A Multi-agent Based Framework for the Simulation of Human and Social Behaviors during Emergency Evacuations

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Abstract

Many computational tools for the simulation and design of emergency evacuation and egress are now available. However, due to the scarcity of human and social behavioral data, these computational tools rely on assumptions that have been found inconsistent or unrealistic. This paper presents a multi-agent based framework for simulating human and social behavior during emergency evacuation. A prototype system has been developed, which is able to demonstrate some emergent behaviors, such as competitive, queuing, and herding behaviors. For illustration, an example application of the system for safe egress design is provided.

1. Introduction

This paper presents a multi-agent based framework to simulate human and social behaviors during emergency evacuations. Among the many regulatory provisions governing a facility design, one of the key issues identified by facility managers and building inspectors is safe egress. Design of egress for places of public assembly is a formidable problem in facility and safety engineering. There have been numerous incidents reported regarding overcrowding and crushing during emergency situations [1]. In addition to injuries and loss of lives, the accompanying post-disaster psychological suffering, financial loss, and adverse publicity have long-term negative effects on the affected individuals and organizations - the survivors, the victims' families, and the local communities.

Among the many factors including overcrowding and evacuation incidents, researchers have come to realize that understanding human and social behaviors in emergencies is crucial to improve crowd safety in places of public assembly [2-6]. In particular, 'nonadaptive crowd behaviors' are recognized to be responsible for the death and injury of most victims in crowd disasters [7]. Nonadaptive crowd behaviors refer to the destructive actions that a crowd may experience in emergency situations, such as stampede, pushing, knocking, and trampling on others. Studying nonadaptive crowd behaviors in emergency situations is difficult since it often requires exposing real people to the actual, possibly dangerous, environment. A good computational tool that takes into consideration the human and social behavior of a crowd could serve as a viable alternative.

Commercially available computational tools for the simulation and design of emergency exits exist. However, most of the current computational tools focus on the modeling of spaces and occupancies but rarely take into consideration of human and

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social behaviors. As a result, none of the current models have been able to cover the range of scenarios suitable for safety engineering purpose [8]. A computational model that incorporates human and social behavior requires not only to simulate human cognitive processes at an individual level but also to capture the emergent evacuation patterns of a crowd during evacuation. Most existing evacuation models do not pay sufficient attention to either the cognitive or social aspects of human behaviors [5,19].

A multi-agent simulation framework is a computational methodology that allows building an artificial environment populated with autonomous agents which are capable of interacting with each other. We believe such a framework is particularly suitable for simulating individual cognitive processes and behavior and for exploring emergent phenomena such as social or collective behaviors. At a microscopic level, the framework represents human individuals as autonomous agents equipped with sensors, decision-making rules, and actuators. At a macroscopic level, the framework models human social behaviors as emergent phenomena through simulating the interactions among agents or groups in a virtual environment. We have prototyped a Multi-Agent Simulation System for Egress analysis (MASSEgress) that is able to model some of the frequently observed human social behaviors in emergencies, such as competitive, queuing, and herding behaviors, through simulating the cognitive processes of individual agents and interactions among multiple agents in an artificial environment.

2. Related Work

A wide variety of computational tools for the simulation and design of exits are now available. To review all existing computational models for egress analysis is beyond the scope of this paper. Generally speaking, most existing models can be categorized into (1) fluid or particle systems, (2) matrix-based systems, and (3) emergent systems:

- Many have considered the analogy between *fluid* and *particle* motions (including interactions) and crowd movement. One example of fluid or particle systems is the panic simulation system built by Helbing et al. [11]. Coupling fluid dynamic and "self-driven" particle models with discrete virtual reality simulation techniques, these systems attempt to simulate and to help design evacuation strategies. Recent studies have revealed that the fluid or particle analogies of crowd are untenable. As noted by Still [8], "the laws of crowd dynamics have to include the fact that people do not follow the laws of physics; they have a choice in their direction, have no conservation of momentum and can stop and start at will." Fluid or particle analogies also contradict with some observed crowd behaviors, such as herding behavior, multi-directional flow, and uneven crowd density distribution. For example, herding behavior is often observed during the evacuation of a crowd in a room with two exits - one exit is clogged while the other is not fully utilized [12]. However, a fluid or particle analogy would likely predict that both exits were being used efficiently. Furthermore, it is difficult for fluid or particle systems to properly model bi-directional flows (with people moving in opposite directions) in a very crowded environment [8]. Earlier "self-driven" particle models, such as Exodus [10], are now enhanced to capture behavioral characteristics of occupants. Exodus is now considered by some as an agent-based system [20].
- The basic idea of a *matrix-based* system is to discretize a floor area into cells. Cells are used to represent free floor areas, obstacles, areas occupied by individuals or a group of people, or regions with other environmental attributes. People transit from cell to cell based on occupancy rules defined for the cells. Two well known examples of the matrix-based systems are Egress [9] and Pedroute [13], which have been

applied to simulate evacuation in buildings as well as train (and underground) stations. It was suggested that the existing matrix-based models suffer from the difficulties of simulating crowd cross flow and concourses; furthermore, the assumptions employed in these models are questionable when compared with field observations [8]. Moreover, because the size of cells and the associated constraints need to be adjusted when creating new models, the output of these models depend highly on the user's skill.

- The concept of *emergent systems* is that the interactions among simple parts can simulate complex phenomena such as crowd dynamics [14-16]. One example of the emergent systems is the Legion system [8,17]. It should be noted that Legion was not designed as a crowd behavioral analysis system but an investigation tool for the study of large scale interactive systems. Current emergent systems typically oversimplify the behavioral representation of individuals. For example, the Legion system employs only four parameters (goal point, speed, distance from others, and reaction time) and one decision rule (based on assumption of the least effort) to represent the complex nature of individual behaviors. Furthermore, all individuals are considered to be the same in terms of size, mobility, and decision-making process. Finally, the model ignores many important social behaviors such as herding and leader influence. Nevertheless, the emergent concept is intriguing since it has the notion that crowd behavior is a collection of individuals'.

In summary, as noted by the Society of Fire Protection Engineers [5], "(computational) models are attractive because they seem to more accurately simulate evacuations. However, due to the scarcity of behavioral data, they tend to rely heavily on assumptions and it is not possible to gauge with confidence their predictive accuracy." There has been increasing interests in studying human factors in emergencies [2,6,18], however, "the fundamental understanding of the sociological and psychological components of pedestrian and evacuation behaviors is left wanting [19]." This view is also echoed by Santos and Aguirre [20], who point out that current models have largely ignored insights regarding human and social behaviors from the fields of social psychology and social organization.

3. Crowd Behaviors

Understanding the emergence and nature of crowd behaviors in emergency situations is necessary prior to the construction of a computational simulation framework. Crowd behaviors are complex phenomena, which may better be examined at three different levels: the individual, the interactions among individuals, and the group. These three levels of categorization are not independent but intimately related and often overlapped.

3.1 The Individual

From a human cognitive psychological perspective, an individual's behaviors can be viewed as the outcomes of his/her decision-making process. We conjecture that an individual's decision-making process follows three basic conventions: following instinct, following experience, and bounded rationality. An individual may select one or a combination of these basic conventions when facing an emergency, depending on the specific situation that the individual encounters.

- *Following instinct:* An instinct refers to an inborn pattern of behavior responsive to specific stimuli. Executing an instinct does not require a conscious thought process. Some examples of human instincts are fear, death and survival. While a new born baby typically functions by following instincts, Wills [21] claims that the behaviors of human adults can also be largely explained in terms of instincts, and human adults can experience and act on instincts without being conscious of them. The knowledge that an adult has learnt through his/her life experience can be viewed as the extension of his/her instincts. When there is a need to make decisions under high stress, following one's instincts is one's most primitive way that an individual relies on in making instantaneous and quick decisions. According to Quarantelli [22], if an individual perceives that he/she is in an extreme life-threatening situation, his/her behaviors are likely driven by the fear instinct such as fight or flight. Behaviors, such as pushing others down, jumping out of windows, and fleeing towards deadly blocked exits, occur because of fear.

- *Following experience:* An individual often relies heavily on his/her personal experiences in making decisions. Because many life events are highly repetitive, an individual usually develops a set of relatively standard routines over time or from past experience and then applies them to similar situations in the future. In the case of emergency egress, it is widely recognized that an individual's experiences can significantly impact his/her behavior [2,5,23,24], such as the familiarity of the surroundings, safety procedures, and fire drills. However, "using prior evacuation experience to guide future evacuation decisions, may or may not produce better outcomes" (p. 146) [25]. One observed phenomenon is that most people tend to exit a building following the route that they are most familiar with, and ignore alternate routes. Decision-making in terms of following experience is usually straightforward and quick. The process typically follows three basic steps: (1) recognize a situation that is the same as or similar to an experience in the past; (2) retrieve the routines that were successful according to prior experience; and (3) carry out the routines.
- *Bounded rationality:* The idea of bounded rationality has been integrated into many conventional social theories and come to dominate most theories of individual decision making [26]. The concept of rational decision-making assumes that a decision is based on an evaluation of alternatives in terms of their consequences for preferences. The process involves four basic steps: (1) search for possible options; (2) anticipate the consequences that might follow each option; (3) weigh each consequence with preferences; and (4) choose the most favorable option. Such a decision process is "bounded", because usually not all options are known, not all consequences are considered, and not all preferences are evoked at the same time. Decision-making in terms of bounded rationality concerns with combining new facts with existing knowledge for problem-solving, and it is one of the fundamental characteristics that constitute human intelligence. The resulted solution usually is more appropriate for the given situation comparing to a solution obtained through either following instinct or experience; but the "rational" decision making process does require a longer processing time. In an emergency situation where decisions need to be made instantly, an individual may opt for a faster method by simply following instincts or experiences, resulting at times what referred to as irrational behaviors [27]. On the other hand, altruistic and prosocial behaviors are commonly observed in emergencies [2,23]; this implies that individuals do practice rational thinking during emergencies. "Rational" or "irrational" behaviors thus depend heavily on the time and severity factor as "perceived" by an individual.

In summary, at the individual level, disruptive or nonadaptive behaviors emerged from emergency situation are the outcome of an individual's decision-making process under severe stress when perceiving a situation as highly important, highly uncertain and highly urgent. As perceived stress increases, an individual may shift decision mechanisms from following experience, bounded rational thinking, to following instincts.

3.2 The Interactions among Individuals

From the perspectives of social interaction, an individual's social behaviors are shaped by social structures through following social identities [26]. Other crucial factors that also strongly influence human social interaction include the respect of personal space [29] and the principle of social proof [30].

- *Social identity:* It is a generally accepted observation that an individual in a crowd usually acts differently than when he/she is alone or in a small group [31]. An individual is also a social being. Being as a part of a society is one essential aspect of a person. A society is organized through various social structures. In order to function properly, each social structure imposes certain rules on the individuals in the forms of laws, regulations, cultures, and norms. A social structure usually is composed of diverse identities (i.e., social roles), and each identity has a set of associated rules, which defines how different identities interact with each other. As noted by March [26], "Social systems socialize and educate individuals into rules associated with age, gender, social positions and identities. Decisions are shaped by the roles played by decision makers." Depending on an individual's identity, his/her behaviors are strongly shaped by these rules. Individual's identity is also "internalized," -- "accepting and pursuing it even without the presence of external incentives or sanctions [28]." Thus, a decision process based on social identity involves four basic steps: (1) recognize a situation; (2) know the identity/role of the decision maker in the situation; (3) find the appropriate behavioral rules associated with the identity/role; and (4) follow the rules. In other words, individuals follow rules or procedures that they see as appropriate to the situation and identify themselves with. While social identity is crucial in daily decision process, during an emergency, an individual who demonstrates nonadaptive behaviors often appears to be highly individualistic and nonsocial [32]. On the other hand, it has been observed that many people (such as trained officers) do behave according to their social identity during an emergency. Therefore, whether or not individuals remain to be consistent with their social identities depends on their stress levels and tolerance. Stress levels, in turn, are determined by the combination of perceived value of loss, time available, and uncertainty of the situation [39].
- *Personal spaces:* From a human psychological perspective, one very important factor that influences an individual's social behaviors and decision making is the notion of personal space. According to Ashcraft and Scheflen [29], "Man is a territorial animal very much like his fellow creatures. He defines a space and marks it out for his particular use. He draws visible and invisible boundaries which he expects others to respect. He will defend a territory against the intrusions of others." Under normal circumstances, an individual seeks social interaction with others; at the same time, the individual also tries to avoid intruding others' privacy as well as to defend intrusions. For example, people who are engaged in face-to-face conversation define a space that others outside the group are expected to respect; an outsider shows such respect by not hearing or pretending not to hear the conversation, by not looking into the occupied space, and by not cutting into the space surrounded by the group. Even though the actual definition of personal space varies among different cultures, genders, and social structures, social norms are respected and maintained by the engaged parties except under anomalous situations such as overcrowding and

emergencies (e.g., fire), or during a confrontation. The respect of personal space functions as a social rule to keep safe distances among individuals. When this rule is violated in a crowded environment, the involved individuals would likely to experience a higher level of stress and agitation than in a non-crowded environment [33]. Even so, people still make efforts to regain their personal spaces and avoid physical contact with others [2]. When the density of a crowd reaches a certain magnitude (such as the safety limit as suggested by Still [8]) any effort of maintaining personal space among individuals is practically impossible, which could potentially lead to nonadaptive or disruptive crowd behaviors.

- *Social proof:* The dominant factor that leads people to seek social proof is the perceived uncertainty of a situation. When an individual encounters a new situation with insufficient information, the individual is more likely to follow the actions of others as a guide to determine how he/she might act – a phenomenon known as social proof. As noted by Cialdini [30], "we seem to assume that if a lot of people are doing the same thing, they must know something we don't… those people are probably examining the social evidence, too." One well known example of social proof under emergency situations is the herding behavior – when under highly uncertain and stressful situations, an individual tends to follow others almost blindly. Sometimes herding behavior helps people to exit safely, and at other times, the herding behavior may lead people to a dead end or cause the blockages of some exits even though other exits are not fully utilized. This is a particularly interesting phenomenon in crowd dynamics and the phenomenon has now been incorporated in some computational models [11]. Other instances in this category include social inhibition and diffusion of responsibility [2,34]. Social inhibition refers to the phenomenon that people do not take initiatives but turn to each other first for social cues. "No one wishes to appear foolishly excited over an event that is not an emergency, so each individual reacts initially with a calm outward demeanor, while looking at others' reactions [35, p.285]." Diffusion of responsibility usually prevents people from taking altruistic actions. People often hesitate to initiate action to offer help in emergency in the presence of others. If no one makes the first move, it is less likely that any one would. However, when others start to offer help, then individuals would likely follow as well. Therefore, initial reactors in an emergency have significant influences in a crowd. If the initial reactors' actions appear to be in a calm and orderly manner, the others would likely to remain calm and orderly. On the contrary, if the initial reactors start to push, then the others would likely to react similarly.

In summary, at the level of social interaction, nonadaptive behaviors emerged from an emergency situation in a crowded environment likely occur if (1) individuals fail to comply with their social identities and act non-socially, (2) individuals lose their personal spaces and perceive a necessity to move urgently, and/or (3) due to a highly uncertain and stressful situation, individuals tend to follow others blindly as to seek social proof.

3.3 The Group

By viewing a crowd or a group within a crowd as an entity, we can identify many significant factors that may contribute to crowd behaviors. Examples of such factors may include: crowd density, environmental constraints, and peers' imposed mental stresses.

- *Crowd density:* The higher the crowd density the more likely it is that comfort is diminished and the risk to the individual increased [2,5]. People movement can be highly restricted in a dense and crowded environment. As pointed out by Chertkoff and Kushigian [32], "[At high crowd density,] people are swept along with the flow, completely unable to free themselves from the direction of that flow." Under such a situation, it becomes difficult for an individual even to keep his/her feet on the ground in a stable way. People may not deliberately knock others down or trample on them but accidents could occur easily under such circumstances. However, people movement also tends to follow and keep in a group, as opposed to freely moving as an individual. For example, members in a hierarchically structured group (such as families) tend to stay together and follow the leader. The density of a crowd is an important factor that can affect individual as well as group behaviors.

- *Environmental constraint:* People movement can also be restricted due to environmental constraints imposed by the spatial geometries. These constraints can be inherent in the design or can be caused by improper usage of the space. A building may have aisles and stairs too narrow to accommodate easy exit by a large crowd, inadequate number of exterior exits, obstructed passageways, locked exterior doors, stairs or doors obscured by dim lighting or confusing signs, etc. When considering crowd dynamics, we need to consider the environmental constraints and their impacts on individual and group behaviors. Unfortunately, as Shields et al. [18] point out, current design practice has primarily focused on emergency exit identification and escape route illumination, but has ignored the cognitive and perceptual processes associated with movement and spatial behavior of crowds under emergency conditions.
- *Perceived emotion and tension:* An emergency can cause a widespread perception among the people in a crowd that negative consequences could result for failing to exit a building within certain time. Field observations have shown that until such a perception becomes widespread, people do not shove others out of the way or trample on them [32]. As more people attempt to exit at once, the less of them are able to get out successfully because of the congested and jammed routes. During emergency, because of the time pressure and the lack of information, an individual normally judges the severity of a situation largely based on his/her observation of others' behaviors. In other words, regardless of the nature of an emergency, how it impacts an individual depends on the way that he/she perceives the situation and the environment, even though such a perception can be inaccurate or misguided. Different perceptions by an individual towards an emergency result in different emotions and mental stress levels, which can in turn provoke different decision mechanisms. Even under non-emergency situations, disruptive crowd behaviors can occur, as long as the situation creates high emotional arousal among the crowd, such as false alarm, group fight, confrontation between a furious crowd and police, and power outage, etc.

In summary, at a group level, nonadaptive crowd behavior can occur if a crowd holds the characteristics of high crowd density, severe environmental constraint, and high emotional arousal. The emotional arousal may or may not be originated from a real emergency.

The above discussions are not meant to be exhaustive, nevertheless it establishes a formal structure to dissect the complex nature of crowd behaviors into simpler components that can be better understood and implemented in a computational framework. For examples, the rules derived at the individual level can be utilized to build the decision-making module of an individual agent, and the rules extracted at the social interaction and group levels can be incorporated to model the interactions among agents in a virtual environment.

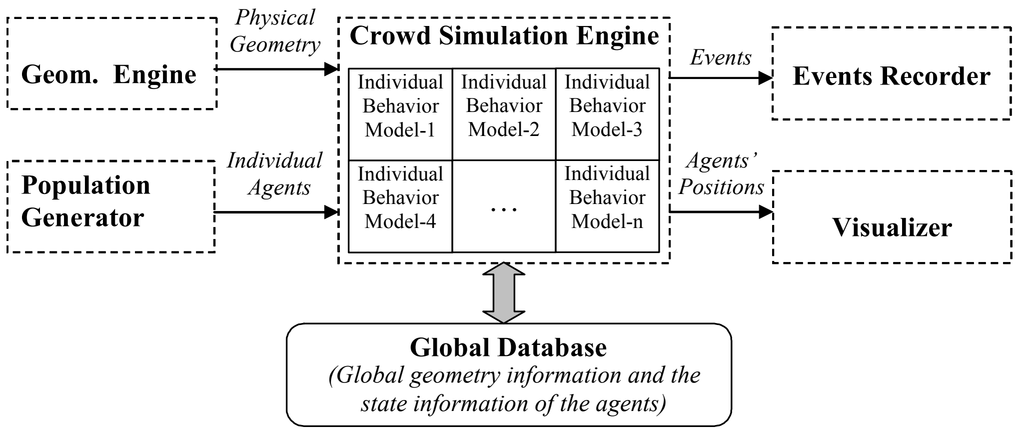


Figure 1: System Architecture.

4. A Multi-Agent Based Computational Framework

There are three main reasons for developing computer simulation for crowd behaviors: first to test scientific theories and hypotheses; second, to test design strategies; third, to create phenomena about which to theorize [36]. Each crowd setting is unique. A full understanding of crowd behaviors normally requires exposing real people to the specific environment for obtaining empirical data, which is difficult since such environments are often dangerous in nature. In addition to studying crowd behavior based on observations and historical records, computer simulation is a useful alternative that can provide valuable information to evaluate a design, to help planning process, and for dealing with emergencies.

Human behaviors are complex emergent phenomena, which are difficult to capture into computers as mathematical equations. Our framework adopts a multi-agent simulation paradigm as a basic scheme. We believe that multi-agent based systems are particularly suitable for simulating human individual cognitive processes and behaviors in order to explore emergent macro phenomena such as social or collective behaviors (which usually are not reducible to or understandable in terms of the micro properties of agents). Multi-agent simulation has been widely accepted as a promising approach to model complex emergent phenomena [14,37].

4.1 Overall System Architecture

In the MASSEgress framework, each human individual is modeled as an autonomous agent who interacts with a virtual environment and other agents according to an *Individual Behavior Model* and some *global rules on crowd dynamics* – rules that derived at the levels of interactions among individuals and group. Each agent has an imperfect model of the world. Depending on the environment and the behavioral levels of individuals and their relationships with the group (or the crowd), the agent could interact and react in a collaborative or competitive manner. In contrast to agent-based systems for design applications, there is no global system control in the simulation model. In fact, the objective here is to be able to observe the potential "chaotic" dynamics among the individuals (agents) as they enact their behavior in the simulation environment. To simulate human cognitive processes, a "perception-action" model is adopted in which an agent continuously assesses or "senses" the surrounding environment and makes decisions based on its decision model in a proactive fashion. The crowd social behaviors are collectively observed as emergent phenomena.

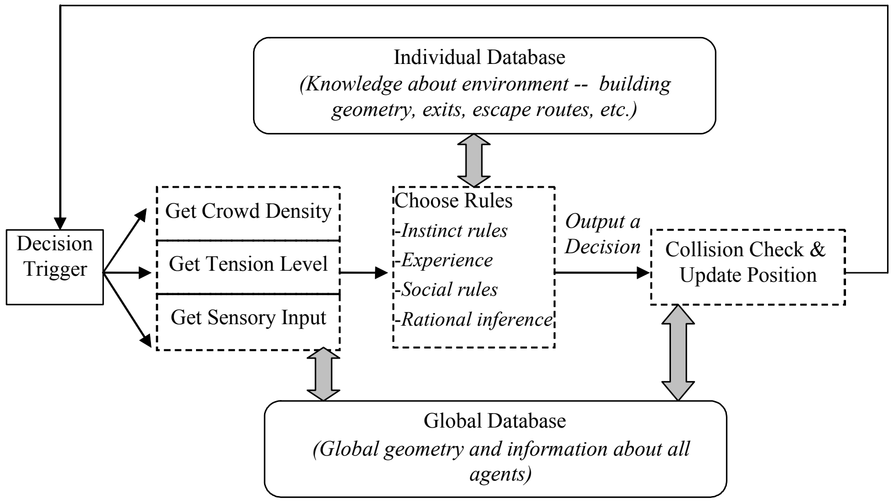


Figure 2: Individual Behavior Model.

The system architecture of MASSEgress is schematically shown in Figure 1. The system consists six basic components: a Geometric Engine, a Population Generator, a Global Database, a Crowd Simulation Engine, an Events Recorder, and a Visualization Environment.

- *Geometric Engine:* The purpose of this module is to produce the geometries representing the physical environment (e.g., a building or a train station, etc.). AutoCAD/ADT (Architectural Desktop Software from AutoDesk, Inc.) is employed in this study. The geometric data is sent to the Crowd Simulation Engine to simulate crowd behaviors.
- *Population Generator*. This module generates occupants based on the distribution of age, mobility, physical size, and type of facility to be investigated. For example, we can assume most (not all) of the occupants in an office building will likely be familiar with the facility; on the other hand, the same assumption cannot be applied to a theme park. This module also generates random populations for statistical study of individual human behaviors and crowd behaviors.
- *The Global Database.* The database module is to maintain all the information about the physical environment and the agents during the simulation. Although the multi-agent system does not have a centralized system control mechanism, the state information (mental tension, behavior level, location) of the individuals is maintained. This database also supports the interactions and reactions among the individuals.
- *The Events Recorder.* This module is intended to capture the events that have been simulated for retrieval and playback. The events captured can be used to compare with known and archived scenarios for evaluation purpose.
- *The Visualizer.* The visualization tool is primarily to display the simulated results. We have developed a simple visualization environment that is able to receive the positions of agents, and then generates and displays 2D/3D visual images in real time.
- *The Crowd Simulation Engine.* The crowd simulation engine is the core module of the multi-agent system. Each agent is assigned with an "individual behavior model" based on the data generated from the population generator. The internal mechanism of *the Individual Behavior Model* is based on the perception-action approach [40] and

consists of the following *iterative* steps (see Figure 2): (1) internally trigger for decision; (2) perceive information about the situation (i.e., crowd density, sensory input, tension level); (3) interpret and choose decision rule(s) to make a decision; (4) conduct collision check and execute the decision. Each autonomous agent proceeds to the (exit) goal subjected to the constraints imposed, interact with and update the Global Database as simulations proceed over time.

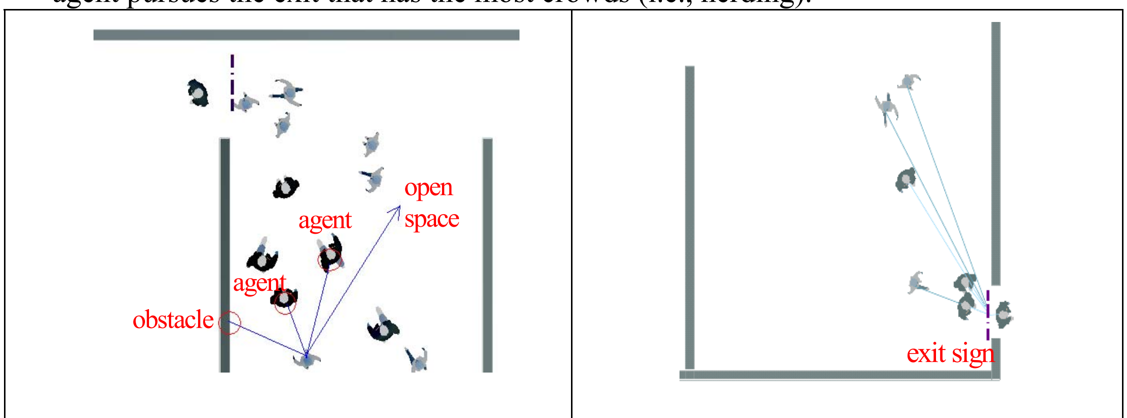
In addition to displaying crowd behaviors, the outputs of the system also include overall and individual evacuation time, individual paths, and blockage locations.

4.2 Autonomous Agents

In the prototype system, we represent human cognitive processes as the "perception-action" behaviors of autonomous agents. That is, autonomous agents interact with a virtual environment and with each other following the simulated sensing, decision-making, and reacting/acting processes (as depicted in Figure 2).

An autonomous agent represents a human individual, and it bears a set of physical as well as cognitive properties of a human individual. These properties include:

- *Population type*. Human individuals are different from each other by age, body dimension, mobility and personality. The system currently includes five general human categorizations, similar to Simulex [41] – Median, Adult Male, Adult Female, Child and Elderly. Each categorization represents a typical type of human population.
- *Sensors*. Each agent is equipped with a visual sensor so that it can analyze the environment. The visual sensor is developed using the ray tracing method [38]. By casting laser rays from the eye position of an agent within a visual angle (e.g., 170 degrees), an agent can compute the intersection of a ray and the near object, which allows it to determine (1) the geometrical distance from the sensor to the intersecting object, and (2) the type of the object that the ray intersects (see Figure 3). An agent can also sense an object through 'body contact', that is, whenever a physical collision is detected, the agent recognizes the location and the type of object it collides with. The information received from the sensors is utilized by an agent to make decisions.
- *Decision rules.* Agent's actions are driven by decision rules. When a situation is perceived, an agent activates a decision rule to produce an action. The choice of a decision rule is determined by the situational cues and the agent's psychological factors (i.e., perceived importance, uncertainty and urgency) at that moment. For example, if an agent detects two exits and its uncertainty level is 'high', then the agent pursues the exit that has the most crowds (i.e., herding).



Sensing objects in a virtual environment | Sensing an exit sign

Figure 3: Visual sensors using the ray tracing method.

- *Actuators.* Actuators of an agent refer to its faculties of being able to walk, run, stop, side-shift and turn. These faculties are the basic locomotion capacity of an agent to maneuver in a virtual environment.

The properties described form the basis of an agent's behaviors in the prototype system, the system that is able to simulate not only simple behaviors (e.g., finding an exit) but also complex social behaviors (e.g., queuing and herding behaviors).

4.3 Simulating Human Social Behavior

Incorporating human and social behaviors in computational egress simulation is difficult and challenging. Following a 'bottom-up' approach, by organizing the decision rules of an agent into a hierarchical structure, we divide an agent's behaviors into three hierarchical layers (from simple to complex): locomotion, steering, and social (see Figure 4). The behaviors on a higher layer are constructed using the behaviors from a lower layer. As an example, for a group of agents to form a queue at a narrow door, the process could involve (1) the motion (such as moving a step) of an agent that takes place at the locomotion layer, (2) avoiding obstacle using a steering behavior, which consists of a sequence of different locomotion, (3) exiting a door in an orderly manner as a type of social behavior. The following sections discuss how various agent behaviors are implemented at each layer.

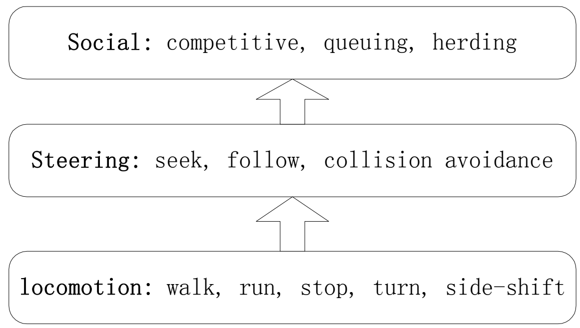


Figure 4: A hierarchy of agent behavior.

4.3.1 Locomotion

Behaviors at the layer of locomotion are directly controlled by the actuators of an agent, corresponding to the simplest behaviors that an agent can conduct. We have implemented six different types of agent locomotion – *walking forward, running forward, stopping, side-shifting, turning,* and *moving backward*. To choose a locomotion type at a particular time step may be determined by either a decision rule or randomly (when rules are not defined for a situation). As an example, if an agent detects an exit in front and there is no obstacle on its path toward the exit, then the agent chooses the *walking forward* locomotion. However, if an agent is blocked by a crowd, it may choose randomly among the *stopping* (i.e., avoiding collision), *turning* (i.e., attempting a different path), or *moving backward* (i.e., maintaining its personal space) locomotion.

4.3.2 Steering Behavior

The concept of steering behavior has been widely used in robotics and artificial life. Steering behaviors are essential for an autonomous agent to navigate its virtual environment in a realistic and improvisational manner. Combining steering behaviors can be used to achieve higher level goals, such as getting from here to there while avoiding obstacles. The following steering behaviors are included in the prototype system:

- *Random walk*. Until a goal point is decided, an agent walks in the virtual environment randomly.
- *Collision avoidance*. This behavior gives an agent the ability to maneuver in the virtual environment without running into an obstacle or other agents. Its implementation is achieved by monitoring an agent's sensory input and reacting to possible collisions. For example, if an agent detects obstacles both in front and on the

right but not on the left, then it steers toward the left. As another example, when two agents are meeting head-on in a corridor, they would steer to the side to avoid running into each other.

- *Seek.* A seek acts to steer an agent toward a goal point. When a goal point is detected, an agent adjusts its orientation and velocity toward the goal. In addition, the agent alters its orientation randomly by a small magnitude and then re-aligns it, producing a life-like motion while approaching the goal (it is interesting to note that from field observations, human individuals usually do not walk along a straight line toward a goal point).
- *Negotiation.* Negotiation enables an agent to exchange information and reach agreements with others. For example, when a group of agents forms a queue at an exit, they negotiate with each other to determine their positions in the queue. The agents achieve this by informing each other their distances to the exit, and the ones who are closer to the exit get higher priority in the queue.
- *Target following*. This behavior allows an agent to follow a moving target. A typical example is that an agent moves forward in a queue by following another agent who is in front.

The steering behaviors described above serve as the basic building blocks for constructing more complex behaviors. In fact, an agent seldom continuously executes a single steering behavior. In order to act in a complex environment, an agent has to select among, and blend between, different steering behaviors to produce more complex and life-like behavioral patterns. Combining steering behaviors can be accomplished either by (1) switching between different behaviors as perceived situation changes (e.g., switching from *random walk* to *seek*), or (2) blending different behaviors together (e.g., blending *seek* and *collision avoidance).*

4.3.3 Social Behavior

Social behaviors are complex phenomena emerged from the interactions of a group of autonomous agents. A single agent's behavior is essentially nondeterministic at a microscopic level; if the system is executed multiple times with the same initial setting, the agents would not behave exactly the same way each time. However, at a macroscopic level, certain behavioral patterns could be observed across the multiple runs. These social behavioral patterns are called emergent phenomena. As of this writing, the prototype system can demonstrate social emergent phenomena including competitive, queuing, and herding behaviors.

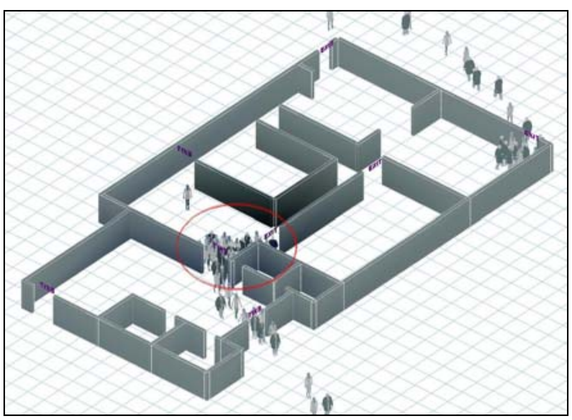


Figure 5: Competitive behavior

Competitive behavior is often observed in emergency situations, when human individuals compete for their own chances of exiting (see Figure 5). Competitive behavior usually leads to inefficient evacuations and/or nonadaptive crowd behaviors. In the system, competitive behavior occurs when agents execute the following decision rules selectively: (1) *walk randomly* until a goal is determined, (2) *seek* the goal with maximum velocity if possible and do not *negotiate* with other agents, (3) do not preemptively *avoid collision*.

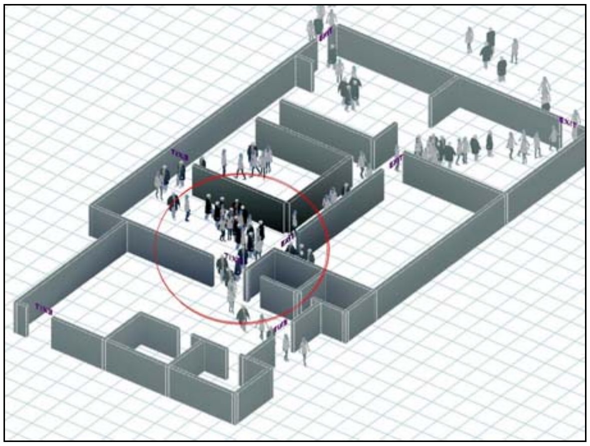


Figure 6: Queuing behavior

Sometimes, queuing behavior emerges spontaneously when a crowd gathers at an exit, permitting the crowd to “stream” out of the exit in an orderly manner. The formation of a queue is largely the manifestation of self-organization. Unlike competitive behavior, queuing behavior does not lead to clogs at exits but often leads to more effective evacuations (see Figure 6). The simulation system illustrates that, queuing behavior could take place when agents carry out the following decision rules: (1) *walk randomly* until a goal is determined, (2) *seek* the goal, (3) if obstructed by other agents, *negotiate* to initiate a queue, (4) join an existing queue if encounter one, and (5) execute *target following* to move forward in a queue.

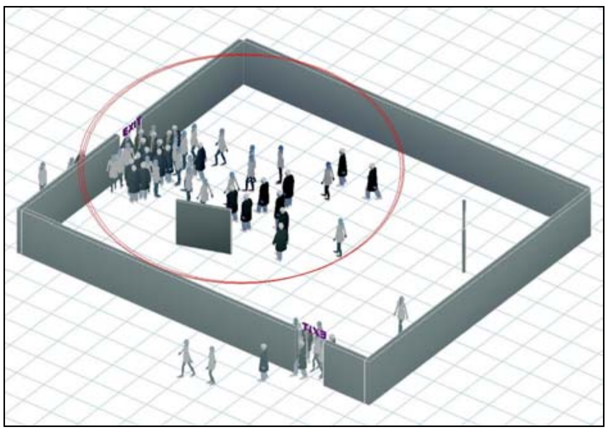


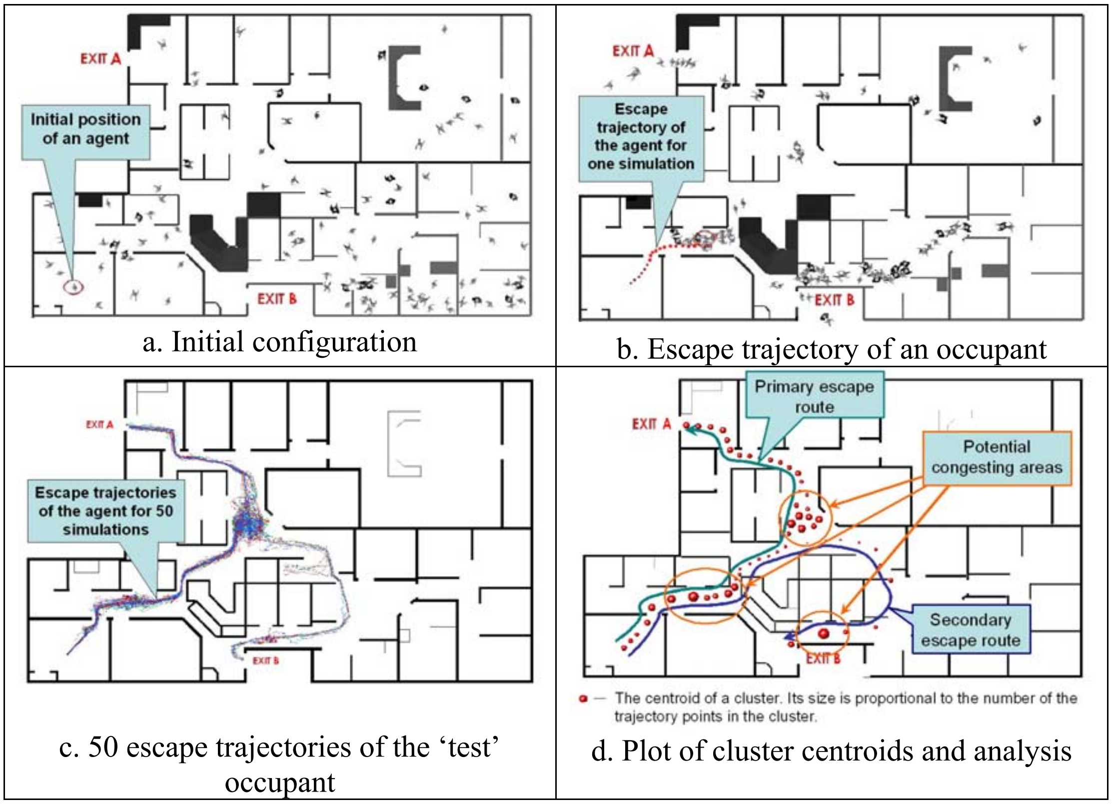
Figure 7: Herding behavior

Herding behavior is often observed during the evacuation of a crowd in a room with two exits – one exit is clogged while the other is not fully utilized (see Figure 7). Sometimes herding behavior helps people to exit safely, and at other times, it may cause blockages at an exit even though other exits are available. Building designers often assume that a crowd would exit evenly among multiple exits of a room in case of an emergency; however, herding behavior invalidates such an assumption. The simulation system shows that, herding behavior could occur when agents exercise the following decision rules: (1) *random walk* until a goal is detected, (2) if multiple goals are detected, compute the ‘popularity’ for each goal by observing other agents, and then choose the goal that has the most crowd, (3) *seek* the goal.

The social behaviors described above are not independent from each other. Similar to steering behaviors, it is possible to combine some of the social behaviors for constructing even more complex behaviors. For example, the simulation shown in Figure 7 demonstrates herding behavior as well as competitive behavior.

5. An Example Application: Egress Design Analysis

The simulation tool, MASSEgress, can potentially be used for many practical applications. One example is to facilitate egress analysis for building designs. When designing a floor plan for a building, although the intended usage of the space is usually known, it is difficult to account for every possible scenario for safe evacuation, because of the uncertainties such as spatial distributions of the occupants and their behaviors. However, with the layout of a floor plan, some typical evacuation patterns can be drawn



a. Initial configuration

b. Escape trajectory of an occupant

c. 50 escape trajectories of the ‘test’ occupant

d. Plot of cluster centroids and analysis

Figure-8: Using simulations for safe egress analysis

statistically by conducting multiple evacuation simulations with different occupant configurations. These evacuation patterns can provide insights to help improve the design. The following scenario represents an instance of how to capture some evacuation patterns for a specific floor plan design.

Figure-8a depicts a hypothetical floor plan of an office building. The floor plan contains a number of office spaces organized along hallways and corridors. There are two egress exits, exit A on the west and exit B on the south. We intend to find out what are the evacuation patterns of the design from a perspective of egress.

At first, we place a ‘test’ occupant in a specific room with the presence of other occupants distributed randomly in other spaces. Evacuation simulations are then performed many times (say 50 times in this example), with different spatial distribution of the occupant. That is, for each simulation, while fixing the location of the ‘test’ occupant, we randomize the locations and behavioral types of other occupants, so that the ‘test’ occupant would exhibit different evacuation behaviors for a range of different situations. Figure-8b shows an example escape trajectory of the ‘test’ occupant in one of the simulations.

Figure-8c shows the 50 trajectories of the ‘test’ occupant from the simulations. Using a K-Means clustering algorithm [42], the trajectory points are categorized into clusters represented by a set of centroids. The resultant centroids are plotted as shown in Figure-8d, and the size of each centroid reflects the number of trajectory points that the centroid contains. By analyzing the distribution of the centroids, we can identify the primary and the secondary escape routes of the occupant, the relative frequency for the usage of the routes, and the potential congested areas during evacuations. By exploring different geometric configurations and re-arranging exit signs, a designer can modify the floor plan to alleviate congested areas and to provide more efficient egress routes.

6. Summary and Discussion

Although there have been some research studies on crowd simulation for safety engineering purposes, few efforts have been conducted to study the core of crowd safety problem – human and social behaviors in emergencies. In this paper, we discussed nonadaptive crowd behaviors from three different levels – the individual, the interactions among individuals, and the groups. Understanding of such potentially disruptive behaviors is important for designing a simulation system for emergency evacuation. We then presented a computational framework for studying human and social behaviors during emergency evacuations. For demonstration purpose, we have prototyped a multi-agent system based on the framework. The computational framework allows pre-defined deterministic or random assignments of individuals and groups in the design space. The system is able to model emergent human social behaviors, such as competitive behavior, queuing behavior and herding behavior through simulating the behavior of human agents at microscopic level. The potential of the framework for studying human and social behaviors appears promising.

Our future efforts include constructing a pool of human individual and social behaviors, which can then be customized by users to model typical population types as to test a broad range of emergency situations and design configurations. Physical models such as pushing, knocking, are also being investigated. Modeling of accidental events will also be a subject of further study. Additionally, we plan to further extend the tool to perform statistical analysis of evacuation patterns, times, flows and other design parameters. It is expected that the computational framework can lead to valuable contributions to the field of crowd safety research, which, due to recent natural and man-made events, is fast becoming an important issue in facility design and management.

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