A MULTI-AGENT BASED SIMULATION FRAMEWORK FOR THE STUDY OF HUMAN AND SOCIAL BEHAVIOR IN EGRESS ANALYSIS

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ABSTRACT

There exist a wide variety of computational tools for the simulation and design of exits. However, due to the scarcity of behavioral data, these tools rely heavily on the assumptions about human individual and social behaviors. Many of these assumptions have been found inconsistent or incorrect. This paper presents a multi-agent based framework for studying human and social behavior during building emergency evacuations. A prototype system has been developed, which is able to demonstrate some emergent human social behaviors, such as competitive, queuing, and herding behaviors.

KEY WORDS

Multi-agent system, human and social behavior, emergencies, egress, crowd simulation.

INTRODUCTION

In this paper, we present a multi-agent simulation framework for the study of human and social behavior during building 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 (Crowd Dynamics Ltd. 2004). 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 related individuals and organizations - the survivors, the victims' families, and the local communities (Lysted 1988).

Among the many factors including overcrowding and evacuation incidents, researchers have come to realize that understanding human and social behavior in emergencies is crucial to improve crowd safety in places of public assembly (Bryan 1997; Fahy et al. 1995; Proulx 2001; Society of Fire Protection Engineering 2002; Galea 2003). It has been reported that there are many inconsistencies and incorrect assumptions of human and crowd behavior embedded in existing simulation systems (Still 2000). A computational framework that can help study human and social behaviors and their consequences may help improve safe egress

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analysis and design. Multi-agent based modeling is a particular type of computational methodology that allows building an artificial environment populated with agents which are capable of interacting with each other. We believe such systems are particularly suitable for simulating individual cognitive processes and behavior and for exploring emergent phenomena such as social or collective behaviors. In the prototype system, each occupant is simulated as an independent agent equipped with sensors for perceiving environment, mind for decision-making, and actuators for taking actions as to walk, run, stop, shift and turn. The prototype system is able to illustrate some of the frequently observed human social behaviors such as competitive, queuing, and herding behaviors in emergencies, along with the egress time corresponding to each type of behavior.

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 fluid or particle systems, matrix-based systems, and emergent systems:

- Many have considered the analogy between *fluid* and *particle* motions (including interactions) and crowd movement. Two typical examples of fluid or particle systems are the Exodus system (Fire Safety Engineering Group 2003) and the panic simulation system built by Helbing et al (2000). 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 (2000), "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. 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 (Still 2000).
- 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 (AEA 2002) and Pedroute (Halcrow 2003), 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 (Still 2000).

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 (Epstein 1996; Johnson 2001). One example of the emergent systems is the Legion system (Legion 2004). 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 (2002), "These (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 have been increasing interests in studying human factors in emergencies (Bryan 1997; Proulx et al. 2002; Shields and Proulx 2000), however, "the fundamental understanding of the sociological and psychological components of pedestrian and evacuation behaviors is left wanting (Galea 2003)." Furthermore, incorporating human behaviors in computational egress simulation is difficult and challenging.

A MULTI-AGENT BASED CROWD SIMULATION FRAMEWORK

This section presents a multi-agent based computational framework that simulates human and social behavior. There are three main reasons for developing computer simulation for studying crowd behaviors: first to test scientific theories and hypotheses; second, to test design strategies; third, to create phenomena about which to theorize (Penn 2003). Each crowd setting is unique. A full understanding of crowd behaviors in emergencies 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 behaviors 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 to develop the simulation system. Multi-agent simulation has been widely accepted as a promising approach to model complex emergent phenomena (Epstein 1996; Sole and Goodwin 1993; Weiss 2000).

In the framework, each human individual is modeled as an autonomous agent who interacts with a virtual environment and other agents according to an *Individual Behavior*

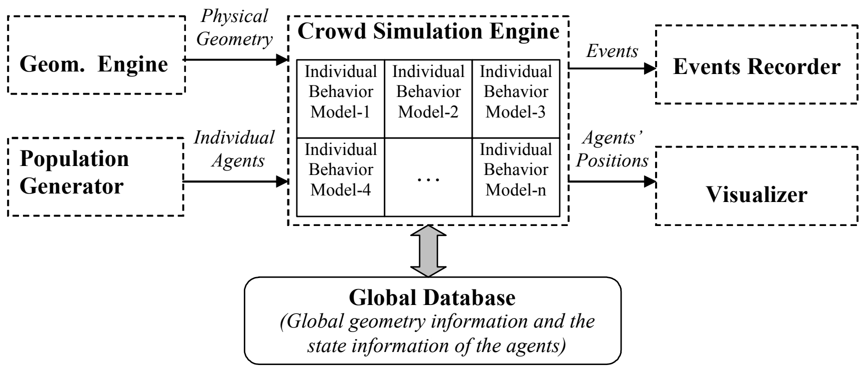


Figure 1: System Architecture.

Model and some *global rules on crowd dynamics*. Each agent has an imperfect model of the world. Depending on the environment and the behavior 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 observe the potential "chaotic" dynamics among the individuals (agents) as they enact their behavior in the simulation environment. A "perception-interpretation-action" model is adopted in that an agent continuously assesses or "senses" the surrounding environment and makes decisions based on its decision model in a proactive fashion. The human social behaviors can then be collectively observed as emergent phenomena.

Our system architecture is schematically shown in Figure 1. The system consists of five 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.

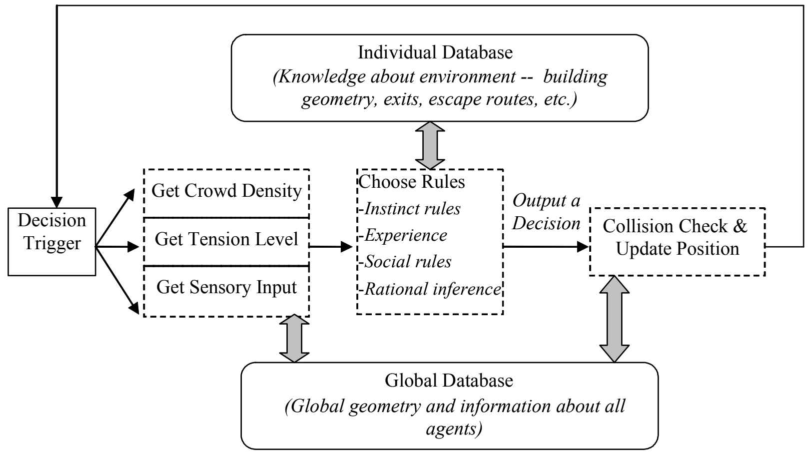


Figure 2: Individual Behavior Model.

- *The Visualizer.* The visualization tool is primarily to display the simulated results. We develop 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 population generator. The internal mechanism of *the Individual Behavior Model* is based on the perception-action approach (Fujii and Tanimoto 2003; Nakamura and Asada 1995) 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.

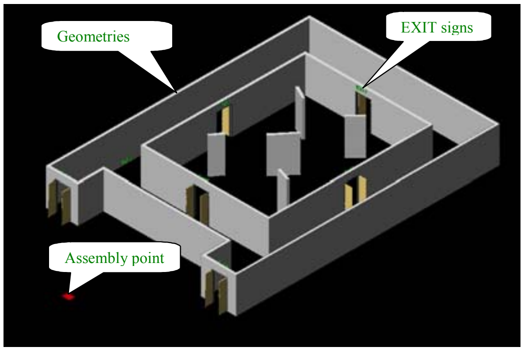
In addition to displaying crowd behaviors, the outputs of the system also include overall and individual evacuation time, individual paths, and blockage locations.

A PROTOTYPE MULTI-AGENT SYSTEM

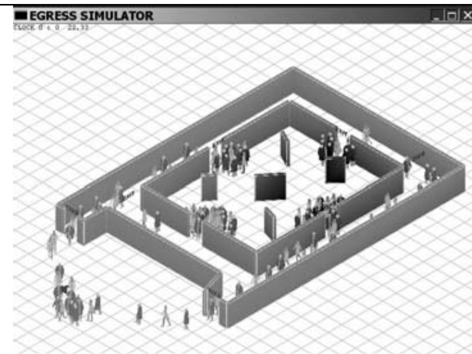
This section discusses the implementation of the multi-agent system for the simulation of crowd behavior. The discussion is divided mainly into two parts: the representation of the environment, and the human and social behaviors, which together make up the simulation scenarios.

REPRESENTING THE ENVIRONMENT

A core step to construct the simulation system is to establish appropriate representation for the physical environment (e.g., a building) consisting of relevant geometric information, and the human individuals as autonomous agents equipped with sensors, decision rules, and actuators. The purpose is to capture human cognitive process - perceiving the environment, processing the information, and acting/reacting to situations – in the computational model.



Geometric information in ADT



Egress simulation as shown in Visualizer

Figure 3: Construction of a virtual environment.

Representation of the Physical Envrionment

The first task is to capture the geometric information about the physical environment. Specifically, we are interested in the geometric information describing obstacles, spaces, exits, exit signs and assembly points. The geometric engine (a software component implemented in Visual LISP) extracts the model built using ADT (Architectural Desktop) and exports the results to the Crowd Simulation Engine (See Figure 3).

- *Obstacles*. Obstacles refer to walls, furniture, and any objects that are inaccessible. Each obstacle has definitive boundaries. Agents detect the obstacle through their sensors.
- *Spaces*. Spaces are the areas where agents may maneuver freely. Examples are corridors, lobbies, rooms, etc. The shapes and dimensions of spaces are obtained based on the arrangement of obstacles.
- *Exits*. Exits, such as doors, connect spaces and allow an agent to transit from one space to another.
- *Exit signs*. Exit signs are devices which label exiting routes to exterior openings. They usually are unidirectional. A human agent can sense an exit sign if (1) there are no obstacles between the eyes of the agent and the sign, and (2) the sign is within a visible range.
- *Assembly points*. Assembly points are locations to specify the destinations upon evacuating from a facility. Assembly points are commonly used in evacuation plans to indicate safe gathering locations in case of an emergency.

Autonomous Agent

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, motility, and personality. Instead of modeling each individual, the prototype system currently includes five categorizations, similar to Simulex (Thompson et al. 2003) – Median, Adult Male, Adult Female, Child and Elderly. Each categorization represents a typical type of human population.

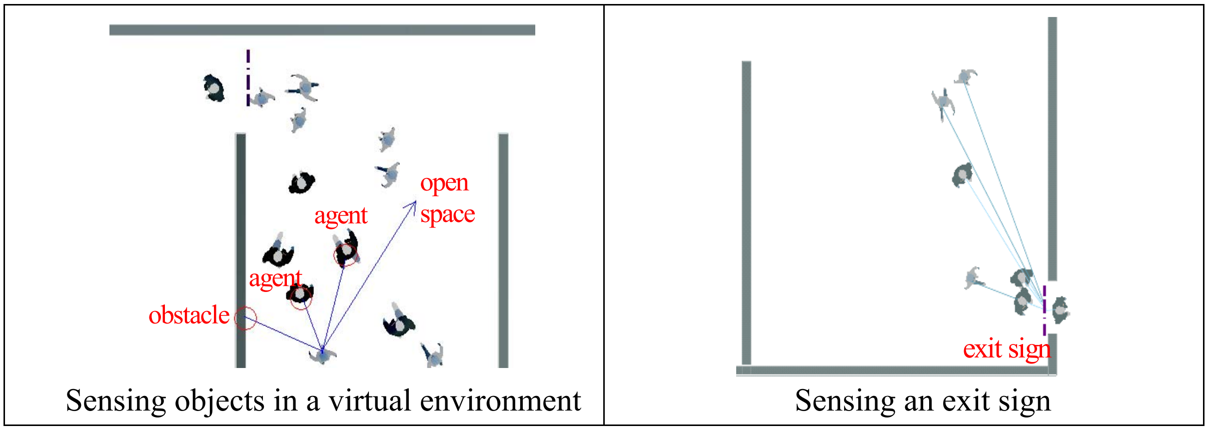


Figure 4: Visual sensors using the ray tracing method.

- *Sensors*. The prototype system includes a visual sensor so that an agent can analyze the environment. The visual sensor is developed using a ray tracing method (Madden and Farid 1995). By casting laser rays from the eye position of an agent within a visual angle (e.g., 170^{o}), 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 object (e.g., an obstacle or an agent) that the ray intersects (see Figure 4). 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 represented in terms of 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).
- *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 behavior in our prototype system, which is able to simulate not only simple behaviors (e.g., finding an exit) but also complex social behaviors (e.g., queuing and herding behaviors).

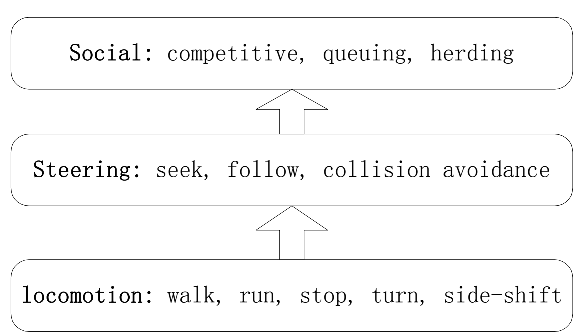


Figure 5: A hierarchy of agent behavior.

AGENT BEHAVIOR

To incorporate human and social behaviors in a computational egress simulation, we divide an agent's behaviors into three hierarchical layers (from simple to complex): locomotion,

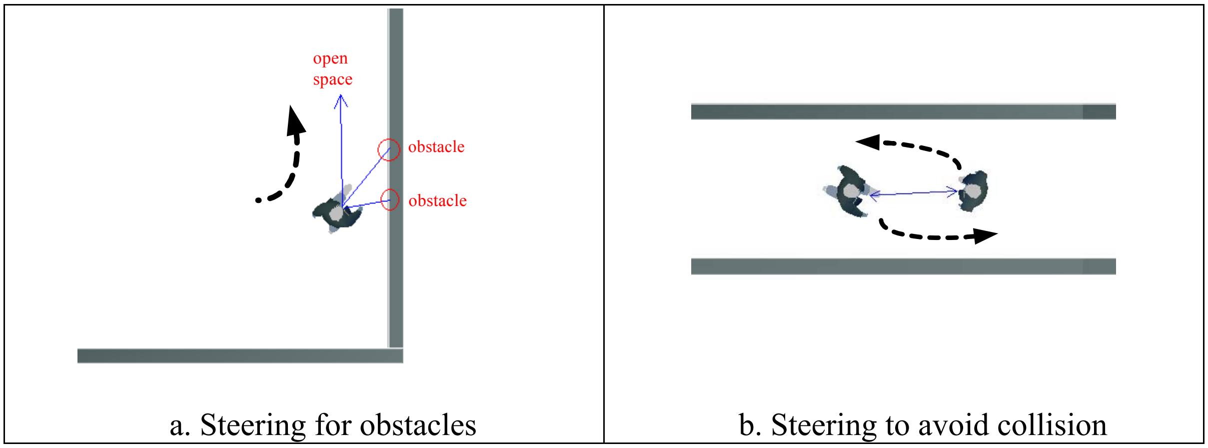


Figure 6: Collision avoidance

steering, and social (see Figure 5). 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. This section discusses how various agent behaviors are implemented at each layer.

Locomotio

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.

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 (Reynolds 1999), 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

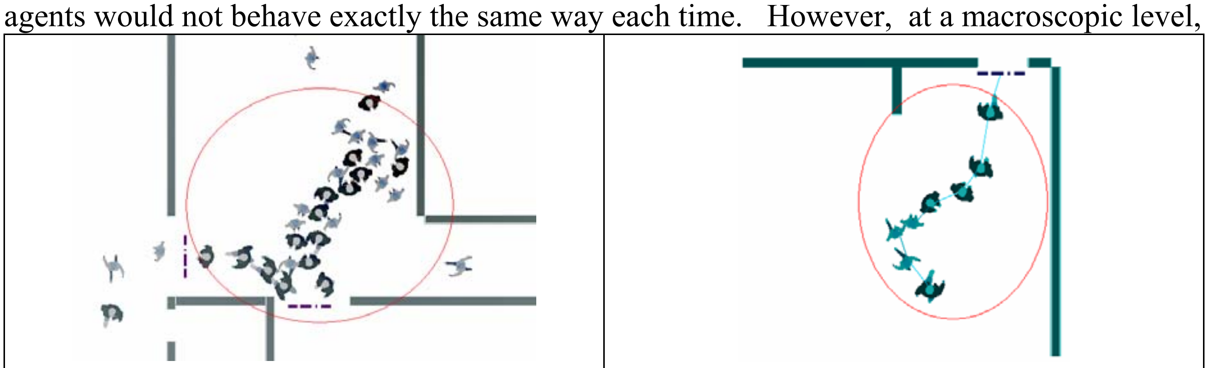
achieved by monitoring an agent's sensory input and reacting to possible collisions. For example, if an agent detects obstacles both in front and on the right but not on the left, then it steers toward the left (see Figure 6a). As another example, when two agents are meeting head-on in a corridor, they would steer to the side to avoid running into each other (see Figure 6b).

- *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 (see Figure 7a). 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 (see Figure 7b).

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).*

Social Behaviors

Social behaviors are complex phenomena emerged from the interactions among 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,



a. Negotiation

b. Target following

Figure 7: Steering behaviors in a queue.

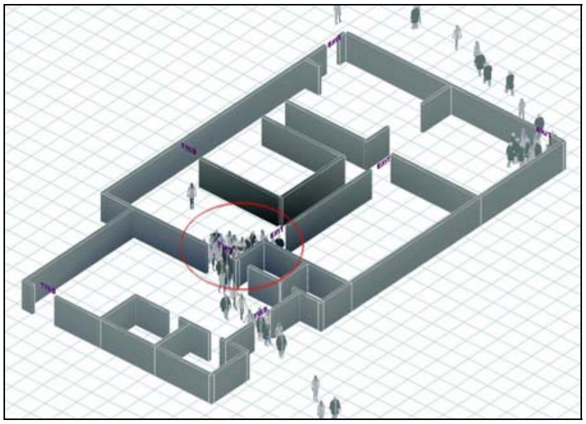


Figure 8: Competitive behavior

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.

Competitive behavior is often observed in emergency situations, when human individuals compete for their own chances of exiting (see Figure 8). Competitive behavior usually leads to inefficient evacuations and/or non-adaptive crowd behaviors. In the system, competitive behavior occurs when agents execute the following decision rules: (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*.

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 and often leads to more effective evacuations (see Figure 9a). Our system shows that, queuing behavior takes 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.

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 9b). 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. Our system demonstrates that, herding behavior occurs 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.

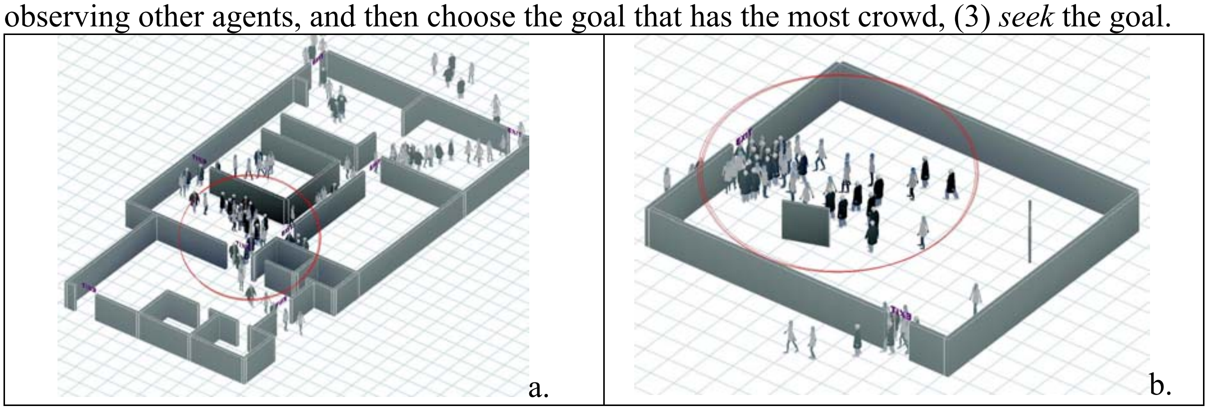


Figure 9: Queuing and herding behavior.

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 9b demonstrates herding behavior as well as competitive behavior.

CONCLUSIONS AND FUTURE WORKS

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 have presented a computational framework for studying human and social behaviors during building emergency evacuations. For demonstration purpose, we have prototyped a multiagent system based on the framework, and 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 is 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. The computational framework will allow pre-defined deterministic or random assignments of individuals and groups in the design space. Additionally, the framework will be able to perform statistical analysis of evacuation patterns, times, flows and other design parameters.

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