A Framework for Modeling Social Groups in Agent-based Pedestrian Crowd Simulations

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Abstract: Grouping is a common phenomenon in pedestrian crowds and social groups can have significant impacts on crowd behavior. Despite its importance, how to model social groups in pedestrian crowd simulations is still an open and challenging issue. This paper presents a framework for modeling social groups in agent-based pedestrian crowd simulations. The developed framework integrates agent behavior modeling, group modeling, and social context modeling in a layered architecture, where each layer focuses on modeling a specific aspect of pedestrian crowds. A model of dynamic grouping behavior is developed to demonstrate the utility of the developed framework, and experiment results are presented.

Keywords: social groups, grouping behavior, dynamic grouping, framework for group modeling, pedestrian crowd simulations.

1 INTRODUCTION

Grouping is a common phenomenon in pedestrian crowds. According to the work of [1, 2], pedestrian crowds contain both grouped and isolated individuals. In the settings of a city, less than a half of the pedestrians walk alone [1]. For example, in a shopping mall, family members stay beside each other and maintain the group in a clustered way during the activity [3]. Grouped pedestrians can be found in emergency situations as well. According to social proof theory, when an individual lacks objective evaluation in the emergency (e.g. evacuate from a building in fire), the individual tends to follow the actions of others as a guide on how he/she might act. One example of social proof is the herding behavior - when under highly emergent situations, an individual tends to follow others almost blindly [4]. This is an example where people form social groups dynamically and follow the “leaders” spontaneously.

Social groups play important roles in affecting crowd behaviors. Social groups affect the flow of pedestrian crowds as well as the evacuation efficiency in emergency situations. As discussed in [5], a leader-follower group may be more smooth and efficient than a clustered group if the group has a large number of members. In this case, a clustered group can result in slow movement, especially in a constrained area. The work of [6] simulates the kin behavior in emergent evacuations and shows that the number of sub-groups and the members in each sub-group influence the evacuation efficiency significantly. The work of [7] studies the effect of group size on the walking speed...
through controlled experiments and concludes that the walking speed decreases as group size increases.

Social group has been an active research topic in sociology and psychology where a group is generally defined as a set of collected persons who share common goals and norms [8]. Although social groups are extensively studied in socio-psychology, how to model social groups is still an open issue [7] and group modeling is not incorporated into most pedestrian crowd models. Group modeling is a challenging task because of the non-linear interactions in pedestrian crowds and the dissimilarity nature of pedestrians. Many factors need to be considered, such as individual characteristics, group size, relationships among groups, and influences among group members [5, 9]. Existing work for simulating social groups mainly focuses on the perspective of reproducing some group-level behaviors based on specific social or psychological theories, such as social comparison theory [10] [11] or five-factor personality model [12-14]. Even though these existing works study some aspects of grouping, they do not provide a unified framework to explicitly model the intra-relationship of group members and inter-connections between groups for exploring the effect of different social or psychological factors on the grouping behavior.

This deficiency motivates us to develop a framework for modeling social groups in pedestrian crowd simulations. Because of the complicated and non-linear nature of social interactions, agent-based simulation is widely adopted in pedestrian crowd systems where each pedestrian is treated as an autonomous entity, which can behave independently according to predefined action rules. Agent-based pedestrian crowd simulations can simulate many intriguing collective behaviors, such as the herding behavior mentioned above, emerging from the interactions between individuals. Our framework adopts the agent-based simulation and incorporates the grouping behavior into the model of pedestrian agents (see Section 3 for details). This paper extends our previous work [3] that focuses on modeling the intra-group structure and the inter-group relationships in pedestrian crowds. Built on the previous work, this paper presents a unified and well-defined framework that integrates agent behavior modeling, group modeling, and social context modeling for modeling social groups in pedestrian crowd simulations. A model of dynamic grouping behavior is developed to demonstrate the applicability of the developed framework.

The remainder of this paper is organized as follows. Section 2 presents the related work of crowd behavior models and group modeling in pedestrian crowd simulations. Section 3 describes our framework for modeling social groups in agent-based pedestrian crowd simulations. One important component of the framework, the group model, is described in Section 4. Section 5 presents an application of the developed framework to simulate the dynamic grouping behavior where groups are dynamically changed during the simulation. Section 6 concludes this paper and proposes some future research directions.
2 RELATED WORK

Pedestrian crowd simulations are used to study crowd behaviors in situations where experiments with humans are impossible to be fulfilled. They are widely applied in civil and safety engineering, city planning, building design, and entertainment industry. For example, in civil and safety engineering, people study the flow of pedestrian crowds in order to ensure safe evacuation under emergent situations. In the city planning and building design, pedestrian crowd simulations are used to test the reliability of public facilities and architectural designs. Pedestrian crowd simulations are also applied in the entertainment industry, e.g. computer games, where people study pedestrian crowd simulations in order to create realistic movement of pedestrians.

Over many years of research, people have developed a lot of crowd behavior models, including physics inspired models [15-17], cellular automata models [18-20], and agent-based models [3, 21-24]. The physics inspired models are inspired from the similarity between crowd behaviors and the dynamics of physical particles, e.g. fluid and gas. A well-known physics inspired model is Helbing’s social force model [15], based on which a lot of extended work is developed [9, 25]. Cellular automata models [18-20] are discrete-space models where pedestrians are located at nodes of a fixed or adaptive grid. The movement of pedestrians is governed by a set of rules. The overall crowd behaviors are emergent from social interactions by means of self-organization. As one of the most popular crowd models, agent-based crowd model treats the pedestrian crowd as a multi-agent system. Unlike idealized gas-like particles, pedestrian agents are heterogeneous, and dynamic in their attributes and behavioral rules [26]. For example, pedestrian agents could have different social and psychological states [27, 28], personality and emotions [29], and cultures [30]. Each pedestrian agent assesses its situation and makes decisions on a set of local behavioral rules [31]. People have studied a set of interesting collective behaviors resulting from interactions among pedestrian agents, such as herding behavior [32], lane formation [15], leader-follower behavior [33], and so on. Researchers have proposed many agent-based pedestrian crowd models [3, 21-24] which try to capture the essence of behaviors of pedestrians. The work of [22] presented a hierarchical model for real-time simulation of virtual human crowds. The work of [4] presented a computational framework, Multi-Agent Simulation System for Egress analysis (MASSEgress), where social identity and social proof theories are modeled in human interactions. The work of [24] described a HiDAC (High-Density Autonomous Crowds) system for simulating the motion of large, dense crowds of autonomous agents in a dynamically changing virtual environments.

Social groups have important effect on crowd behaviors. While much research has been conducted in pedestrian crowd simulations, less work focused on the aspect of group modeling. Group modeling is mainly studied in the entertainment industry where people model social groups in order to create realistic animations. In this field, the
definition of a group is often given by a list of people who share common goals and movement parameters, for example, the same average moving speed and destinations. In the work of [21], a group is configured with some parameters: the goals (i.e., specific positions which the group should reach), group size and the level of dominance (i.e., the role of group leader and group members). The work of [34] described a model to generate and animate groups which emerge as a function of interactions among virtual agents. In their model, each pedestrian is featured with a set of social parameters and has the capability of movement, perception, interaction, and memory. During the simulation, each pedestrian is able to follow others, to evaluate the quality of interactions, to select the pedestrians with good quality of interactions, and to form groups with those having good quality of interactions. During the simulation, an interaction happens when both pedestrians resides within the perception area of each other. An interaction makes a change to the social states of the participants according to a set of predefined equations. The work of [11] described a computational framework for pedestrian crowd simulations based on Festinger’s social comparison theory [10] which states that when lacking objective means for evaluation of the current situations, people tend to compare their behavior with others that are most like them. In Fridman’s framework, each pedestrian is equipped with a set of features, to each of which a real number is assigned to indicate its weight. During the simulation, each pedestrian calculates the similarity with the nearby pedestrians. The pedestrian with the greatest similarity value is selected. The comparing pedestrian then applies actions to minimize the differences between the target pedestrian and itself. The similarity is calculated as the weighted sum of the features. The work states that the framework can simulate some behavior scenarios such as the lane formation with the existence of individual or grouped pedestrians.

Existing work of group modeling mainly focuses on reproducing one or several phenomena based on a specific social-psychological model, such as social comparison theory or five-factor personality model. These existing works cannot easily study other aspects, such as the relationships among members inside a group and the relationships among different groups, and cannot easily study the effect of different socio-psychological models, such as social identity theory and social proof theory, on crowd behaviors. In this paper, we develop a unified framework for studying social groups so that different aspects of social groups and the effect of socio-psychological factors on the grouping behavior can easily be studied.

3 A FRAMEWORK FOR MODELING SOCIAL GROUPS

Because of the dissimilarity of individuals and the non-linear nature of social interactions, pedestrian agents’ behaviors are emergent phenomena and they are too complicated to be described in formal mathematical equations. To study social groups and the grouping behavior in pedestrian crowds, each pedestrian is an autonomous agent, which has the capability of forming social groups. The purpose of this framework is to
provide a unified approach based on which people can easily simulate different social groups, and study the effect of different factors, e.g. socio-physiological factors, on agents’ grouping behavior. To achieve this goal, a layered architecture is developed as shown in Fig. 1. A pedestrian crowd system is envisioned as including a set of functionalities, from the facility of locomotion and behaviors, visualization and animation, to the capability of forming social groups, and to the social/psychological context that influencing the group forming. Each layer focuses on modeling a specific functionality of pedestrian crowd systems, and each layer impacts its immediate lower layer. With well-defined interfaces, this layered architecture provides the capability of modeling both isolated and/or grouped pedestrian agents. From bottom to top, this architecture includes an agent modeling layer, a group modeling layer and a context modeling layer. The agent modeling layer specifies different behaviors, such as avoid and move, as well as the locomotion and perception of pedestrian agents. The group modeling layer defines the inter-group and intra-group relationships for setting up various social groups. The context modeling layer models the social context of the agents and the groups in the crowd, which allows users to study how different factors affect agents’ grouping behavior and the crowd behaviors as well. Detailed description of each layer is given below.

3.1 Agent Modeling Layer
The agent modeling layer models the primitives of an agent-based pedestrian crowd simulation. It provides a set of facilities in simulating agent-based pedestrian crowds. Besides the functionality of visualization and animation, this layer also contains the model of virtual simulation environment, as well as the model of pedestrian agents. Visualization and animation are used to visualize and animate the simulation results, i.e. agents’ physical, social and psychological states, respectively. In this framework, simulation results are displayed as a series of two-dimensional images. Animation is an important approach to produce stereoscopic simulation scenarios. People have developed a lot of animation techniques for pedestrian crowd simulations. Detailed descriptions and
literature review of this functionality are out of the range of this paper. However, it is possible to use different techniques of visualization and animation in the framework to create stereoscopic and sophisticated simulation scenarios.

The environment model specifies the information of spatial objects as existing in the virtual simulation space. The information includes the size and shape (e.g. circle or rectangle) of pedestrian agents and obstacles, as well as the boundary of the constrained simulation area. The environment model also accommodates a set of common facilities for agents to communicate with each other, as listed in Table 1. These facilities include the functionality of retrieving the desired agent(s), calculating the distance to other agents or obstacles, applying the movement action, and checking if an agent’s position is within the boundary of the simulation area.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
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<tbody>
<tr>
<td>A set of functionalities provided by the environment model.</td>
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</table>

<table>
<thead>
<tr>
<th>Get Agent(s)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Get the specified agent by id</td>
<td>GetAgent(AgentID)</td>
</tr>
<tr>
<td>Get the nearby agents which are within the perception</td>
<td>GetNearbyAgents(Agent)</td>
</tr>
<tr>
<td>Get members in the specified group</td>
<td>GetGroupMembers(GroupID)</td>
</tr>
<tr>
<td>Get the leader of the specified group</td>
<td>GetGroupLeader(GroupID)</td>
</tr>
<tr>
<td>Get the agent which is most similar to the specified agent</td>
<td>GetMostSimilarAgent(AgentID)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Get distance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Get the Euclidian distance between an agent and another agent/obstacle</td>
<td>GetDistToAgent(AgentID, AnotherAgentID)</td>
</tr>
<tr>
<td>Get IR distance between an agent and another agent/obstacle</td>
<td>GetIRDistToAgent(AgentID, AnotherAgentID)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agent motion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Move an agent according to the specified speed and direction</td>
<td>MoveAgent(AgentID, Speed, Direction)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position check and generation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Check whether the specified agent collides with others</td>
<td>LegalPositionToNearbyAgents(AgentID)</td>
</tr>
<tr>
<td>Check whether the specified agent collides with obstacles</td>
<td>LegalPositionToNearbyObstacles(AgentID)</td>
</tr>
<tr>
<td>Check whether the specified agent is inside the environment</td>
<td>InsideEnvironment(AgentID)</td>
</tr>
<tr>
<td>Generate a random position in the environment</td>
<td>GenerateRandomPosition(Randomer)</td>
</tr>
</tbody>
</table>

An important component in this layer is the agent model. This model defines the social, psychological and physical status, the perception, and more importantly the behaviors of pedestrian agents. Each agent is featured with a set of attributes, which represent its physical and socio-psychological status. The physical status is represented by the position, moving speed and moving direction. The socio-psychological status is represented by identification, group identification, social role, and several other attributes (described in Section 4). Identification and group identification uniquely identifies an agent in pedestrian crowds, and in the group which the agent belongs to, respectively.
These two identifications are assigned automatically when the simulation begins. Each agent is designated with a social role, which could be a hierarchical and dominant structure as existing in social organizations. In this paper, there are two roles in pedestrian crowds - group leader and group member, and one of the group members is designated as the group leader (usually the agent with the smallest identification number within a group). It should be noted that, the framework could be easily extended to include more fine-grained roles.

Besides the attributes, each pedestrian agent is also equipped with a perception model and a behavior model. The perception model specifies a limited area where an agent can perceive the approaching individuals and obstacles, which allows the agent to avoid collision with others. It is an important input for many functions as listed in Table 1. For example, only the nearby agents that are within the perception of the source agent will be considered as the neighbors of the source agent.

There are many different ways for modeling the behaviors of pedestrian agents. In this paper, the behaviors of pedestrian agents are controlled by a behavior network. A behavior network features a set of behaviors working in parallel, each of which corresponds to a specific behavior of the agents. A behavior is an independent computation module, which can fulfill some particular task (i.e. action) of an agent. The action is represented by a speed vector that indicates the moving speed and direction the agent should follow when making the movement. Behavior network defines how different behaviors compete or cooperate with each other for controlling the agent. This competitive or cooperative action selection mechanism acts as the decision-making component of the agent. In this paper, we adopt only the cooperative action mechanism, the architecture of which is shown in Fig. 2. In the figure, input, \( v_i \), and \( w_i \) represent the external input, speed vector, and weight of behavior \( b_i \) respectively. Specifically, \( \text{input}_i \) is from the perception model, e.g. the nearby agents that are within the perception of the agent; \( w_i \) is a real number defined in \([0, 1]\) that represents the amount of contribution of behavior \( b_i \) in calculating the speed vector \( v_{\text{final}} \); \( v_{\text{final}} \) combines the speed vectors of the multiple behaviors using the vector sum principle. More details of the action selection mechanism and the architecture of behavior network are described in [35].
Figure 2. The behavior network of a pedestrian agent

An agent can contain arbitrary number of behaviors, which depends on the model needs. In particular, in order to support group modeling, each agent has a special behavior, named \texttt{MaintainGroup} in our framework, which is responsible to define the grouping behavior of the agent. The \texttt{MaintainGroup} behavior is just like other behaviors, i.e., it works cooperatively with other behaviors as shown in Figure 2. Nevertheless, how to compute the speed vector of this behavior is governed by the group modeling layer which is described in the next section.

3.2 Group Modeling Layer

The group modeling layer provides the support for modeling social groups in pedestrian crowds. It enables the grouping behavior through the \texttt{MaintainGroup} behavior of pedestrian agents.

Included in the group layer is the group model, which is used to create different social groups. In this paper, social groups are modeled 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 [36] where interpersonal interaction is modeled to study navigation behaviors of humans that socially interact with virtual agents, the intra-group structure captures not only the structure of the relationship network among group members, e.g. the leader-follower structure, but also the strength of the relationships, e.g., the degree of liking and familiarity. Unlike the intra-group structure, the inter-group relationships are the relationships among different social groups. This is used to model the fact that social groups also interact and impact each other. For example, it is generally observed that a group follows other nearby groups during an emergency evacuation process [32, 36]. Both intra-group structures and inter-group relationships are specified using two-dimensional matrices where entries of the matrices define the strengths of the social interactions. Section 4 provides more technical details for the group model.
There are two types of social groups – static groups and dynamic groups. Static (or predefined) groups mean that the social structures and relationships between group members are not changed during the social interactions. That is, the intra-group structure is pre-defined and not changed during the simulation. In reality, it is common for group members to change their relationships with each other under different social contexts. This results in dynamic groups, where pedestrian agents dynamically change their group structures or the strengths of their relationships. In this paper, how different social contexts can influence the intra-group structures and/or inter-group relationships is modeled in the context modeling layer described below.

3.3 Context Modeling Layer

With the change of social/psychological contexts, pedestrians may change their grouping behaviors. This dynamic feature of grouping behavior commonly exists in pedestrian crowds. An example of dynamic grouping behaviors is the herding behavior as existing in uncertain and emergent situations. It is important to provide the capability of modeling dynamic social groups in order to create realistic simulations.

The dynamic grouping behavior is often driven by socio-psychological factors, such as the culture, personality, and sociality of pedestrian agents. Researchers have proposed a lot of socio-psychological models, e.g. social proof theory, social comparison theory and five-factor personality model. In our framework, the context modeling layer models the social contexts of grouping behavior, and thus makes it possible to study the effect of socio-psychological factors on the grouping behavior of pedestrian agents. The changes of social context influence the dynamic grouping behavior by dynamically changing the group model, i.e. the intra-group structure and/or the inter-group relationship matrices. Section 5 shows an application that studies the dynamic grouping behavior modeled under social comparison theory and utility theory.

3.4 Relationship between Layers

It is necessary to explore the relationship between the proposed layers in order to understand how a pedestrian crowd simulation system works. Figure 3 shows the relationship between adjacent layers. Each layer models one aspect of pedestrian crowds, and it affects the immediate low layer by adding extra functionality. The grouping behavior is implemented in the MaintainGroup behavior. The effect of socio-psychological factors on crowd behaviors is realized by dynamically changing the intra-group and inter-group matrices during the social interactions.
Note that each layer is highly configurable. For example, pedestrian agents could be equipped with different perception models. It is possible that agents have other behavior models, e.g. rule-based behavior models. The simulation can also adopt a variety of techniques of visualization and animation.

3.5 Overview of the Crowd System

This section provides an overall description of the system specification of agent-based pedestrian crowd simulations as defined in our work. The specification is illustrated in Fig. 4.

A pedestrian crowd contains a set of social groups. The influence between social groups is specified in a two-dimensional matrix (i.e. inter-group matrix), where the column and row indices of the matrix represent the identifications of the groups. Each entry of the inter-group matrix defines the relationship between two social groups. A social group contains at least one pedestrian agent. All pedestrian agents of a social group are called the group members of the group. One member is designated as the leader of the group (see Role as described in Section 3.1). The relationships between two group members (if the group contains more than one agent) are specified in a two-dimensional matrix (i.e. intra-group matrix), where the column and row indices of the matrix represent the identifications of the group members. Each entry of the intra-group matrix defines the relationship between two group members. An agent has attributes ID, GroupID, Role, Speed, and Direction which represents identification, group identification, role, moving speed, and moving direction respectively. Role is group leader or group
A member. An agent also has two other important attributes GP and GD that are used in modeling social groups and are described in Section 4.

Similar to the work of [31], we adopt a perception model that specifies an elliptical area as shown in Fig. 5. The current moving direction is indicated by the arrow labeled with “Direction”. Dist1 and Dist2 represent the maximum front and side distance of visibility respectively. Angle indicates half of the maximum visibility range the agent can perceive. Each agent uses this perception model to perceive local (neighborhood) pedestrians. In this paper, Dist1, Dist2, and Angle are 20°Radius, 6°Radius, and 120 degrees, respectively.

![Figure 5. An elliptical agent perception model.](image)

In our work, each agent has three basic behaviors - Move, Avoid, and MaintainGroup. The Move behavior lets agents wander inside the environment. The Avoid behavior lets agents avoid collision with approaching agents and obstacles. The MaintainGroup behavior allows agents to maintain the desired social group during the simulation. Below we provide more details for the MaintainGroup behavior - the group model.

4 THE GROUP MODEL

As a key component in modeling social groups, the group model is implemented in the MaintainGroup behavior, which represents the grouping behavior for both group leaders and group members. To maintain the desired intra-group structure and inter-group relationship, each agent’s MaintainGroup behavior is composed of two movements - Aggregation and Following.

Aggregation means an agent moves towards the center of the agents that belong to the same group and have non-zero influence (as defined in the intra-group matrix) on this agent. This center is called the group position, denoted as GP, of this agent. For a group member, Following means the member heads towards the average moving direction of other group members belonging to the same group as the member and have non-zero influence on this member. For a group leader, Following means the leader follows the moving direction of an agent of a different group to maintain the inter-group relationship. Note that, for simplicity, only group leaders maintain the inter-group relationships. However, it could be easily extended to let all group members maintain the inter-relationships as well. In both cases, the moving direction associated with Following is called the group direction, denoted as GD, of this agent.
GP and GD are key attributes in deciding the aggregation and following movement. Section 4.1 defines the intra-group and inter-group matrices, which are used in the calculation of the aggregation and following movement as explained in the following sections.

4.1 Intra-group and Inter-group Matrices

Each entry of the two-dimensional matrix is a normalized number defined in the range of [0.0, 1.0]. A matrix with all entries being 0.0 (denoted as I(0.0)) indicates that agents of the same group (for intra-group matrix) or the social groups in the pedestrian crowd (for inter-group matrix) have no impact on each other. A matrix with all entries being 1.0 (denoted as I(1.0)) indicates that agents or groups have the strongest influence on each other. Each social group is equipped with an intra-group matrix where the number at row with ID i and column with ID j, denoted as I(i, j), defines how much agent i’s movement is influenced by agent j. Note that, the intra-group matrix could be different for different social groups, and the intra-group matrix specifies not only the network structure of the influence among pedestrian agents, but also the strength of social interactions. Similarly, the crowd is featured with an inter-group matrix where the entry at row i and column j, denoted as E(i, j), defines how much group i’s movement is impacted by group j.

Table 2
A Sample Intra-group Matrix

<table>
<thead>
<tr>
<th>ID</th>
<th>Agent_0</th>
<th>Agent_1</th>
<th>Agent_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent_0</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Agent_1</td>
<td>1</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Agent_2</td>
<td>0</td>
<td>1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 3
A Sample Inter-group Matrix

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

Table 2 and Table 3 show a sample intra-group and inter-group matrix respectively. In Table 2, the group has three agents with ID 0, 1 and 2, among which Agent_0 is the group leader. Table 2 defines a linear group structure where Agent_2 follows Agent_1, which in turn follows the Agent_0 (the leader). In Table 3, the crowd has three groups with ID 0, 1, 2. Table 3 defines a scenario where groups are fully influenced by each other during the simulation, which is a common situation as illustrated by previous work.
such as the work of Festinger [10]. It should be noted that an agent or a group cannot be impacted by itself – indicated by “N/A” in the tables.

4.2 Modeling Intra-group Structures

Each social group in the pedestrian crowds has an intra-group structure that is shared by all its members. Different groups could have different intra-group structures depending on their social status, e.g. culture and personality, which are captured in the context modeling layer. Recall that GP is the group position an agent should head towards and GD is the average moving direction of other group members that have non-zero influence on the agent.

For both static and dynamic social groups, Eq.(1) and (2) show the calculation of GP and GD for group member i. Here, i is the ID of the member, and \( N_i \) is the number of agents that 1) belong to the same group as member i, 2) are within the perception range of member i, and 3) have non-zero influence on member i. \( I(i, j) \) represents the strength of the intra-group influence between member i and j. CurrentPosition\(_i\) and SpeedVector\(_j\) represent the current position and moving speed (both are vectors) of member j. As can be seen, GP and GD is the weighted position and speed vector of members within the same group, respectively. The direction of the aggregation vector is the direction from CurrentPosition\(_i\) to GP\(_i\), and the direction of the following vector is the direction indicated by GD\(_i\).

\[
GP_i = \frac{\sum_{j=1}^{N_i} I(i, j) \times \text{CurrentPosition}_j}{N_i} \quad (1)
\]

\[
GD_i = \frac{\sum_{j=1}^{N_i} I(i, j) \times \text{SpeedVector}_j}{N_i} \quad (2)
\]

4.3 Modeling Inter-group Relationships

Similar to the influence between pedestrian agents, social groups may influence each other as well. The influence between social groups is captured in inter-group relationships (i.e. inter-group matrix), and only group leaders maintain the inter-group relationships. It should be noted that, only the agents from different groups, are considered as the candidates, which a leader may follow. The calculation of the influence strength between the leader and the candidates, and the decision of which candidate to follow are based on social factors modeled in the context modeling layer.

Here we give an example showing how a group leader selects a candidate to follow based on Festinger’s social comparison theory presented in the work of [10]. The idea is to select the agent that has the greatest similarity as the one that has greatest influence on the group leader. This similarity depends not only on the inter-group relationships between the two groups, which the leader and the agent belong to, respectively, but also on the Euclidian distance between them.
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 agent $i$ and $j$ belong to respectively. Suppose agent $i$ is a group leader. Eq. (3) – (5) shows the decision of leader $i$. For each agent $j$ from another group which is within the perception 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 follow agent $j$. Eq. (4) and (5) show that the agent with the greatest similarity is selected as the one to follow.

$\text{Similarity}_{ij} = E(G(i), G(j)) \times 100 / \text{EuclidianDistBetween}(i, j)$  \hspace{1cm} (3)

$\text{MostSimilarId} = \text{Maximum}(\text{Similarity}_1, ..., \text{Similarity}_n)$  \hspace{1cm} (4)

$\text{PedestrianToFollow} = \begin{cases} \text{Pedestrian with MostSimilarId} & \text{If MostSimilarId exists} \\ \phi & \text{Otherwise} \end{cases}$  \hspace{1cm} (5)

Once a valid PedestrianToFollow is found, $GP_i$ and $GD_i$ for leader $i$ is the position and moving direction of PedestrianToFollow respectively. Otherwise, leader $i$ will not follow any agent from other groups.

4.4 Calculation of Aggregation and Following Vectors

The aggregation and following movement is represented by speed vectors, based on $GP$ and $GD$, the calculation of which is shown in Eq.(6). Speed is the agent’s current moving speed.

$v = \text{factor} \times <\text{Speed} \times \cos(a), \text{Speed} \times \sin(a)>$  \hspace{1cm} (6)

For the aggregation vector, $a$ is the direction from the agent’s current position $P$ to the group center $GP$, and factor is reverse proportional to the Euclidian distance between $P$ and $GP$. For the following vector, $a$ is the direction represented by the group direction $GD$ and factor is 1.

The final speed vector, which governs the maintaining group behavior at each simulation step, is the vector sum of the aggregation and following vectors. For an agent $s$, it will try to move towards $GP_s$ to keep within a desired distance, and try to follow the direction $GD_s$. In this approach, both the intra-group structure and the inter-group relationship can be maintained.

5 AN APPLICATION – THE DYNAMIC GROUPING BEHAVIOR

Pedestrian crowds are often situated in changing and complicated external environments, especially in the highly urgent situations. Due to changes of the evaluation of external environments, social groups can also dynamically changed based on their spatial distances (i.e. Euclidian distance), similar goals (i.e. evacuation from emergent situation), and social proximities (i.e. family members). A pedestrian agent may not
belong to the same social group at all the times and pedestrians may follow different social groups during the simulation. This section develops an application that models the dynamic grouping behavior of pedestrian crowds based on the proposed framework. The dynamic grouping behavior is studied through a dynamic group model. This dynamic group model also illustrates how different artificial and socio-psychological theories can be combined together to influence agents’ grouping behavior.

5.1 Modeling Dynamic Grouping Behavior

The dynamic grouping behavior is modeled through a two-step process. For an agent, the first step, denoted as group formation, is to decide which social group to follow. The decision could be following a selected social group, staying at its current group, or starting a new social group (which contains the agent itself). The second step, denoted as individual selection, is to decide which member (of the selected group) to follow (if the agent does not start a new group). These two steps are modeled using utility theory and social comparison theory, respectively.

Utility theory provides a formal framework for specifying the preferences, or utilities, of agents’ potential actions under uncertain worlds. It is an important component in decision theories which assume that a person, even under a dangerous situation, can still make rational decisions [37] (this is also the assumption of our dynamic group model). In a dynamic and ever changing external environment, adaptability is critical for agents to behave rationally and intelligently in order to survive in such situations. The adaptability is achieved by comparing the degree of desirability of grouping behaviors – joining another group, staying at the current group, or starting a new group. For each grouping behavior, a preference, which represents the strength of the desirability of performing a grouping behavior, is calculated through a utility function. Each time agents perform the grouping behavior that has a highest preference value.

The other theory used in modeling the dynamic grouping behavior is Festinger’s social comparison theory [10]. The idea is that, after the decision of following another group, staying with the current group or starting a new group has been made, a pedestrian follows a member in the target group who is most similar to the pedestrian agent (see Section 4.3 for details).

5.2 Context Modeling and Group Modeling Layer

In this example, each agent initially belongs to a group that consists of the agent itself only. At every time step, an agent makes a decision on whether to join another group, to stay with the current group, or to start with a new group (which only contains the agent itself). The two steps involved in the decision, group formation and individual selection, of agent \( i \) at time step \( t \), are illustrated in Fig.6.
The top and bottom rectangle indicates group formation and individual section, respectively. The solid dot represents agent i. Circles G_i (i=1-5) indicates the nearby groups which agent i can perceive (the nearby groups are detected through the agent’s perception model). Assume at the step of group formation, agent i decides to join group G_4. Then agent i decides which member (from G_4) to follow in the step of individual selection. The outer circle in the bottom rectangle indicates the selected group G_4. The dots inside the outer circle represent members in the group G_4 which agent i can perceive. As can be seen, the top rectangle provides the group context for the bottom rectangle to make the decision of individual selection. The group context includes the information of its members as well as the relationships among its members. Note that, the group which agent i belongs to is not shown in Fig. 6. If agent i decides to stay with its current group, the individual selection is fulfilled between agent i and other members in the same group as agent i. Before the detailed description of group formation and individual selection, several parameters used in the modeling of dynamic groups are introduced as follows.

- \( U_f \) and \( U_s \) represents the utility of joining another group and staying with the current group, respectively.
- Sociality indicates how socially active an agent is. The greater the value is, the more likely the agent will join another group (rather than stay with its current group). Sociality is a normalized value in the range of \([0, 1]\).

5.2.1 The step of group formation

Group formation decides the group that an agent should follow. One of the three alternatives, joining another group, staying with the current group, or starting a new group, will be selected. The selection is based on utility theory where utilities are used to measure the preference of the three alternatives. An agent starts a new group if both utilities \( U_f \) and \( U_s \) are smaller than a predefined threshold. Otherwise, an agent joins another group if \( U_f > U_s \), and the agent stays with its current group if \( U_f \cdot U_s \). The calculation of \( U_f \) and \( U_s \) for agent i is described in Eq.(7)-Eq.(11), where \( c \) is a constant number, Duration is the number of times agent i has been staying with the current group. It is reset to 0 once the agent joins another group. Threshold indicates the maximum
number of times within which agent $i$ can join other groups. DesiredDist is a predefined number. Eq. (7) shows that the distance between agent $i$ and the nearby group $G_j$ is the distance between $i$ and the closest agent $j$ which is a member of the group $G_j$. $U_f$ is the maximum desirability of joining a nearby group as shown in Eq.(9). Eq.(8) and (9) show that the closer to a nearby group, the more desirable to follow the group. Eq. (9) and (10) show that, the longer staying with the current group, the stronger an agent desires to stay at the same group. Eq. (11) shows that when the agent decides to join another group, it will join the group with the maximum utility $U_f$.

$$\text{Dist}_{GP_i} = \text{Dist}(i, j)$$  \hspace{1cm} (7)

$$t = \frac{\text{DesiredDist}}{\text{Dist}_{GP_i}}$$ \hspace{1cm} (8)

$$U_{i, t} = \max\left(t \cdot e^{\text{Sociality}_i \cdot (1 - \text{Duration} / \text{Threshold})}\right)$$ \hspace{1cm} (9)

$$U_{i, s} = c \cdot e^{\text{Sociality}_i \cdot \text{Duration} / \text{Threshold}}$$ \hspace{1cm} (10)

$$\text{GroupToJoin} = \begin{cases} \text{The group with } U_{i,t} \geq U_{i,s} \text{ for all } G_P \text{ otherwise} \end{cases} \hspace{1cm} (11)$$

5.2.2 The step of individual selection

The basic idea of individual selection is for agents to follow a member (from the selected group $G_{PT}$) that has the greatest similarity to the agent. The selection of the target agent is described as follows.

Assume $i$ and $j$ are two agents, $v_i$ and $v_j$ are speed vector of agent $i$ and $j$ respectively, $v_l$ and $v_m$ are vectors pointing from agent $i$’s current position to the position of the selected member and agent $i$’s destination, respectively. Eq. (12)-Eq.(14), together with Eq.(4) – Eq.(5) show the individual selection process for agent $i$, where $a=10$ and $b=5$. For each agent $j$ that belongs to the selected group $G_{PT}$ and is in the perception of pedestrian $i$, the similarity between $i$ and $j$ is calculated using Eq. (12). As can be seen, the greater the sociality of agent $i$, and the closer the distance from $i$ to $j$ is, the more likely agent $i$ will follow agent $j$. The moving direction also has effect on the similarity. Pedestrians prefer to follow the pedestrian moving in the same direction. The agent with the greatest similarity is selected as the one to follow as shown in Eq.(4) and (5). If no agent is selected, agent $i$ will not follow any agent.

$$\text{Similarity}_i = \text{Sociality}_i \cdot D_1 \cdot (a \cdot D_2 + b \cdot e^{-\text{dist}(i, j)/\text{Dist1}})$$ \hspace{1cm} (12)

$$D_1 = \begin{cases} 1 & \text{if } v_i \cdot v_m \geq 0 \\ 0 & \text{otherwise} \end{cases} \hspace{1cm} (13)$$

$$D_2 = \begin{cases} 1 & \text{if } v_i \cdot v_i \geq 0 \\ 0 & \text{otherwise} \end{cases} \hspace{1cm} (14)$$

5.2.3 The dynamics of intra-group and inter-group matrices

Once the agent with the greatest similarity, denoted as agent $j$, is selected, we can calculate the possibility that agent $i$ will follow agent $j$, as shown in Eq. (15). Similarity,$
represents the greatest similarity (i.e., the value of the similarity between agent i and agent j). Smax and Smin are the predefined value of the maximum and minimum similarity respectively. In this paper, Smax and Smin are specified as 20 and 5 respectively. As can be seen, the greater the value of the similarity is, the more likely agent i will follow agent j. Note that, the possibility is a normalized value within the range [0, 1].

\[
\text{Possibility}_i = \frac{(\text{Similarity}_i - S_{\text{min}})}{(S_{\text{max}} - S_{\text{min}})}
\]

(15)

We can also calculate the influence strength of agent j on agent i, as shown in Eq. (16). In the equation, \( \xi \) is the noise applied in the calculation of forces, and is a small number; \( \text{ran}_\text{num} \) is a random number generated by a random number generator; \( t \) is proportional to the ratio of the distance between agent i and j, which is a predefined desired distance. As can be seen, the larger the possibility, the larger the distance between agent i and j, the greater the weight will be. Note that, if no agent is selected to follow, or the value of the similarity is out of the specified range \([S_{\text{min}}, S_{\text{max}}]\), the weight will be 0 and pedestrian i will not follow any agents.

\[
\text{Weight}_i = \begin{cases} 
  t \cdot e^{\text{Possibility}_i} + \xi & \text{if } \text{ran}_\text{num} \leq \text{Possibility}_i \\
  0 & \text{otherwise} 
\end{cases}
\]

(16)

\[
t = \text{Sociality}_i \cdot \text{dist}(i, j) / \text{desired dist}
\]

(17)

Weight, as calculated in Eq. (16) is the strength of the intra-group influence, i.e. the strength of the influence between two agents. Each agent keeps a list of weights (the non-zero influence strength from other group members). As the simulation proceeds, the list could be dynamically changed which reflects a dynamic intra-group structure, and thus the dynamic grouping behavior.

The inter-group relationships are not explicitly specified in this application. However, it is possible to incorporate the inter-group relationships by specifying an agent as the group leader within each group, and let the group leaders follow each other. Note that, since social groups keep changing, both group members and group leaders could be dynamically changed as well.

5.3 Agent Modeling Layer

Besides the attributes and models (BehaviorModel and PerceptionModel) as presented in Section 3.1, each pedestrian agent is also featured with a set of attributes which are used in the modeling of the dynamic grouping behavior. These attributes are described as \(<\text{Radius}, U_r, U_s, \text{Sociality}, \text{Similarity}, \text{Possibility}, \text{Weight}>\). Each agent is represented as a circle shape the radius of which is specified by Radius; \( U_r, U_s, \text{Sociality}, \text{Similarity}, \text{Possibility}, \text{and Weight> are described before.}
Each agent represents an autonomous pedestrian equipped with the behavior of random movement, obstacle avoidance, and maintaining group. Random movement lets an agent move to a randomly generated destination. Obstacle avoidance lets an agent avoid collision with obstacles (i.e. walls), other agents and groups. Maintaining group lets an agent follow a member in the selected group GroupToJoin, if such member exists. The three behaviors of pedestrian agents are built on the Craig Reynolds’s OpenSteer environment [38]. A set of vectors are used to represent the forces applied to an agent. Each agent has a speed vector for obstacle avoidance behavior, a speed vector for random movement behavior and a speed vector for maintaining group behavior. At every time step, each agent computes an overall speed vector using the vector sum principle to govern its movement.

\[
\begin{align*}
CM\_SpeedVector_i &= 0.5 \times \text{force} \times CM\_UnitVector \\
OA\_SpeedVector_i &= 1.0 \times \text{force} \times OA\_UnitVector \\
MG\_SpeedVector_i &= \text{Weight} \times \text{force} \times MG\_UnitVector
\end{align*}
\]

Eq.(18)–Eq.(20) calculate the speed vector of random movement, obstacle avoidance, and maintaining group for pedestrian \(i\) respectively. \(\text{force}\) is a constant number. \(\text{UnitVector}\) is the vector indicating the moving direction of the corresponding speed vector. As can be seen from Eq.(20), the greater the weight, the greater the force of maintaining group. Note that, \(MG\_UnitVector\) is calculated from the vector sum of the following and aggregation vector (as described in Eq. (6)).

5.4 Experiments and results analysis

This section presents experiment results of the dynamic grouping behavior in agent-based pedestrian crowd simulations. Two experiments are designed to simulate dynamic groups, and to study the effect of sociality on crowd behaviors. The experiments are carried out in a circular rectangle-shaped environment with 600m in length and 200m in width as shown in Fig. 7. The crowd contains 60 agents and the lane width is 50m. In what follows, the green and gray circles represent the agents that are and are not in maintaining groups, respectively. The numbers in circles indicates the IDs of the agents.

![Figure 7. The circular rectangle-shaped simulation environment.](image)

Experiment 1 – Simulate dynamic groups

This experiment studies the dynamic grouping behavior in pedestrian crowds. The purpose is to show that the developed dynamic group model can simulate the dynamic
grouping behavior of pedestrian agents. Fig. 8 shows a simulation scenario. Half of the agents move in clockwise while the other half moves in anti-clockwise. All agents are fully active in social interactions (i.e. sociality is 1.0). Each agent follows the member that is the most similar with the agent. This scenario shows a linear intra-group structure where members follow each other in a line formation.

Experiment 2 - The effect of sociality on crowd behaviors

This experiment explores the effect of sociality on the dynamic grouping behavior in pedestrian crowds. The purpose is to evaluate whether the developed model can reproduce the phenomenon that, the greater sociality is, the more likely an agent will interact with others and the closer the agents will move together. Fig. 9 shows the relationship between sociality and the average distance (measured in meters) between members in dynamic groups. The average distance is calculated as the average of the distances between members in all dynamic groups during 50 cycles starting at the same simulation time. Five cases are tested. For each case, all agents are set to have the same sociality. Fig. 9 shows that the greater the sociality, the closer agents move together, and the average distance decreases linearly as the sociality increases.

6 CONCLUSIONS AND FUTURE WORK

Built on previous work [3], this paper presents a unified and well-defined framework that integrates agent behavior modeling, group modeling, and social context modeling for modeling social groups in pedestrian crowd simulations. This framework allows users to simulate different social groups, and to study the effect of socio-psychological factors on
the grouping behavior of pedestrian agents. A group model is developed to model social groups from two aspects, intra-group structure and inter-group relationships. These two aspects are captured in two-dimensional matrices, which can be changed by socio-psychological factors modeled in the context modeling layer. As an application of this framework, a dynamic group model is developed to simulate dynamic grouping behaviors in pedestrian crowds, based on social comparison theory and utility theory. Experiments show that the framework can be used to simulate social groups and it can also be used to study the effect of sociality on crowd behaviors.

Future research directions of this paper include applying the framework to applications such as computer games to make the games generate more realistic crowds. Other future research directions include verification of the framework using realistic observation data, and parallelizing the framework to make it more efficient especially for large-scale crowd simulations.

REFERENCES


