Modeling group structures in pedestrian crowd simulation

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A B S T R A C T

Grouping is a common phenomenon in pedestrian crowds and plays important roles in affecting crowd behavior. Group modeling is still an open challenging problem and has not been incorporated by existing crowd simulation models. Motivated by the need of group modeling for crowd behavior simulation, this paper presents a unified and well-defined framework for modeling the structure aspect of different groups in pedestrian crowds. Both intra-group structure and inter-group relationships are considered and their effects on the crowd behavior are modeled. Based on this framework, an agent-based crowd simulation system is developed and crowd behavior simulations using two different group structures are presented. The simulation results show that the developed framework allows different group structures to be easily modeled. Besides, different group sizes, intra-group structures and inter-group relationships can have significant impacts on crowd behaviors.

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1. Introduction

Modeling and simulating crowd behaviors has been an active research topic in recent years. It has been studied in many disciplines, such as safety and civil engineering, transportation research, social science, and computer games. Simulations of pedestrian crowd study a crowd of people's movement behavior in a virtual environment. These simulations have been used to study the evacuation behavior in emergent situations, such as building on fire, to test the reliability of architectural design, and to aid the design of 3D animation etc. Over the years, researchers have developed many models to simulate pedestrian crowds. These include physics-inspired models such as Helbing's social force model [8], cellular automata models based on predefined rules [4], and agent-based models that use multiple agents to simulate a crowd where each agent has its own behavior and interacts with other nearby agents [26,37].

Grouping is a common phenomenon in pedestrian crowds. As discussed in [2], crowds contain both isolated individuals as well as persons in groups. Considering a scenario of a shopping mall or a museum, family members walk beside each other in a clustered way; friends stay together and maintain the group during their movement. This kind of grouping relationship is an important characteristic of pedestrian crowd, and can play important roles in crowd behavior. Nevertheless, group modeling is still an open challenging problem in pedestrian crowd simulations [17]. Little work incorporates the influence of groups on the dynamics of crowd movement. One important aspect of group modeling is modeling the structure of various groups. As discussed in [13], different group structures affect the flow as well as evacuation efficiency in emergency situations, e.g., a leader–follower structure may be more smooth and efficient than a clustered structure if a group has a large number of members. In this case, a clustered group structure can result in slow movement, especially in a constrained area. It is the belief of this paper that modeling group structures can lead to more realistic crowd behavior simulations, and modeling group structures can facilitate the understanding of the effect of grouping on crowd behavior.

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To effectively model group structure, it is important to define a unified framework that captures the essential features of various intra-group connections and inter-group relationships. This is challenging due to the heterogeneity nature of different groups and many factors that need to be considered, such as individual characteristics, group size, relationships among groups, and influences among group members [1,13]. In this work, we model the group structure of a pedestrian crowd from two aspects, intra-group structure and inter-group relationship. Intra-group structure refers to the network relationship among the members inside a group. Similar to the work of [23] where interpersonal interaction is modeled to study navigation behaviors of humans that socially interact with virtual agents, intra-group structure captures not only the relationship network structure among group members, but also the strength of the relationships, e.g., the degree of liking and familiarity. As will be shown later, different intra-group structures give rise to different shapes of a group. Different from the intra-group structure, the inter-group relationship refers to the relationships among different groups. This is used to model the fact that groups also influence each other. For example, it is common for a group to follow other nearby groups during an emergency evacuation process [21,23]. In this work, both intra-group structure and inter-group relationship are specified by a two-dimensional matrix. The goal is to provide a unified and well-defined framework to model the different group structures and to study their effects on crowd behavior.

The remainder of this paper is organized as follows. Section 2 reviews the related work in crowd behavior simulation and group modeling. Section 3 presents the unified framework that models both the intra-group structure and inter-group relationship of pedestrian crowds. Section 4 describes an implementation of this framework in an agent-based simulation environment. Sections 5 and 6 provide experiment results to demonstrate and to quantify the grouping effect on crowd behaviors from three aspects: inter-group relationship, intra-group structure, and group size. Section 7 discusses several possible extensions of this work. Finally, we summarize and discuss the major findings, evaluate the model scope and provide some directions for future work.

2. Related work

Pedestrian crowd simulation has been widely studied using different models. A well-known model is Helbing’s physics and social force model [8] where the pedestrian behavior is described as the vector addition of the separate force terms reflecting different environmental influences. This model has successfully simulated several important features of crowd behavior, such as lane formation in crowds with opposite walking direction, oscillations of the crowd passing direction at a bottleneck, alternating collective patterns of motion at intersections and so on. Kaup’s work [9] extends Helbing’s model to produce more realistic behaviors of an individual pedestrian under panic or non-panic conditions. Blue’s work [4] simulates bi-directional pedestrian flow using a small set of rules under a cellular automata micro-simulation. It shows that the micro-level behaviors can be captured while attaining realistic macro-level activity. Schadschneider’s work [32] uses floor field to model the long-range individual interactions. It allows simulations of large crowds faster than real time since only nearest-neighbor interactions are included in the model. In a different perspective, Hoogendoorn et al. [15] models pedestrian walking under three inter-related levels, strategic level, tactical level and operational level, which can simulate fundamental characteristics of pedestrian flows. Antonini et al. [14] proposed a discrete choice framework for pedestrian modeling, where a plausible behavioral model is provided. Hughes [16] proposed a continuum theory where the equations for the two-dimensional flow of pedestrian motions are derived for flows of both single and multiple pedestrian types. The work of [19] explored macroscopic behavioral patterns in pedestrian crowds in a large crosswalk through two studies.

An important application area of crowd behavior simulation is emergency evacuation and safe egress. The work of [38] developed a prototype system to study some emergent human and social behaviors, such as competitive, queuing, and herding behaviors, during emergency evacuations. Song et al. [36] introduces the force concept of a social force model into the lattice gas (LG) model which can simulate some basic behaviors of the social force model, for example the arching and clogging behavior. The work of [3] presents a novel methodology involving a Virtual Reality (VR)-based Belief, Desire, and Intention (BDI) framework where the effect of various factors on the simulation metrics such as crowd evacuation time is examined. Advantages and disadvantages of seven models used in the crowd evacuation are compared in the work of [40], which concludes that a variety of different kinds of approaches should be combined to study crowd evacuation. Another application field where crowd behavior simulation has been studied is computer animation and virtual environment, for which a survey can be found in [13]. Crowd simulation in this area pays close attention to real time 3D animation and human computer interaction. The well-known work of [29] presents the steering behaviors of autonomous characters with the ability to navigate around their world in a life-like and improvisational manner. The work of [30] presents an implementation of spatial hashing for PLAYSTATION3 for fast crowd simulation. Bransilav and Daniel [5] proposed a crowd simulation system for interactive virtual environments which is used to create scenario of urban emergency situation. Yu and Terzopoulos [28] proposed a decision network based framework for advanced behavioral animation in virtual humans.

To achieve more realistic simulations, sociological and psychological theories are often incorporated in pedestrian crowd modeling. The work of [38] proposed a computational framework, Multi-Agent Simulation System for Egress analysis (MASS-Egress), where social identity and social proof theories are modeled in human interaction. According to social identity, individuals follow rules or procedures that they see as appropriate to the situation and with which they identify themselves. Social proof is a phenomenon in which individuals, when faced with perceived uncertainty, for example insufficient information about new situations, follow the actions of others to guide behavior. Fridman and Kaminka [25] proposed a crowd
behavior model based on Festinger's Social Comparison Theory, where humans, lacking objective means to evaluate their state, compare themselves to others that are similar. Several other works [10,24,33] incorporate the OCEAN personality model into their simulation system to make the simulation more realistic.

While much research has been conducted in crowd behavior simulation, less work focused on the aspect of grouping and group structures. Yang et al. [22] provided a 2D CA model to simulate the kin behavior in occupant evacuation. It concludes that if the number of the subgroups and the members in each sub-colony is small, the evacuation time and efficiency will not be affected a lot. Otherwise, the evacuation efficiency will be reduced a lot. And the typical phenomena of waiting and back-tracking in real evacuation do reduce the evacuation efficiency. Fridman and Kaminka [25] implemented several crowd behavior scenarios with the existence of individual or grouped pedestrians. Qingge [27] simulated the evacuation of crowd with different groups; and each group is based on a leader–follower model where the leaders find the exit entry and followers follow the nearest follower through a dynamic grouping process based on the A* algorithm. Loscos et al. [6] showed the importance of group behavior in a realistic crowd simulation. Musse and Thalmann [34] explored an approach based on the relationship between the autonomous virtual humans of a crowd and the emergent behavior originated from it. None of these works has considered the various group structures, which can have important impact on crowd behavior. As discussed before, different group structures affect the flow as well as evacuation efficiency in emergency situations, especially in a constrained area.

3. Framework of modeling group structures

A main goal of this research is to define a unified framework to systematically model the different aspects of group structures in pedestrian crowds. In our work, a pedestrian crowd consists of many individuals who can form groups. In the current model, each individual belongs to one and only one group. Note that if an individual does not form group with others, we consider this individual to be a group of itself. With this point of view, a crowd is composed from multiple different groups and each group is composed from different individuals. Two special cases are: (1) each group only has one individual – this is the same case as no group structure is considered; and (2) the whole crowd is a single group.

Each individual has a unique ID and each group has a unique GroupID. The total number of individuals in a group is denoted as the group size. Different groups may have different group sizes. We define that each group has one and only one group leader. The rest of the individuals in the group are group members. By default, the first individual (whose ID is smallest in its group) is the leader in the group. The group leader is considered as a “special” individual in the group because this is the only individual who could be influenced by individuals in other groups due to inter-group relationships (more details are given later). A group member can only be influenced by other members (including the group leader) of the same group. In the following description, members and group members are used interchangeably. Within a group, different individuals influence each other. These member-to-member influencing relationships are referred to as intra-group structure, which is specified by an intra-group matrix. Besides member-to-member influence, different groups may influence each other as well. The group-to-group relationships are referred to as inter-group relationship, which is specified by an inter-group matrix. These two influence matrices: intra-group matrix and inter-group matrix capture all the information needed to specify the group structure in a crowd. Note that the purpose of this work is to simulate a predefined group structure, that is, both the intra-group and inter-group matrices are pre-specified by the user. In other words, we assume that crowd groups are formed when the simulation starts and they will not be changed during the simulation. Possible extensions such as dynamic groups and formation of crowd groups will be discussed in Section 7.

Modeling of each pedestrian individual is inspired by Reynolds’s work [29] where a set of vectors are used to represent the forces applied to an individual. This vector-based approach is flexible, extensible and can be easily implemented. In our crowd system (see Section 4 for more details), each individual has a speed vector for obstacle avoidance behavior, a speed vector for random movement behavior and two speed vectors for maintaining group behavior. At every time step, each individual computes an overall speed vector using the vector addition to govern its movement. The focus of this work is the maintaining group behavior and its speed vectors.

Each individual’s maintaining group behavior is composed of two aspects of movements: Aggregation and Following, which allow an individual to maintain its desired intra-group structure and inter-group relationship. These two aspects of movements are represented by two speed vectors, aggregation vector and following vector, respectively.

- **Aggregation** means an individual moves towards the center of the individuals that are in the same group and have non-zero influences (as defined by the intra-group matrix) on this individual. This center is called the group position, denoted as GP, of this individual.
- **For a group member, Following** means the member heads towards the average moving direction of other group members who are in the same group and have non-zero influences on this member. This is similar to the alignment behavior in Reynolds’s work [29]. For a group leader, **Following** means that the leader follows the moving direction of an individual of a different group to maintain the inter-group relationship. In both cases, the moving direction associated with Following is called the group direction, denoted as GD, of this individual.

**GP** and **GD** are two crucial parameters in the calculation of aggregation vector and following vector. As will be seen in Section 3.3, both aggregation vector and following vector can be calculated directly from these two parameters. Before introduc-
ing how to calculate these two vectors, Sections 3.1 and 3.2 present the modeling of intra-group structure and inter-group relationship, respectively. These two sections also present the calculation of GP and GD based on intra-group and inter-group matrices, and the position and speed vector of other group members.

3.1. Modeling intra-group structures

3.1.1. Intra-group matrix

Each group has an intra-group matrix which is a two-dimensional table, where each element is a real number in the range of [0.0, 1.0]. The number at row with ID i and column with ID j, denoted as \( l(i, j) \), defines how much pedestrian i’s movement is influenced by pedestrian j due to the intra-group structure. Since each \( l(i, j) \) has a value, the intra-group matrix specifies not only the network structure of influences among the individuals, but also the strength of the influences. For example, \( l(i, j) = 0.0 \) means pedestrian j has no influence on pedestrian i, and \( l(i, j) = 1.0 \) means pedestrian i is fully influenced by pedestrian j. An intra-group matrix with all elements being 0.0 represents the case that individuals of the same group have no influence to each other. Table 1 shows a sample intra-group matrix for a group having three pedestrians with ID 0, 1 and 2, among which Pedestrian_0 is the group leader. As can be seen from Table 1, Pedestrian_1 is influenced by Pedestrian_0; Pedestrian_2 is influenced by Pedestrian_1; and Pedestrian_0 (the leader) is not influenced by other pedestrians. Because of these influence relationships, Pedestrian_2 follows Pedestrian_1, which in turn follows the Pedestrian_0 (the leader). As will be discussed later, this table defines a linear group structure.

Note that in the current model all agents in the group share the same intra-group matrix. We think this makes sense especially when group size is small. However, when group size increases to a large-scale, it may not be practical for all agents in the group to have such global information, i.e., the shared intra-group matrix. In that case, each agent can have its own intra-group matrix based on its own view of the group structure. This is not considered in this paper but can be easily extended.

Besides the intra-group matrix, three other parameters are used to describe how far pedestrians can stay away from each other within the same group: SideDist, CenterDist, and DesiredDist.

- **SideDist** is the maximum perpendicular distance from GP to the line indicated by the individual’s current moving direction. Such a perpendicular distance is also called side distance.
- **CenterDist** is the maximum Euclidian distance from GP to the individual’s current position. Such a Euclidian distance is also called center distance.
- **DesiredDist** is the desired distance from GP to the individual’s current position. It is the maximum distance the individual wants to maintain during the movement. This is also called desired distance.

At every time step, the current center distance and side distance will be calculated. Only if center distance is greater than desired distance, the individual’s maintaining group behavior will be triggered. During this process, the center distance and side distance are used to calculate the weight of the aggregation vector (see Section 3.3 for more details). They accelerate the aggregation movement, as long as the moving speed does not exceed a predefined maximum speed. The smaller the center distance and side distance, the faster an agent will move towards the group center GP, and the more compact the group will be.

3.1.2. Calculation of GP and GD for group members

Recall that GP is the group position an individual should move towards and GD is the average moving direction of other group members that have non-zero influences on the individual. Eqs. (1) and (2) show how GP and GD are calculated based on the intra-group matrix and the positions and speed vectors of other group members. Suppose the intra-group matrix is labeled with \( l(i, j) \) where i, j is ID of pedestrian i and j. \( N_i \) is the total number of group members that are in the perception range (see the perception model later) of pedestrian i. Note that only those pedestrians that belong to the same group of pedestrian i are counted. \( \text{CurrentPosition}_j \) and \( \text{SpeedVector}_j \) are the current position and speed vector of pedestrian j, respectively.

\[
GP_i = \left( \sum_{j=1}^{N_i} l(i, j) * \text{CurrentPosition}_j \right) / N_i
\]

\[
GD_i = \left( \sum_{j=1}^{N_i} l(i, j) * \text{SpeedVector}_j \right) / N_i
\]

Table 1

A sample intra-group matrix.

<table>
<thead>
<tr>
<th>ID</th>
<th>Pedestrian_0</th>
<th>Pedestrian_1</th>
<th>Pedestrian_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian_0</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pedestrian_1</td>
<td>1</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Pedestrian_2</td>
<td>0</td>
<td>1</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Note that Eqs. (1) and (2) only apply group members. Generally, the greater the perception range, the more neighborhood members can be detected, thus, the more likely the computed \( GP \) and \( GD \) will be the global group center and group direction (where all members of the same group are involved in the computation), and the faster the desired group structure will be formed. For a group leader \( i \), \( GP_i \) and \( GD_i \) is the position and moving direction of some individual in other groups, respectively. For both group member and group leader \( i \), the direction of the aggregation vector is the direction from \( i \) to \( GP_i \), and the direction of following vector is the direction indicated by \( GD_i \). The calculation of \( GP \) and \( GD \) for a group leader will be based on inter-group relationships. This is described in the following sections.

3.2. Modeling inter-group relationships

3.2.1. Inter-group matrix

Besides the influence between group members, different groups may also influence each other. As an example, a group may follow other nearby groups during an emergency evacuation process because of the lack of objective evaluation of the emergent situations [25]. In our work, this kind of inter-group relationship is specified by an inter-group matrix. Similar to intra-group matrices, the inter-group matrix is a two-dimensional table, which specifies the group-to-group relationships. Note that there is only one inter-group matrix for the whole crowd, while each group may be configured with different intra-group matrices.

Similar to the intra-group matrix, each element in the inter-group matrix is a real number in \([0.0, 1.0]\). The element at row with GroupID \( i \) and column with GroupID \( j \), denoted as \( E(i, j) \) specifies how much group \( i \) (specifically the group leader of that group) is influenced by the individuals in group \( j \). Value 0.0 means that the row group is not influenced by the column group even when the two groups are close to each other. Value 1.0 means the row group is fully influenced by the column group if the two groups are close to each other. Note that the situation of no inter-group relationships can be represented by setting all elements of the inter-group matrix to be 0.0. Table 2 shows a sample inter-group matrix for a crowd including four groups with GroupID 0, 1, 2 or 3, all of which fully influence each other (because all elements in the inter-group matrix have value 1.0). Based on definitions of intra-group matrix and inter-group matrix, one can see there are two ways to specify a crowd that is equivalent to having no group structure: (1) the whole crowd is one group and the intra-group matrix elements are all zero; and (2) each group in the crowd has only one individual and the inter-group matrix elements are all zero.

3.2.2. Calculation of \( GP \) and \( GD \) for group leader

As mentioned before, only the group leader is influenced by individuals in other groups. The goal of modeling inter-group relationships is to let each group leader follow the individual that has the greatest influences on the leader. To do this we need to calculate each individual’s influence weight. Note that we only consider the individuals that are from different groups. In this work, the calculation of influence weight is based on Festinger’s Social Comparison Theory presented in the work of [25]. The idea is to select the individual that has greatest similarity as the one that has greatest influence on the group leader. This similarity depends on not only the inter-group relationships between the two groups that the leader and the individual belong to but also the Euclidian distance between the leader and the individual.

Specifically, suppose the inter-group matrix is \( E \) and each element of the matrix is \( E(G(i), G(j)) \), where \( G(i), G(j) \) is GroupID of the groups which pedestrian \( i \) and \( j \) belong to, respectively. Suppose pedestrian \( i \) is a group leader. Eqs. (3)–(5) show the decision of leader \( i \). For each pedestrian \( j \) from another group in the perception range of leader \( i \), the similarity between \( i \) and \( j \) is calculated using Eq. (3). As can be seen, the greater the inter-group relationship between two groups, and the closer the distance from \( i \) to \( j \) is, the more likely leader \( i \) will choose pedestrian \( j \) to follow. Eqs. (4) and (5) show that the pedestrian with the greatest similarity is selected as the one to follow. If no such pedestrian exists, leader \( i \) will not follow any other individual.

\[
\text{Similarity}_j = \frac{E(G(i), G(j)) + 100}{\text{EuclidianDistBetween}(i, j)}
\]

(3)

\[
\text{MostSimilarId} = \text{Maximum}(\text{Similarity}_1, \ldots, \text{Similarity}_n)
\]

(4)

\[
\text{PedestrianToFollow} = \begin{cases} \text{Pedestrian with MostSimilarId} & \text{If MostSimilarId exists} \\ \phi & \text{Otherwise} \end{cases}
\]

(5)

The specific procedure for leader \( i \) to find a pedestrian (of other groups) with the greatest similarity is shown in Fig. 1.

<table>
<thead>
<tr>
<th>GroupID</th>
<th>Group_0</th>
<th>Group_1</th>
<th>Group_2</th>
<th>Group_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group_0</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Group_1</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Group_2</td>
<td>1</td>
<td>1</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Group_3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2
A sample inter-group matrix.
The procedure shows that only nearby pedestrians who belong to the different group are considered as candidates. Leader $i$ selects the one with greatest similarity value to follow. Once a valid $\text{PedestrianToFollow}$ is found, $GP_i$ and $GD_i$ for leader $i$ is the position and moving direction of $\text{PedestrianToFollow}$, respectively. Otherwise, leader $i$ will not follow any pedestrian from other groups.

### 3.3. Calculation of the following and aggregation vectors

With the value of $GP$ and $GD$, the following vector and aggregation vector can be calculated. Fig. 2 shows a scenario where the two vectors of pedestrian $s$ are presented. Without loss of generality, suppose pedestrian $s$ is moving horizontally from right to left. The elliptical area represents a perception model of each pedestrian (see Section 4 for a specific perception model). Pedestrian $c$, $d$, and $e$ are neighbors in the perception range of $s$, where pedestrian $c$, $d$, $e$ and $s$ belong to the same group. The black solid circle is denoted as the group position $GP_s$ that $s$ should move towards. The side distance and center distance are denoted as $sd$ and $cd$, respectively.

Let $v_1$ and $v_2$ be following vector and aggregation vector, respectively. There are two assumptions. One assumption is that neighbors in perception range of $s$ are $c$, $d$, and $e$, which have non-zero influence on $s$. The other assumption is that the direction of $v_1$ is the average moving direction of those neighbors.

Eqs. (6)–(8) show the calculation of $v_1$. Speed is the current moving speed of pedestrian $s$, and $a$ is the direction indicated by $GD_s$. For a group leader, it follows the moving direction of $\text{PedestrianToFollow}$; while for group members, they follow the average moving direction of nearby neighbors in perception range.

$$v_1 = \text{factor} \times (\text{Speed} \times \cos(a), \text{Speed} \times \sin(a))$$

$$\text{factor} = \begin{cases} T & \text{s is a group leader} \\ 1.0 & \text{s is a group member} \end{cases}$$

$$T = \begin{cases} 0.0 & \text{PedestrianToFollow} = \phi \\ 1.0 & \text{Otherwise} \end{cases}$$

The calculation of $v_2$ is shown in Eqs. (9)–(12). $a$ is the direction from $s$ to $GP_s$. If $s$ is a group leader, $\text{factor}$ is calculated through Eq. (11). Otherwise, $\text{factor}$ is calculated through Eq. (10). The Euclidian distance from $s$ to $\text{PedestrianToFollow}$ is denoted as $\text{dist}$. For each individual, it moves towards $GP$ and tries to keep the distance from the individual to $GP$ within DesiredDist. For group members, they also move towards each other to satisfy the predefined CenterDist and SideDist.

---

**Fig. 1.** Procedure of finding the most similar pedestrian.

**Fig. 2.** Brief description of two vectors.
\[ v/2 = \text{factor} \times (\text{Speed} \times \cos(a), \text{Speed} \times \sin(a)) \]  
\[ \text{factor} = \begin{cases} \text{cd}/\text{CenterDist} & \text{cd} > \text{CenterDist} \\ \text{sd}/\text{SideDist} & \text{cd} \leq \text{CenterDist} \text{ and } \text{sd} > \text{SideDist} \\ 0.0 & \text{Otherwise} \end{cases} \]  
\[ \text{factor} = \begin{cases} E \times 20 \times \text{DesiredDist}/\text{dist} & \text{PedestrianToFollow} \neq \phi \\ 0.0 & \text{Otherwise} \end{cases} \]

\[ E = E(G(s), G(\text{PedestrianToFollow})) \]

The overall speed vector to govern the maintaining group behavior is the vector addition of \( v_1 \) and \( v_2 \). For an individual \( s \), it will try to move towards \( G_P \), to keep within \( \text{ DesiredDist } \) (not shown in Fig. 2), and try to follow the direction \( GD_s \). In this way, both the intra-group structure and the inter-group relationship can be maintained.

### 4. An agent-based simulation system for modeling crowd behavior with group structures

Based on the described framework for modeling group structure, this section provides a specific implementation by adopting agent-based approach. The system is built on the Craig Reynolds’s OpenSteer environment [29], where each agent represents an autonomous pedestrian with the ability of random movement, obstacle avoidance, and maintaining group. The specification of the system is shown in what follows.

The system contains a crowd and a rectangle environment with walls situated around it. The system may also include other stationary obstacles, for example columns. The crowd is described by \((\text{Groups})\), where \((\text{Groups})\) specify that the crowd contains a set of groups, each of which has a configurable group size; \( \text{inter-group matrix} \) is used to model the group-to-group relationships. Each group can be described as \((\text{Agents})\), \( \text{intra-group matrix} \), where \((\text{Agents})\) is a set of individual agents in the group; \( \text{intra-group matrix} \) is used to model the member-to-member influences. Either \( \text{inter-group matrix} \) or \( \text{intra-group matrix} \) is a two-dimensional table (see details in the previous section).

In our simulation, each agent adopts a behavior-based control model [11,37]. Specifically, each agent has a set of behaviors, such as random movement, obstacle avoidance and maintaining group. Each of these behaviors is a steering behavior excited by some “sensory” inputs. These behaviors compete with each other using a mutual inhibition mechanism. The winner behavior controls the agent to carry out the associated action for that time step. More details of this behavior-based model can be found in [11,37]. Note that the maintaining group behavior, used for the agent to maintain group structures, is one of the behaviors of the agents.

Specifically, each agent is described by \((\text{Role}, \text{GP}, \text{GD}, \text{Direction}, \text{Speed}, \text{MaxSpeed}, \text{GroupID}, \text{ID}, \text{DesiredDist}, \text{CenterDist}, \text{Radius}, \text{PerceptionModel}, \text{BehaviorBasedModel}, \ldots)\), where \( \text{Role} = \{\text{group leader}, \text{group members}\} \). As mentioned before, \( \text{GP} \) is the group position the agent should move towards; \( \text{GD} \) is the average moving direction of local agents of the same group; \( \text{Direction} \) and \( \text{Speed} \) specify the moving speed and direction of the agent, respectively; \( \text{MaxSpeed} \) specifies the maximum moving speed of agents, which is not changed during the simulation; \( \text{GroupID} \) specifies which group this agent belongs to; \( \text{ID} \) specifies the order of this agent in its group, which is assigned automatically; \( \text{DesiredDist}, \text{CenterDist} \) and \( \text{SideDist} \) are three parameters in modeling the intra-group structures (see details in Section 3.1.1). Each agent is represented as a circle shape whose radius is specified by \( \text{Radius} \). \( \text{PerceptionModel} \) specifies the visible distance and range of this agent. \( \text{BehaviorBasedModel} \) specifies how an agent decides its movement. In this work, each agent has three behaviors: \( \text{RandomMove}, \text{Avoid} \) and \( \text{MaintainGroup} \), which are described blow.

- \( \text{RandomMove} \): moving to a randomly generated destination;
- \( \text{Avoid} \): avoiding collision with obstacles (i.e. walls) and other agents;
- \( \text{MaintainGroup} \): maintaining the intra-group structure and the inter-group relationship.

The details of \( \text{PerceptionModel} \) and \( \text{BehaviorBasedModel} \) are presented in Sections 4.1 and 4.2, respectively.

#### 4.1. Agent perception model

Similar to the work of [31], the perception model specifies an elliptical area which each pedestrian can perceive, as shown in Fig. 3. The current moving direction of the pedestrian is indicated by the arrow labeled with “Direction”. \( \text{Dist1} \) and \( \text{Dist2} \) represent the maximum front and side distance for visibility respectively. \( \text{Angle} \) indicates half of the maximum visibility range the pedestrian can detect. Each pedestrian is equipped with this perception model which is used to detect local (neighborhood) pedestrians. In this work, \( \text{Dist1}, \text{Dist2}, \) and \( \text{Angle} \) are 20 \( \text{Radius} \), 6 \( \text{Radius} \), and 120 degrees, respectively.
4.2. Agent behavior models

As mentioned before, each agent adopts a behavior-based control model [11,37] and has three steering behaviors. In each step, these behaviors compute their own excitation levels and mutually inhibit each other. Then the behavior with the highest activation level is selected as the one to decide the agent’s movement in that step. Below we describe each behavior, and show how its excitation is calculated and the action associated with it. The detail implementation will be skipped for simplicity. Also, the maximum moving speed \( \text{MaxSpeed} \), 0.5, is same among all agents and kept unchanged during the simulation.

4.2.1. Behavior: RandomMove

This behavior is used to simulate the random movement of each agent. The moving path is the shortest path from the agent’s current location to the destination, computed through the Dijkstra algorithm. When a specific destination is reached, the agent will move to another destination which is generated randomly.

- **Excitation**: \( Ex = 0.6 \), which means that this behavior will be moderately excited.
- **Action**: If the agent is not at the destination area, it walks towards the destination according to the shortest path. Otherwise, if it arrives at its destination, it will move to a new destination that is randomly generated.

4.2.2. Behavior: Avoid

This behavior is used to simulate the obstacle avoidance in the movement. When an agent is within a predefined minimum distance from the nearest-neighbor agent or obstacle, it will stay away from it.

- **Excitation**: The excitation of this behavior is calculated through Eq. (13),

\[
Ex = \begin{cases} 
\exp\left(1 - \frac{\text{closestDistToObstacle}}{(1.5 + \text{Radius})}\right) & \text{To avoid wall or column} \\
\exp\left(1 - \frac{\text{closestDistToAgent}}{(2.5 + \text{Radius})}\right) & \text{Otherwise}
\end{cases}
\]  

where \( \text{closestDistToObstacle} \) is the distance from the agent to the surface of the closest obstacle to avoid and \( \text{closestDistToAgent} \) is the distance from the agent to the center of the closest agent to avoid. Note that the closest obstacle or agent should be within the perception range of the agent. Otherwise, \( \text{closestDistToObstacle} \) and \( \text{closestDistToAgent} \) will be positive infinity.

The constant factors 1.5 and 2.5 indicate that once the safety margin between the agent and the nearest wall or agent is less than half of \( \text{Radius} \), this behavior will be excited. The exponential function indicates that as \( \text{closestDistToObstacle} \) or \( \text{closestDistToAgent} \) decreases, the more likely this behavior will be excited.

- **Action**: The separation and friction forces from the wall and the closest agent are applied on the agent and the acceleration (or deceleration) is calculated, the velocity is updated and the agent moves one step according to the direction indicated by the velocity.

4.2.3. Behavior: MaintainGroup

This behavior let agents maintain both the intra-group structures and the inter-group relationship during the movement.

- **Excitation**: The excitation of this behavior is calculated in the following Eq. (14),

\[
Ex = \begin{cases} 
\exp\left(\frac{\text{Dist}(\text{myPos}_i, GP_i) - \text{DesiredDist}}{3}\right) & \text{For group members} \\
\exp\left(\frac{\text{Dist}(\text{myPos}_i, GP_i) - 20 \times \text{DesiredDist}}{3}\right) & \text{For group leaders}
\end{cases}
\]  

where \( \text{Dist} \) is used to calculate the Euclidian distance from agent \( i \) to its group position \( GP_i \). \( \text{myPos}_i \) is the position of agent \( i \). The exponential function indicates that as \( \text{Dist} \) decreases, the more likely this behavior will be excited.
• Action: GP, GD, and the following and aggregation vector are computed based on the specific group structure and inter-group relationship. The overall speed vector is calculated as the vector addition of these two speed vectors. The computing agent moves within the predefined maximum speed in the direction indicated by the overall speed vector.

We note that since MaintainGroup is one of the three behaviors, an agent maintains its group only when the MaintainGroup behavior is selected. This may result in situations such as the MaintainGroup behavior is not selected thus causing agents do not maintain their groups. For example, in the very crowded environment, a group can be separated by members from other groups. In such situation, collision avoidance will have a higher priority which makes the agent avoid collision with others, rather than maintain its group. Also note that since our focus is the simulation of group structures, the avoid behavior used in this paper is simple, e.g., sometimes agents will still intersect with others using the current avoid model. Also for simplicity the environment is not explicitly modeled and obstacles are not included in this paper.

5. Effect of grouping on crowd behavior

Based on the proposed agent-based simulation system, this section illustrates several studies of group modeling. It shows how different parameters, for example group size, intra-group structure and inter-group relationships, affect the crowd movement. The effect of the two aspects, group shape and member-to-member influence strengths, of the intra-group structure will be explored first. Two typical group shapes, a linear shape and a leader-follower shape, are considered.

In the linear shape, members of the same group move in a line formation. Each group member follows another member. The intra-group matrix \( I \) is defined in Eq. (15), which indicates that member \( i \) will follow the member \( j \) with an ID which is one less than the ID of member \( i \).

\[
I(i,j) = \begin{cases} 
c & i! = 0 \text{ and } j = i - 1 \\
0.0 & \text{Otherwise}
\end{cases}
\] (15)

In the leader–follower shape, members follow the group leader during the movement. The intra-group matrix \( I \) is defined in Eq. (16), which indicates that all members will move close to the leader.

\[
I(i,j) = \begin{cases} 
c & i! = 0 \text{ and } j = 0 \\
0.0 & \text{Otherwise}
\end{cases}
\] (16)

In Eqs. (15) and (16), \( c \) is a positive real number defined in \((0.0, 1.0]\), which indicates the member-to-member influence strength. In both shapes, the group leader finds the path and moves forward. Figs. 4–6 show three group shapes, linear, leader-follower and mixed respectively. For each group shape, the intra-group matrix and a simulation scenario are given. Blank
cells in intra-group matrices indicate the corresponding elements being 0.0. These three figures show how to use an intra-group matrix to present the desired group shape and use the proposed system to simulate it. First, the group shape is presented as a network structure (Figs. 4–6a). The relationships between network nodes are then expressed in the intra-group matrix (Figs. 4–6b). Finally, the group shape is simulated (Figs. 4–6c).

For a developed shape, the effect of member-to-member influence strengths can also be investigated through the simulation system. To show the effect of member-to-member influence strengths, we consider a linear group shape under four intra-group matrices: one with all elements in the intra-group matrix being 1.0, one with all elements in the intra-group matrix being 0.7, with all elements in the intra-group matrix being 0.4, and the other with elements being 0.1. The effect of intra-group influences is measured by the average distance, from group members of the first group to its group center GP. The crowd contains 10 groups, each of which has 6 agents. To only show the effect of intra-group influence strengths, there is no inter-group relationship between groups.

Fig. 7a shows a simulation scenario of a full member-to-member influence on crowd behavior. The average distance from members of the first group to its group center, for the four intra-group matrices, is shown in Fig. 8. For all four intra-group matrices, the average distance is measured over same simulation time interval. In Fig. 8, “I=C” represents the case that all elements in the intra-group matrix are C. As can be seen, intra-group influence strength does affect the crowd movement. The greater the intra-group influence strengths, the smaller the average distance since the greater the intra-group influence weights, the more compact the group shape will be, thus the average distance is less than that of smaller intra-group influence strengths. For example, the average distance of the case “I=0.7” is less than that of the case “I=0.4”. For the comparison purpose, a simulation of the crowd without group structures is shown in Fig. 7b. Correspondingly, the average distance for the crowd without group structures (I= 0.0) is also shown in the top-most curve in Fig. 8. In this case, the average distance is the mathematical average of the distance from the first 6 members to the center of these members. As can be seen in Fig. 8, the crowd without group structures has greater average distance than the crowd with group structures, since without group structures, each individual moves randomly and no specific shape will be formed.

Besides intra-group structure, inter-group relationships also have effect on crowd behavior. The effect is shown in Fig. 10 where four inter-group matrices: one with all elements in the inter-group matrix being 1.0, one with all elements in the inter-group matrix being 0.7, with all elements in the inter-group matrix being 0.4, and the other with elements being 0.1, are
studied. The crowd contains 10 groups, each of which has 6 agents. Each group takes a leader-follower group structure with all elements of the intra-group matrix are 1.0 ($c = 1.0$ in Eq. (16)). The effect of inter-group relationships is measured by the number of clusters at a specified simulation time. The rationale is that, the greater the inter-group relationship, the more likely two groups will move together and a larger cluster will be formed. Thus the number of clusters can represent the strength of group-to-group relationships. Each cluster could contain several groups. The calculation of the number of clusters is based on the QT (quality threshold) clustering algorithm presented in the work of [20] where the closest distance between two clusters is no more than the quality threshold, which is 8 times the pedestrian radius $R$. Procedure of the modified QT clustering algorithm is shown in Fig. 9. Once pedestrian $j$ is added into a cluster, the members (including the leader) of the group which pedestrian $j$ belongs to are also added into the same cluster since group members generally stay together during the movement.

As can be seen in Fig. 10, as the inter-group relationship becomes greater, the number of clusters is decreasing. Since the greater the inter-group relationship, the more likely a group leader will follow other groups, and the closer the group leader will move towards other groups, as well as the higher probability that a larger cluster will be formed. As an example, when the inter-group relationship is 1.0 (see Fig. 10d), many groups move together and a large cluster is formed, and the number of clusters is much less than that of other three cases.

As indicated by the work of [13], group size may also affect the crowd movement. To only explore the effect of different group sizes, the inter-group relationship $E$ is set as 0.0 and intra-group structure $I$ is set as 1.0. The effect of group sizes is measured by the number of clusters. Fig. 11 presents a simulation scenario of a grouped crowd. Group size is 5. The number of clusters for different group sizes is shown in Fig. 12.

As can be seen, the larger the group size, the fewer the formed clusters, because it is more likely that pedestrians will follow each other. When the group size is large enough (greater than or equal to 12), the number of clusters is same as

![Fig. 8. Average distance from members of the first group to its group center.](image-url)

```plaintext
procedure QT_Modified_Clust(G, d)
1 if |G| ≤ 1 then output G, else do
2 for each $i \in G$
3 set flag = TRUE; set $A_i = \{i\}$; /* $A_i$ is the cluster started by $i$*/
4 while flag = TRUE and $A_i \not\in G$
5 find $j \in (G - A_i)$ such that $diameter(A_i \cup \{j\})$ is minimum;
6 if $diameter(A_i \cup \{j\}) > d$
7 then set flag = FALSE;
8 else /* Also add all members of the group to cluster $A_i$*/
9 find all members (including the leader) $T$ of the group $j$ belongs to;
10 for each $t \in T$
11 if $t \not\in A_i$, then set $A_i = A_i \cup \{t\}$;
12 end for;
13 end while;
14 end for;
15 identify set $C = \{A_1, A_2, ..., A_{10}\}$ with maximum cardinality;
16 output $C$;
17 call QT_Modified_Clust(G - C, d);
end procedure QT_Modified_Clust.

Fig. 9. Algorithm QT_Modified_Clust takes as input the set $G$ of pedestrian positions and a diameter threshold $d$, and returns a set of clusters.
```
the number of groups, since pedestrians in the large group cannot move so freely as that in the small groups, and the probability that pedestrians follow each other is less than the small groups.

In summary, group size, intra-group structure and inter-group relationship have effect on crowd behaviors. The proposed framework can be used to simulate desirable group structures. A further quantitative exploration of the proposed framework will be described in next section.
Designing experiments for pedestrian crowd simulation is also a challenging task, since many input factors and output responses, and their relationships should be considered. An interesting work related to experimental design, as well as the identification of the process variables of interest, is proposed by Daamen and Hoogendoorn [7]. To simplify the experiments, we only focus on the effect of intra-group structure, inter-group relationships and group sizes, on one of two principal characteristics of pedestrian movement, the flow. Pedestrian flows are important in the design of pedestrian facilities, such as shopping mall, bus station, museum, and so on. The simulation includes 60 agents which are situated in a circular rectangle-shaped hallway environment with the size 600 in length and 200 in width. A simulation scenario of the environment is shown in Fig. 13, where the lane width is 50.

To calculate the flow, we defined a virtual “gate” in the hallway (in the middle of top most lane), and monitored agents that move through them during a specified simulation time interval. Similar to the work of [18,25,35], the flow is then calculated as the number of agents passed by the “gate” divided by the length of the simulation interval. Two experiments are designed to show the effect of intra-group structure, inter-group relationships, and group sizes on pedestrian flow.

One experiment explores the relationship between intra-group structure/inter-group relationships and pedestrian flow. We consider four intra-group or inter-group matrices for the linear shape: one with all elements in the inter-group matrix being 1.0, one with all elements in the inter-group matrix being 0.7, with all elements in the inter-group matrix being 0.4, and the other with elements being 0.1. Each group contains 6 agents. To explore the effect of intra-group structure, the inter-group relationship $E$ is set to 0.0 to eliminate the effect of group-to-group relationships on crowd behavior. While in exploring the effect of inter-group relationships, elements of the intra-group matrix $I$ are set as 1.0. Fig. 14 shows the pedestrian flow under different intra-group or inter-group matrices. The upper curve represents the relationship between pedestrian flow and inter-group relationships. The other curve represents the relationship between pedestrian flow and intra-group influences. The pedestrian flow decreases as the intra-group influence strengths or the inter-group relationships decrease. The smaller influence strengths or relationships, the less desire an agent will follow others, thus the fewer agents passing the “virtual” gate.

The other experiment explores the relationship between group sizes and the pedestrian flow. The inter-group relationship $E$ is set as 0.0 and intra-group structure $I$ is set as 1.0. Fig. 15 shows the effect of group sizes on pedestrian flow under the leader-follower group shape. X and Y axis represent group size and the corresponding pedestrian flow, respectively.

When the group is not so large, the pedestrian flow increases as the group size increases. Otherwise, the pedestrian flow decreases as the group size increases. The reason is that, when the group is not so large, the larger the group sizes, the more agents will pass the “virtual” gate thus the flow becomes larger. However, when the group becomes very large, more effort
will be needed on the group formation and obstacle avoidance, and the agents passing the “virtual” gate are fewer than those of the smaller group sizes.

The two experiments show that the pedestrian flow decreases as the intra-group influence strengths or the inter-group relationships increase. The experiments also show that when the group is not so large, the pedestrian flow increases as the group sizes increase. Otherwise, the pedestrian flow decreases as the group sizes increase.

7. Discussions

Grouping is an important feature of crowd. Group modeling in pedestrian crowds can make crowd simulation more realistic. However, little research has been reported in the literature for modeling and simulating group structures. This is the motivation of this work. This work builds a foundation for systematic modeling of group structure in crowd simulations. Built on this work, several extensions can be developed for more advanced group structure modeling.

First, this work assumes a predefined group structure (as specified by the intra-group and inter-group matrices) that is maintained through the whole simulation. It also assumes a preselected leader that is not dynamically replaced by others. In other words, this work does not concern how the group structure is formed and how it will be dynamically changed. Thus one extension of this work is to support dynamic group formation and dynamical change of the group structure.

In pedestrian crowd simulations, group formation decides who belong to the group and the relationship between members. Leader selection is part of that decision too. In this work, without loss of generality, the leader is preselected as the first individual of a group. In more advanced simulations the leader might be changed during the simulation. For example, the leader can be replaced by the member who is more familiar with the surroundings when an emergent situation happens.

During the simulation, individuals’ group structure can also be dynamically changed based on their spatial distance (i.e. Euclidian distance), similar goal (i.e. evacuation from emergent situation), and social proximity (i.e. family members). For example, a “clustered” group structure can be dynamically changed to a “linear” group structure when a group approaches a narrow entrance of a building. Besides these factors, groups can also be dynamically formed and/or evolved by the change of group members and group structures. For example, a group member may leave the group and join another group; groups may be dynamically divided into multiple groups or combined together into a single group. In all these situations, the computation of the intra-group matrix and inter-group matrix depends on the desired relationships among group members that are application specific.

To extend this work to support these kinds of dynamic group structure features, a separate layer of social or psychological models, such as the Five Factor Model (see [10,24,33] for more details) can be added on top of our current model to support the decision of group formation and dynamic groups. This layer calculates the intra-group and inter-group matrices and updates them in each agent. At the bottom layer, based on these matrices, an agent computes its group position and group direction in the same way as described in this paper. This is considered as a future extension of this work.
Another extension of this work is to extend the three-level structure of crowd, crowd, group, and individual, considered in this paper to include more levels in a hierarchical manner. For example, a cluster level can be added on top of the group level: a crowd can include multiple clusters, each of which includes multiple groups. In this case, the model can be extended to have not only inter-group/intra-group matrices, but also inter-cluster/intra-cluster matrices.

8. Conclusion and future work

This work provides a unified framework for modeling various intra-group structures and inter-group relationships through a limited set of model parameters. The framework is implemented in an agent-based crowd behavior simulation system built on the OpenSteer environment. Experiment results show that the developed framework allows different group structures to be easily modeled. Furthermore, different group sizes, intra-group structures and inter-group relationships can have significant effect on crowd behaviors.

Future research of this work will be carried out along several directions. One direction is to incorporate different socio-psychological factors such as culture and personality into the framework of group structure modeling. In particular, we are interested in making agents form groups dynamically based on the external environment and its own socio-psychological status. Another future work is to develop simulations to study the effect of group structure on crowd behavior in situations such as emergent evacuation. Also it is desired to develop animations to give more realistic display of agent’s individual behavior and group level behaviors.

Future work will also include improvement of the performance of large-scale group-based crowd simulations. By adding the group structures, crowd simulation would need extra memory space to store intra-group and inter-group matrices. Also, group-based crowd simulations would be slower than those without group structures since more logics are involved. The performance might be possibly improved on the basis of the work of exploiting the spatial-temporal heterogeneity existing in pedestrian crowds [12] which is derived from the work of [39].

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References