furthermore, the self-driving force $\boldsymbol{f}_i^{drv}$ is specified by

$$\boldsymbol{f}_i^{drv} = m_i \frac{\boldsymbol{v}_i^0(t) - \boldsymbol{v}_i(t)}{\tau_i}, \quad (2)$$

This force describes an individual tries to move with a desired velocity $\boldsymbol{v}_i^0(t)$ and expects to adapt the actual velocity $\boldsymbol{v}_i(t)$ to the desired velocity $\boldsymbol{v}_i^0(t)$ within a certain time interval τ_i. In particular, the desired velocity $\boldsymbol{v}_i^0(t)$ is the target velocity existing in one's mind while the actual velocity $\boldsymbol{v}_i(t)$ characterizes the physical speed and direction being achieved in the reality. The gap of $\boldsymbol{v}_i^0(t)$ and $\boldsymbol{v}_i(t)$ implies the difference between the human subjective wish and realistic situation, and it is scaled by a time parameter τ_i to generate the self-driving force. This force motivates one to either accelerate or decelerate, making the realistic velocity $\boldsymbol{v}_i(t)$ approaching towards the desired velocity $\boldsymbol{v}_i^0(t)$. This mathematical description of the self-driving force could be dated back to the Payne-Whitham traffic flow model (Payne, 1971; Whitham, 1974). Sometimes $\boldsymbol{v}_i^0(t)$ is rewritten as $\boldsymbol{v}_i^0(t) = v_i^0(t)\boldsymbol{e}_i^0(t)$, where $v_i^0(t)$ is the desired moving speed and $\boldsymbol{e}_i^0(t)$ is the desired moving direction. In a similar manner, we also have $\boldsymbol{v}_i(t) = v_i(t)\boldsymbol{e}_i(t)$ where $v_i(t)$ and $\boldsymbol{e}_i(t)$ represent the physical moving speed and direction, respectively.

The interaction force of pedestrians consists of the social-force $\boldsymbol{f}_{ij}^{soc}$ and physical interaction $\boldsymbol{f}_{ij}^{phy}$. i.e., $\boldsymbol{f}_{ij} = \boldsymbol{f}_{ij}^{soc} + \boldsymbol{f}_{ij}^{phy}$. The social-force $\boldsymbol{f}_{ij}^{soc}$ characterizes the social-psychological tendency of two pedestrians to stay away from each other, and it is given by

$$\boldsymbol{f}_{ij}^{soc} = A_i \exp\left[\frac{(r_{ij} - d_{ij})}{B_i}\right]\boldsymbol{n}_{ij} \quad \text{or} \quad \boldsymbol{f}_{ij}^{soc} = \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\varphi_{ij}}{2}\right) A_i \exp\left[\frac{(r_{ij} - d_{ij})}{B_i}\right]\boldsymbol{n}_{ij} \quad (3)$$

where $\boldsymbol{A}_i$ and $\boldsymbol{B}_i$ are positive constants, which affect the strength and effective range about how two pedestrians are repulsive to each other. The distance of pedestrians i and j is denoted by d_{ij} and the sum of their radii is given by r_{ij}. $\boldsymbol{n}_{ij}$ is the normalized vector which points from pedestrian j to i. The geometric features of two pedestrians are illustrated in Figure 1. In practical simulation, an anisotropic formula of the social-force is widely applied where Equation (3) is scaled by a function of λ_i. The angle φ_{ij} is the angle between the direction of the motion of pedestrian i and the direction to pedestrian j, which is exerting the repulsive force on pedestrian i. If $\lambda_i = 1$, the social force is symmetric and $0 < \lambda_i < 1$ implies that the force is larger in front of a pedestrian than behind. This anisotropic formula assumes that pedestrians move forward, not backward, and thus we can differ the front side from the backside of pedestrians based on their movement.

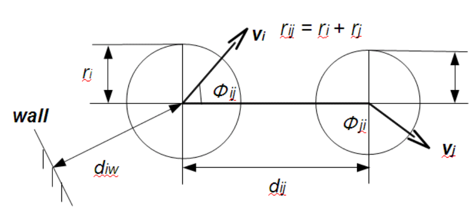


Figure 1. A Schematic View of Two Pedestrians (Equation 3)

The physical interaction $\boldsymbol{f}_{ij}^{phy}$ describes the physical interaction when pedestrians have body contact, and it is composed by an elastic force that counteracts body compression and a sliding friction force that impedes relative tangential motion of two pedestrians. Both of them are valid only when $r_{ij}>d_{ij}$. In Helbing, Farkas and Vicsek, 2000 the interaction force is repulsive. The model may also include an attraction force in its original version (Helbing and Molnar, 1995, Helbing et al., 2002 Korhonen, 2017). The interaction of a pedestrian with obstacles like walls is denoted by $\boldsymbol{f}_{iw}$ and is treated analogously, i.e., $\boldsymbol{f}_{iw} = \boldsymbol{f}_{iw}^{soc} + \boldsymbol{f}_{iw}^{phy}$. Here $\boldsymbol{f}_{iw}^{soc}$ is also an exponential term and $\boldsymbol{f}_{ij}^{phy}$ is the physical interaction when pedestrians touch the wall physically.

By simulating many such individuals in collective motion, several scenarios in crowd movement were demonstrated, and one is called the "faster-is-slower" effect. This scenario was observed when a crowd pass a bottleneck doorway, and it shows that increase of desired speed (i.e., $|\boldsymbol{v}_i^0(t)|$) can inversely decrease the collective speed of crowd passing through the doorway. Another paradoxical phenomenon is called "freezing-by-heating," and it studies two groups of people moving oppositely in a narrow passageway, and the simulation shows that increasing the fluctuation force in Equation (1) can also cause blocking in the counter-flow of pedestrian crowd. Other spatio-temporal patterns include herding effect, oscillation of passing directions, lane formation, dynamics at intersections and so forth.

The validation of the model has been partly conducted based on data sets from real-world experiments. The method of validation involves comparing the simulation of the model with associated observations drawn from video-based analysis (Johansson, Helbing and Shukla, 2007; Johansson et al., 2008).

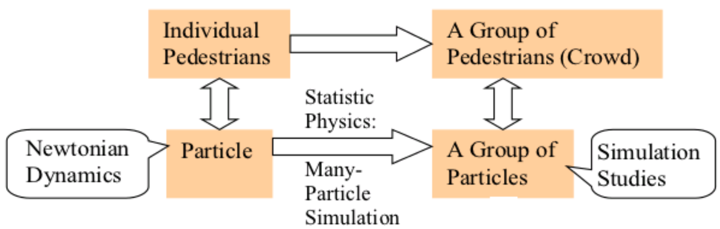


Figure 2. From Particle Dynamics to Crowd Simulation
The Framework of Many-particle Simulation in Helbing, Farkas, and Vicsek, 2000

III. GROUP SOCIAL FORCE

An important issue is that the social force may also include attractions to describe people's tendency to keep together and form groups in motion. In Helbing and Molnar, 1995 and Helbing et al., 2002 attractions were presented, but separate from the social force. This section will present the a new mathematical formula of group social force. The group social force is used to combine individuals in certain circumstances, and it describes attraction and repulsion within the same social context: repulsion makes people to keep proper distance while attraction makes them cohesive and form groups. The resulting interaction force is either repulsive or attractive, and it contributes to modeling group dynamics in crowd behavior. The group social force is defined as below.

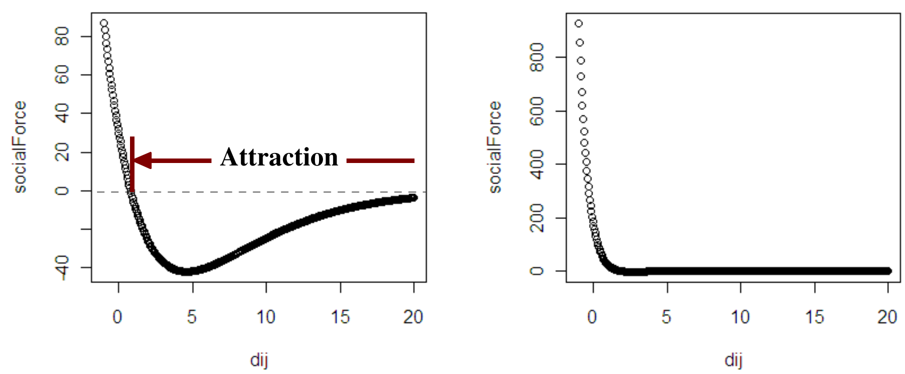
$$\boldsymbol{f}_{ij}^{soc} = A_{ij}(d_{ij}^0 - d_{ij})\exp\left[\frac{(d_{ij}^0 - d_{ij})}{B_{ij}}\right]\boldsymbol{n}_{ij} \qquad \text{or} \qquad \boldsymbol{f}_{ij}^{soc} = \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\varphi_{ij}}{2}\right)A_{ij}(d_{ij}^0 - d_{ij})\exp\left[\frac{(d_{ij}^0 - d_{ij})}{B_{ij}}\right]\boldsymbol{n}_{ij} \tag{4}$$

Similar to desired velocity $\boldsymbol{v}_i^0$, the desired distance d_{ij}^0 is the target distance in one's mind, specifying the distance that one expects to adapt oneself with others. The physical distance d_{ij} is the distance achieved in the reality. The gap of d_{ij}^0 and d_{ij} implies the difference between the subjective wish in one's mind and objective feature in the reality. Similar to $\boldsymbol{v}_i^0 - \boldsymbol{v}_i$, as an indication of time-related stress concerning emergencies, $d_{ij}^0 - d_{ij}$ is an indication of interpersonal stress related to the social composition of crowd. Such stress depends on the intrinsic social characteristics of the crowd, not directly related to the emergency situation. Here A_i and B_i are parameters as introduced before, and $\boldsymbol{n}_{ij}$ is the normalized vector which points from pedestrian j to i. The group social force also functions in a feedback manner to make the realistic distance d_{ij} approaching towards the desired distance d_{ij}^0. A difference is that $\boldsymbol{v}_i^0$ and $\boldsymbol{v}_i$ are vectors while d_{ij}^0 and d_{ij} are scalars.

The mathematical characteristics of Equation (4) is discussed as below.

When d_{ij} is sufficiently large, the group social force tends to be zero so that individual i and j have almost no interaction. This trend is the same as the traditional social force as given by Equation (3). If d_{ij} is comparable to d_{ij}^0, interaction of individual *i* and *j* comes into existence. If $d_{ij}^0 < d_{ij}$, the group social force is attraction whereas it is repulsion if $d_{ij}^0 < d_{ij}$. The attraction reaches the maximal when $d_{ij}^0 - d_{ij} = B_{ij}$, and the maximal is $A_{ij} B_{ij} \exp(1)$. The desired distance d_{ij}^0 makes the curve move horizontally with a certain interval. The curve shape is affected by parameter A_{ij} and B_{ij}. A_{ij} is a linear scaling factor which affects the strength of the force whereas B_{ij} determines the effective range of the interaction.

Two plots of Equation (4) are given as below: Figure 2(a) shows that individual *i* is attracted by individual *j* when they are sufficiently close, and this suggests that individual *i* and j probably know each other. Figure 2(b) does not show such relationship and their interaction is mainly repulsion.



$d_{ij}^0 = 0.8m$ $A_{ij} = 30$ N $B_{ij} = 3.8$m $\quad$ $d_{ij}^0 = 1.8m$ $A_{ij} = 10$ N $B_{ij} = 0.8$m

(a) Familiarity (b) Stranger

Figure 2. Social-force from individual *j* to individual *i*

In the above curve the negative segment represents attraction (See Equation 4), and it represents a kind of social cohesion which helps form groups. In contrast the positive segment denotes repulsion and it is similar to the traditional social force. As below we present a diagram to describe the interplay between individuals and their surroundings and it illustrates how the desired velocity and desired distance interact with physical velocity and physical distance in a feedback loop.

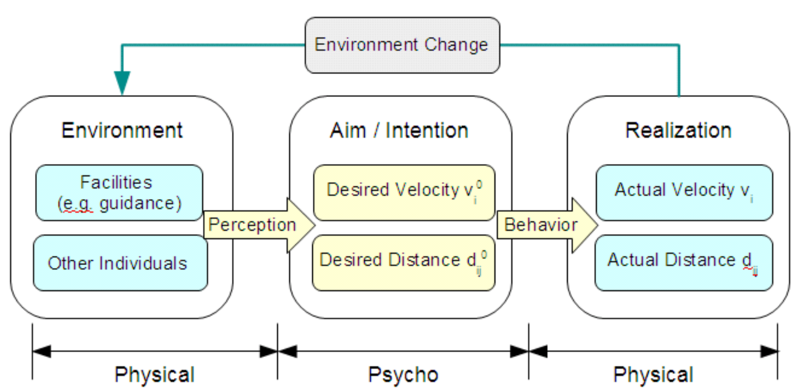


Figure 3. Perception and Behavior in a Feedback Mechanism

To elaborate the above group social force especially from the psychological perspective, we have the following remarks.

(a) Proxemics and Desired Interpersonal Distance

The first remark refers to proxemics and interpersonal distance. In Hall, 1963 and 1966 the study of interpersonal distance was named by proxemics, and it was defined as "the interrelated observations and theories of man's use of space as a specialized elaboration of culture." In brief, proxemics suggests that people surround themselves with a "bubble" of personal space that they claim as their own region, and they normally feel stressed when their personal space is invaded by others. Our personal space protects us from too much arousal and helps us keep comfortable when we interact with surrounding people.

When the interpersonal distance is smaller than the desired, it is reasonable to assume that repulsion comes into being in this situation, and repulsion increases when the distance further decreases. This theory justifies the assumption of repulsive social-force in Equation (3). However, the repulsion is not related to physical size of two people (i.e., r_{ij}), but the social relationship, culture and occasions. Comparing social force with self-driving force, we suggest that there should be a subjective concept of desired distance d_{ij}^0 in the pedestrian model, and it replaces r_{ij} in Equation (3). Here d_{ij}^0 is the target distance that individual *i* expects to maintain with individual *j*. This distance describes the desired interpersonal distance when people interact, and it is a function of the social relationship of individual *i* and *j* as well as the culture and social occasions.

(b) Social Norms and Proxemics

The interpersonal distance reflects a kind of social norms, and it is also redefined in different cultures. For example, in a crowded train or elevators, although such physical proximity is psychologically disturbing and uncomfortable, it is accepted as a social norm of modern life. Also, it is also known that the male and female commonly keep larger distance in public place in Muslim culture than other cultures.

Because people may follow different social norms and expect different proximal distance in different occasions, , d_{ij}^0 is occasion-dependent and it is not a static concept. For example in elevators or entrance of a passageway, people usually accept smaller interpersonal distances than in other occasions. The accepted proximal distance is much smaller than other cases. Thus, d_{ij}^0 could be scaled down with a smaller value in these places. A straightforward method is scaling down each element d_{ij}^0 when people stay together in these places. In brief d_{ij}^0 should be a function in both temporal and spatial sense and it varies temporally and spatially. In addition, culture is another important factor but it is a little beyond the scope of our discussion.

IV. Group Dynamics

Individuals in a group exhibit some degree of social cohesion based on their relationship or inter-dependencies and they are more than a simple collection or aggregate of individuals. Based on Equation (4), considering a group composed by *n* individuals, the social relationship of the group members is described by a $n \times n$ matrix D^0, of which the element is d_{ij}^0. In a similar way, there are $n \times n$ matrices *A* and *B*, and the elements are A_{ij} and B_{ij}, respectively. Generally speaking, D^0, *A* and *B* are asymmetrical, implying that Newton 3rd law does not hold for group social force.

$$\boldsymbol{D^0} = [d_{ij}^0]_{n\times n} \qquad \boldsymbol{A} = [A_{ij}]_{n\times n} \qquad \boldsymbol{B} = [B_{ij}]_{n\times n} \tag{5}$$

The group social force is specified by the matrices D^0, *A* and *B*, and the method has been tested in FDS+Evac in version 6.5.3. A testing result is illustrated in Figure 4, where the built environment is obtained from an example in Pan et. al., 2007. Several groups are identified in the simulation result. Some small groups merge into a large group and regrouping may occur at intersections or bottlenecks when different groups meet. In sum, grouping behavior is not a static concept in our model, but a dynamic feature. Structure of groups change dynamically, resulting in a self-organized phenomenon during the movement.

In the above problem the group social force is a kind of long-range forces and the range of the force is individual-dependent. Different individuals have different effective ranges of group social force. To save computational efforts a list method is used for each individual agent. If other agents are far away sufficiently, they will not be calculated for interaction force. We call it "attention list" for the list includes surrounding agents who draw one's attention. Below is the criterion used to generate the attention list, where ai means agent *i* and aj means agent *j*.

```
if dij < ai.B_CF*BFactor[idai, idaj] + rij*DFactor[idai, idaj] and no_wall_ij and see_i2j:
    ai.others.append(aj)
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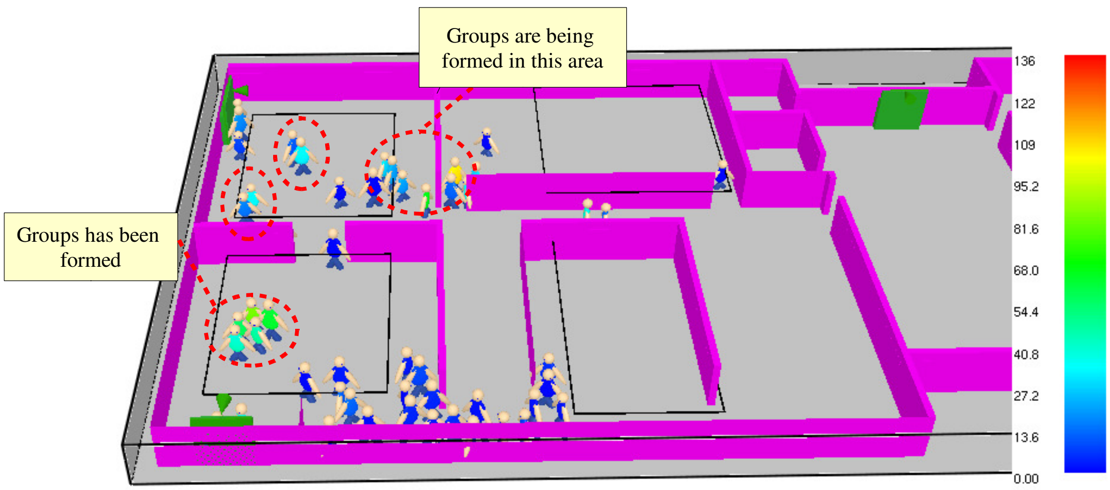
In brief, the surrounding individuals (aj) are in the list (ai.others) if three conditions hold: (1) The long-range force (group social force) is within the effective range. (2) There is no wall between ai and aj. (3) ai can see aj (i.e.,aj is in the front of ai, not in the back of ai.) When the above three conditions hold together aj is recorded in ai's attention list and interaction force from aj to ai will be calculated.

Based on Equation (4) and (5), a typical kind of social relationship is described as the leader-and-follower group, where there is a kind of individual whose behavior is mainly motivated by himself, and if others would like to follow them, they become leaders in a group. Thus, if individual i is the leader in a group, his motion is mainly motivated by the self-driving force (i.e., desired velocity). Follower is the one whose behavior is mainly motivated by others. Thus, if individual i is the follower in a group, his motion is mainly governed by group force, and the self-driving force is secondary. As mentioned before imbalance (asymmetry) of d_{ij}^0 and d_{ji}^0 will contribute to model leadership in crowd behavior. If i is a leader, d_{ji}^0 is much smaller than d_{ij}^0. As a result, the leader will attract his surrounding people, but not easily be attracted by them. In brief an individual's motion can be classified into two types. One type of motion is mainly motivated by the self-driving force, not by surrounding people, and thus is called active motion. The other type of motion is motivated by surrounding people, and is called passive motion. In general, an individual's motion is a combination of both types, but we can differentiate such two types in simulation and identify whether one's motion is dominated by either active or passive type.

In sum, imbalance (Asymmetry) of d_{ij}^0 and d_{ji}^0 will contribute to model leadership in crowd behavior. If i is a leader, d_{ji}^0 is much smaller than d_{ij}^0. As a result, the leader will attract his surrounding people, but not easily be attracted by them. As a result, such active and passive types of motion form the pattern of leader and follower in crowd dynamics.

As shown in Figure 4 we use the color bar to observe the magnitude of the group social force in simulation (Forney, 2018). An individual in active motion usually moves in the front of a group. Individuals in passive motion are followers in the group and they usually move behind the leaders. The leaders are under smaller group social force than the followers.



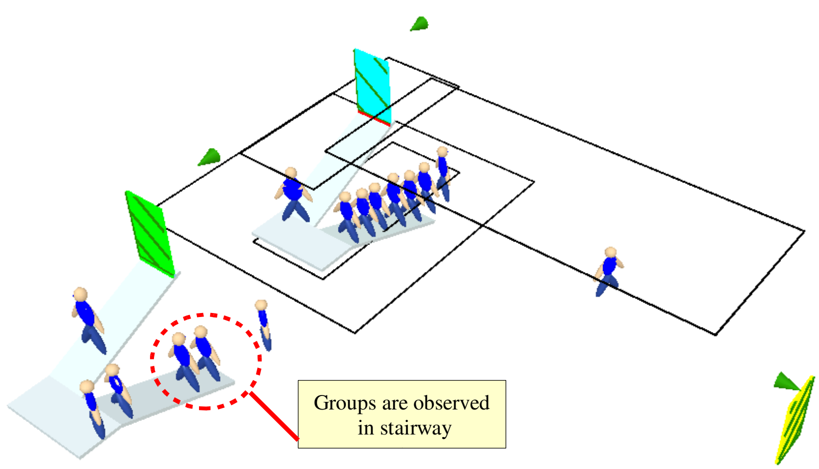


Figure 4. Simulation of Group Dynamics in FDS+Evac (The color bar indicates the magnitude of the group social force given by Equation (7)).

About group dynamics we have the following two remarks regarding psychological study.

In evacuation simulation Equation (4) and (5) can be better explained by flight-or-affiliation effect in psychological studies. The self-driving force motivates one to flee while the group social force makes one affiliated with others. This effect agrees with social attachment theory in psychological study (Mawson, 2007; Bañgate et al., 2017). The social attachment theory suggests that people usually seek for familiar ones (e.g., friends or parents) to relieve stress in face of danger, and this is rooted from our instinctive response to danger in childhood when a child seek for the parents for shelter. Affiliated with familiar and trust individuals relieves our stress. Thus, different from the fight-or-flight response (Cannon, 1932), the modified social model well agrees with the flight-or-affiliation effect. Therefore, the pedestrian model presented above is especially useful to model crowd behavior in pre-movement stage in crowd evacuation (Sorensen, 1991, Kuligowski, 2009). In brief, when the alarm or hazard is detected, people usually do not head to exits immediately, but go to find their friends or trust ones to form groups. Such grouping effect usually delays the movement towards exits, and thus is called pre-movement stage. Thus, the new model contributes to modeling the crowd behavior in pre-movement period and will be useful to investigate how the initial delay is formed and influenced by the group dynamics.

V. Herding Effect and Opinion Dynamics

Herding is especially evident when people are responding to an emergency (Low, 2000). Emergency implies time-pressure and excessive time-pressure weakens the ability of logical thinking and reasoning, and independent decision making is more difficult in a stressful condition. Thus, people are more inclined to follow others (e.g., neighbors' decisions) rather than make decisions by themselves. This effect is characterized by an existing model in opinion dynamics as below (Deffuant, 2000).

$$\boldsymbol{v}_i^{\boldsymbol{0}}(t+1)=(1-p_i)\boldsymbol{v}_i^{\boldsymbol{0}}(t)+p_i\boldsymbol{v}_j^{\boldsymbol{0}}(t) \tag{6}$$

The desired velocity $\boldsymbol{v}^0_i$ is updated by mixing itself with another individual's desired velocity $\boldsymbol{v}^0_j$. Both options are weighted with some parameter ($1-p_i$) and p_i , and two options follow two-point distribution with probability ($1-p_i$) and p_i , and $\boldsymbol{v}^0_i$ is updated by the statistical average. As a consequence, an individual keeps his own opinion if p_i is low whereas follows others if p_i is high. An important issue relates to the meaning of parameter p_i and how it evolves in the simulation. In a statistical sense p_i means probability that individual expects to follow others. In Helbing, Farkas and Vicsek, 2000 and Helbing et al., 2002, p_i is considered to indicate one's panic level, and it is given by ratio of $(v_i^0 - v_i)/v_i^0$, and it is called a "nervousness" parameter. This ratio critically affects several testing results in their work, and it has been applied in FDS+Evac (Korhonen, 2017). Because the gap of $(v_i^0 - v_i)$ is measured in the parameter, it also can be understood as an indicator of one's stress level, and the parameter is normalized by dividing the gap by v_i^0. As a result, the "nervousness" parameter can be explained as a normalized stress indicator, and it shows that people are more inclined to follow others when they feel more stressed in an emergency situation. This is a reasonable assumption and is also consistent with psychological findings.

From the perspective of opinion dynamics the effective range of p_i can be further extended by $p_i \in [-1, 1]$. As a result, p_i is not just a probability measure, but a weight parameter which causes the individuals' opinions to either converge or diverge. $0<p_i<1$ means that one intends to stay in somewhere between his or her own opinion and others' opinion, and this moderate strategy brings the individuals' opinions to converge in a sense. In contrast, $-1<p_i<0$ means that one is against others' opinion. In other words, the negative value of p_i implies that others' standpoint has an inverse impact on one's opinion. Thus, the more others state their opinion to individual *i*, the more individual *i* will reject it and hold more firmly on his or her own standpoint. This strategy brings the individuals' opinions not to converge, but diverge. In sum, $p_i \in [-1, 1]$ implies that interactions bring opinions either closer to each other, or more apart from each other (Altafini, 2013).

Table 4.1

$-1<p<0$	$p=0$	$0<p<1$
Against others' opinions	Hold his own opinion and do not care about others' opinions	Support others' opinions

Based on the social-force model, two individuals interact only if the physical distance is less than R_i and this assumption is applicable in Equation (6). That is, $\boldsymbol{v}_i^0$ is updated when the distance of two individuals is less than R_i. This is a reasonable and relatively straightforward assumption. Based on existing model in opinion dynamics, there are several models which are applicable to improve this assumption. For example, an existing theory suggest that interactions bring opinion closer to each other if they are already close sufficiently, and thus one's opinion is inclined to selectively follow similar opinions of others. Moreover, the social relationship of individuals are also useful, and the interaction range is not only determined by physical distance d_{ij}, but also the desired distance d_{ij}^0. As a result, one tends to follow those in close social relationship.

Another major issue about Equation (6) is whether people should follow others' opinion or behavior. In other words, it remains a question in Equation (6) whether to use desired velocity $\boldsymbol{v}_j^0(t)$ or the actual moving velocity $\boldsymbol{v}_j(t)$ to aggregate others' characteristics. In brief, if we assume opinion can be directly affected by surrounding people (Le Bon, 1895), we will use $\boldsymbol{v}_j^0(t)$ in Equation (6). If we assume that an individual observes what others are doing and directly copy their behavior, $\boldsymbol{v}_j^0(t)$ will be replaced by $\boldsymbol{v}_j(t)$ in Equation (6). In general, people can exchange ideas in mind by talking, and they are able to learn from others in both opinion and behavior.

In this paper we will apply opinion dynamics to modeling pre-evacuation behavior of crowd. The pre-evacuation time of each individual agent is updated by Equation (7).

$$tpre_i(t+1) = (1-p_i)\,tpre_i(t) + p_i\,tpre_{others}(t) \qquad tpre_{others}(t) = \left(\textstyle\sum_{R_i} tpre_j(t)\right)/N \tag{7}$$

The pre-evacuation time of an individual $tpre_i$ is updated by mixing itself with the average pre-evacuation time of surrounding ones within radius R_i. Both options are weighted with some parameter ($1-p_i$) and p_i, and two options follow two-point distribution with probability ($1-p_i$) and p_i, and $tpre_i$ is updated by the statistical average. As a result, individualistic behavior is dominant if p_i is low whereas herding behavior emerges if p_i is high.

As below we illustrate a simulation result of herding behavior with group dynamics. The red agent has *tpre* much earlier than the green ones, and when it interacts with the green agents, Equation (7) is effective to drive the green agents move out earlier with the red one. As a result, the red one will lead the entire group in egress and the herding effect is well observed in the result.

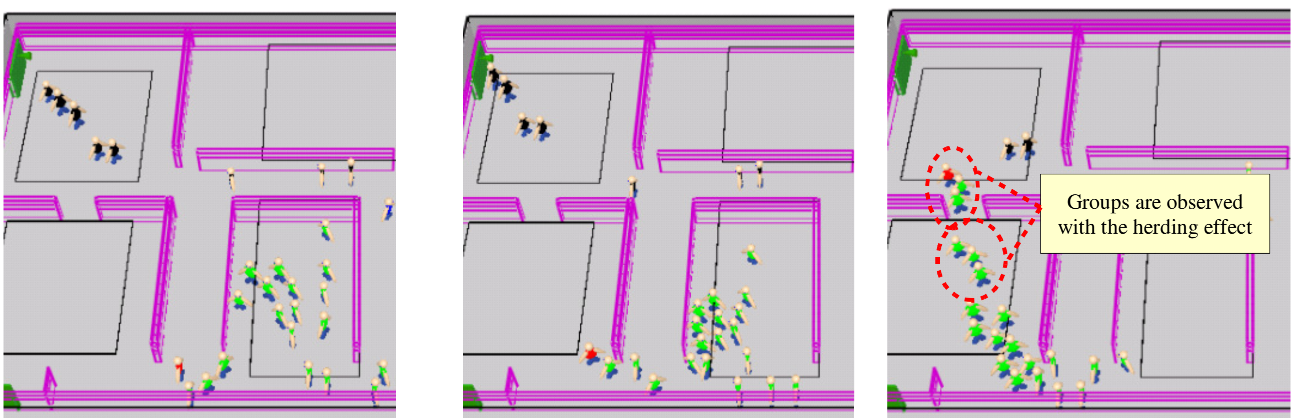


Figure 5 Herding Effect in Pre-Evacuation Stage

In the above simulation result group dynamics are also identified. The red agent together with two green agents forms a small group and they move earlier than other green ones. The herding effect of pre-evacuation behavior does not only exist in this small group, but also between this group and other follower green agents. Thus, the herding effect is a mixture of intra-group and inter-group dynamics, and it is observed by pre-evacuation scenarios as above.

With combination of group social force and interactive opinion dynamics, a kind of convergent pattern is supposed to emerge in a crowd. Here the social cohesion and opinion effect are related but different concepts in group formation. Social cohesion describes the social relationship of individuals, and it emphasizes whether there is a social tie between individuals, and it brings people together. When people are close to each other sufficiently, herding behavior becomes effective. The herding effect, or generally considered as opinion dynamics, emphasizes how an individuals' opinion interacts with others' to form a common motive or destination. Suppose you meet your friend on the street, but if you do not have a common destination, you and your friend will head to each destination individually after greeting or talking briefly. Another example is evacuation of a stadium where people follow the crowd flow to move to an exit. There are a multitude of small groups composed of friends or family members, and they keep together in egress because of their social relationship. These small groups also compose a large group of evacuees, and herding effect widely exists among these small groups, contributing to form a collective pattern of motion. In sum, group social force makes individuals socially bonded with each other, and it emphasizes the social relationship of individuals. Opinion dynamics does not focus on such social relationship, but emphasizes people tend to follow their neighbors' characteristic or choices, and thus help to form a common motive.

APPENDIX

!! Group social force is added. Here I declare a 2D matrix when the number of EVAC lines is determined. Users may initialize or modify the matrix by using EVAC Namelist, and this matrix characterizes the social relationship of agents.

!! The total number of groups is NPC_EVAC, then DFAC AFAC and BFAC are in dimension of NPC_EVAC*NPC_EVAC.

!! DFAC: DFactor(I, IE)   AFAC: AFactor(I, IE)   BFAC: BFactor(I, IE)

!! I: Index of the current agent (outer loop)   IE: Index of the other agent (inner loop)

!! The following Fortran code is in the loop where social force is computed.

!! GROUP_FORCE is a boolean variable which enables the group dynamics in computation.

```
FCG_X = 0.0_EB
FCG_Y = 0.0_EB
IF (GROUP_FORCE) THEN
   TIM_DIST = MAX(0.001_EB,SQRT((X_TMP(2)-X_TMP(5))**2 + (Y_TMP(2)-Y_TMP(5))**2))
   FCG_X = (X_TMP(2)-X_TMP(5))*HR_A*AFAC*COSPHIFAC*EXP( -(TIM_DIST-( R_TMP(2)+R_TMP(5) )
              *DFAC)/HR_B/BFAC)/TIM_DIST*(( R_TMP(2)+R_TMP(5) )*DFAC-TIM_DIST)
   FCG_Y = (Y_TMP(2)-Y_TMP(5))*HR_A*AFAC*COSPHIFAC*EXP( -(TIM_DIST-( R_TMP(2)+R_TMP(5) )
              *DFAC)/HR_B/BFAC)/TIM_DIST*(( R_TMP(2)+R_TMP(5) )*DFAC-TIM_DIST)
END IF

!HR_A_CF
!HR_B_CF
HR%FX_Group = HR%FX_Group + FCG_X
HR%FY_Group = HR%FY_Group + FCG_Y
```

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