Human and Social Behavior in Computational Modeling and Analysis of Egress

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Abstract: Safe egress is one of the key design issues identified by facility planners, manager and inspectors. Computational tools are now available for the simulation and design of emergency evacuation and egress. However, these tools rely heavily on assumptions about individual human and social behaviors, which have been found to be oversimplified, inconsistent and even incorrect. Furthermore, the behaviors are usually incorporated into the computational model in an ad hoc manner. This paper presents a framework for studying human and social behavior, from the perspectives of human decision-making and social interaction, and for incorporating such behavior systematically in a dynamic computational model suitable for emergency egress analysis.

Keywords: human and social behavior; decision-making; egress; emergency; computational modeling; multi-agent system.

1. INTRODUCTION

Design of egress for places of public assembly is a formidable problem in facility and safety engineering. Although the regulatory provisions governing egress design are prescribed in code, the actual performance of the evacuation systems is difficult to assess. There have been numerous incidents reported regarding overcrowding and crushing during emergency situations. They occur in sport stadiums (e.g., the stampede incident in a soccer stadium that killed more than 120 people in Ghana, Africa in 2001), schools (e.g., the incident due to power outage that killed 21 children and injured 47 in Beijing, China in 2002), social gathering places (e.g., the incident at a nightclub in Chicago, IL in 2003 that killed 21 people) and other facilities. 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 individuals and organizations, including the survivors, the victims' families, and the communities [1].

Studies to improve crowd safety in places of public assembly involve many disciplines including architectural design for safe egress [2-4], crowd planning and management [5], crowd simulations [6-20], emergency planning, leadership training and many others [21]. Even for well-planned events in well-designed facilities, an undeniable fact is that real danger lies within the crowds. In a crowded environment, it has been observed that most victims were injured or killed by the so-called "nonadaptive" behaviors of the crowd, rather than the actual cause (such as fire or explosion) of the disaster. For example, in the Iroquois Theatre fire (in 1903), the initial fire was brought under control quickly; however, 602 people were trampled to death in the end. Another example is the Hillsborough English FA Cup Stampede (in 1981); though there were no real cause for the emergency, 95 people were killed and more than 400 people were injured.

Nonadaptive crowd behaviors refer to the destructive actions that a crowd may experience in emergency situations, such as stampeding, pushing, knocking and trampling on others, etc.; these actions are responsible for a large number of injuries and deaths in man-made and natural disasters. To study nonadaptive behavior in a crowded environment, we need to gain an understanding of human and social behavior in emergency situations from both psychological and sociological perspectives. On a microscopic level, individuals in a crowd act and make decisions differently than when they are alone or in a small group. On a macroscopic level, nonadaptive crowd behaviors are collective phenomena triggered by some external crises or emergencies (fire, smoke or explosion). Surprisingly, there have been very few studies focusing on nonadaptive crowd behaviors from a psychological and sociological perspective in the area of facility and safety engineering.

Building codes contain "means of egress" provisions designed to ensure the safety of a building [4]. However, these codes only provide basic guidelines, are not exhaustive and are often insufficient for many practical situations [19]. First, current codes and guidelines contain inconsistencies which may lead to misinterpretations. An effective computational tool can test whether a specific guideline is appropriate for a particular situation. Second, each building is unique, and compliance with design guidelines does not automatically ensure safety. Often, local geometries – shapes and sizes of spaces and obstacles – can have significant influence on egress, albeit in a subtle way. For instance, a widening in a corridor could actually exacerbate crowd flow, rather than allow people to move faster [12]. To date, very few studies can be found in existing literature that examine how environmental constraints and local geometries impact crowd behaviors and movements. This type of study is difficult since it often requires exposing real people to the actual, and possibly dangerous, environment. A good computational tool which takes human and social behavior of a crowd into consideration could serve as a viable alternative.

Computational tools are now commercially available for the simulation and design of emergency evacuation and egress. However, most current computational tools focus on the modeling of spaces and occupancies but rarely take crowd behavior into consideration. On the other hand, the usefulness of a simulation tool is preconditioned by its ability to model properly and correctly the crowd who will occupy the facility and their behavior. Understanding nonadaptive crowd behaviors is essential to the development of effective egress strategies and models for achieving safety. Current computational models are unable to cover the range of scenarios suitable for safety engineering purposes [19]. As noted by the Society of Fire Protection Engineers [23], "These (computational) models are attractive because they seem to more accurately simulate evacuations. However … they tend to rely heavily on assumptions and it is not possible to gauge with confidence their predictive accuracy."

In this paper, we present a framework to study nonadaptive crowd behaviors from the perspective of human behavior and social interactions, and to incorporate such behavior in a dynamic computational model suitable for safe egress analysis. By incorporating different behavior-based models, we can gain better insight into the design of egress and to assess the performance of evacuation systems. The computational tool can potentially serve as a means to study safety engineering, such as assessing building codes and designs, testing safety and evacuation procedures and crowd management.

2. BACKGROUND

2.1 Human and Social Behavior and Crowd Dynamics

The study of the "crowd" has a long history in sociology. Traditionally, the crowd has been seen as a dangerous phenomenon, in which individual identities, motivations and rationalities dissolve into a collective mind. The modeling of crowd behavior using fluid dynamics and particle systems thus has a firm basis in sociological thinking about mass assemblies. In terms of the history of social theory, this is an echo of Durkheim's [24] identification of socially-induced religious ecstasy as the material base of the experience of a phenomenon that transcends the individual. The secular analogy of religious ecstasy is panic, or the yielding of individual rationality to an overwhelming collective force, albeit fear rather than joy.

Over the last two decades, this view of the crowd as unitary and overwhelming to its individual constituents has been eroded by a contrary perspective that: (1) sees individuals as retaining their rationality (though perhaps in bounded form, in Herbert Simon's sense [25]); and (2) identifies social structures of interaction below the level of the crowd, including both pre-existing structures (such as family and friendship groups) and structures like queues, arcs and rings that serve a particular function in the context of the gathering [26]. If these features of crowds and other gatherings are operative in both "normal" events and those in which emergencies occur, then these propositions have some clear implications for modeling emergency egress.

Studies of collective action in crowds, including studies of collective locomotion, have demonstrated that preexisting social relationships play a very significant role in structuring behavior [27-29]. People who come together to a gathering tend to move in concert with each other, orient their action to each other and leave together. This means that gatherings have a "lumpy" quality; an event with a thousand people might be composed of several hundred constituent groups moving as internally self-regarding and coordinated units. This has some obvious modeling implications, for example: (1) flow through exits is likely to be smoother if the path through the exit can accommodate groups as a whole, rather than requiring the group to disperse or string out; (2) if group (for example, family) members become separated from each other, individual members may seek to reconstitute the group before exiting, producing contrary movements and impeding the flow of the crowd as a whole; and (3) groups that are hierarchically organized (for example, parents plus children) will probably behave differently than those that are not.

The state of individual rationality defines a second broad set of issues in modeling crowd behavior. If crowd members retain purposive rationality, even under conditions of emergency and 'panic,' then two questions arise: (1) How should this rationality be modeled? and (2) What are the relevant aspects of the situation that affect decision-making? The simplest model of rationality is to assume that group members assess all of the available options and select the alternative that maximizes their utility; in the case of emergency egress, their likelihood of exiting safely. One possibility is to use a game theoretic approach to capture that an important part of the decision environment is other actors who are themselves making rational decisions. An interesting line to pursue might be the extent to which altruistic behavior appears, and how it manifests itself. For example, is there a mix of selfish and altruistic actors? How do they behave differently? Are there classes of actors that are more likely to be the target of altruistic behavior, for example children or the elderly? Does altruistic behavior actually work?

Another model of rationality, and one that is probably more realistic, is bounded rationality [25]. Models of bounded rationality assume that people are purposively rational, but that they are limited by the extent of their information and by their cognitive capacities for calculation, prediction and action. To compensate, people (1) satisfy rather than optimize, (2) pursue courses of action until they fail, rather than constantly scan for better alternatives; and (3) search for alternatives that are in the neighborhood of the problem, and that represent smaller rather than large deviations from current practice. These assumptions provide a lot of space for alternative descriptions of behavior. For example, it may be that people are strongly disposed to exit the same way that they entered, rather than evaluating all of the possible exits. This suggests that directing flows of people into a space through varying pathways would make it more likely that they would use the full range of exits in an emergency. Another modeling issue is how people decide that there is a problem and that they should exit, or alternatively that the exit process is presenting problems, and that they should do something differently. Bounded rationality would suggest that (1) the perception of a problem will lag its appearance, and (2) the local state will predominate over distant states in guiding behavior.

Bounded rationality could also explain reinforcing behavior that produces negative consequences. For example, if a queue stops moving, it is difficult for most queue participants to identify the cause. For them, it manifests itself as a sudden slowing of the person immediately in front of them. This might well produce a pushing reaction, in order to resolve the immediate problem. This could easily produce a chain reaction. A design for compensating for this problem could take several directions: (1) distribute information about the queue to its members, perhaps through displays; (2) provide or introduce interruptions in the queue, to limit the extent of the chain reaction, or (3) prevent the formation of queues through some other mechanisms.

The discussion above points to many interesting issues related to crowd dynamics. To study crowd behavior, particularly in emergency situations, we need to take into consideration an individual's self-identity, group behavior and interactions and rationality. The computational framework to be described in this paper is designed to handle many of the issues discussed.

2.2 Nonadaptive Crowd Behavior

Although the study of crowd behavior can be dated back to the 1800s, relative few studies about nonadaptive crowd behaviors have been reported in the literature. Most of the fundamental studies on behavioral models were conducted prior to the 1960s before computers were commonly used as simulation tools. Generally speaking, existing theories on crowd behavior in emergency situation can be classified into three basic categories: (1) panic [30-33], (2) decision-making [34,35], and (3) urgency levels [36]:

- *Panic* theories deal primarily with the factors that may cause panic during emergencies. The basic premise is that when people perceive danger, their usual conscious personalities are often replaced by the unconscious personalities which in turn lead them to act irrationally unless there is a presence of a strong positive social (such as a leader) influence.
- *Decision-making* theories assume that a person, even under a dangerous situation, can still make (albeit limited) rational decisions, attempting to achieve good outcomes and objectives in the situation [35]. In a situation such as a fire, cooperating with others and waiting one's own turn can likely be beneficial to the group and, in turn, increasing the individual's likelihood of exiting a facility. On the other hand, if some people are pushing, then an individual may feel that his/her chances of exiting safely are threatened if he/she does not react; the best course of action for the individual may be to join the competition and push, in order to maximize the chance of exiting safely.
- Another theory suggests that the occurrence of (human) blockages of exiting space depends on the *levels of urgency* to exit [36]. There are three crucial factors that could lead to such situation: the severity of the penalty and consequence for not exiting quickly; the time available to exit; and the group size. A problem arises when the urgency to leave reaches a high level of anxiety; for example, too many people try to exit quickly at the same time. Thus, any effort that can reduce the number of people having a high urgency to leave will cause a decrease in jams and less entrapment.

Although these theories have provided many insights into human behavior and reactions in an emergency situation, to date, not a coherent and comprehensive theory about nonadaptive crowd behaviors has emerged. One common shortcoming of existing theories is that the factors considered are incomplete [37]. Another problem is the inconsistencies among the different theories. For example, panic theories and decision-making theories have opposite assumptions regarding whether or not people are rational under emergencies. Chertkoff and Kushigian [21] enlisted the factors that could be responsible for inducing crowd nonadaptive behaviors. However no comprehensive analyses were given regarding the dynamics and the effects among these factors. There have been increasing interests in studying human factors in emergencies [38-41], however, "the fundamental understanding of the sociological and psychological components of pedestrian and evacuation behaviors is left wanting [42]." Also, incorporating human behaviors in computational egress simulation is difficult and challenging.

2.3 Computational Models

There has been a wide variety of computational tools, many of them are now commercially available, for egress simulation and design of exits. Many of the commercial systems were originally developed in academic research [6,9,19,43]. 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 [9] and the panic simulation system built by Helbing et al. [12,44]. 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 [19], "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 [45]. 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 [19].
- The basic idea of a *matrix-based* system is to divide 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 [6] and Pedroute [11], 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 [19]. 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 [46-49]. One example of the emergent systems is the Legion system [14,19]. It should be noted that Legion was not designed as a crowd behavioral analysis system, but as an investigative 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. 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.

3. A FRAMEWORK FOR STUDYING NONADAPTIVE CROWD BEHAVIORS

Crowd dynamics are complex phenomena that involve a variety of possible human and social behaviors. To establish a framework to study nonadaptive crowd behaviors, we categorize human and social behavior in three levels: the individual, the interactions among individuals and the group and the environment. These three levels of categorization are not independent, but rather are intimately related and often overlap.

3.1 The Individual

A crowd is a collection of individuals. In order to understand crowd behaviors, we need to first study individual's behaviors. From a human psychological perspective, individual's behaviors are 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.

- *Following instinct:* An instinct refers to an inborn pattern of behavior response to specific stimuli. While a new born baby typically functions by following instincts, Wills [50] 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. 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], in case of an emergency, 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. Nonadaptive behaviors, such as pushing others down and fleeing towards deadly blocked exits, occur because of fear. Because following instincts is highly "automatic," an individual may or may not be well aware of his actions under the circumstances.

- *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 [23,38,39], such as the familiarity of environments and safety procedures and fire drills. 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 [55]. 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. The resulting solution from bounded rational thinking usually is more appropriate for the given situation compared 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[30-33].

It has been pointed out that human decision-making in emergency differs from normal situation in at least three ways: (1) higher stake, (2) higher degree of uncertainties and (3) limited time [51]. According to the crisis model by

Billings et al [52], these three factors would lead to increase in stress. Making a decision under severe stress is different from normal situations, and different levels of stress usually give rise to different decision patterns. According to Sime [53], when an individual is under increasing stress, there is a decrease in productive thoughts and an increase in distractive thoughts. When stress reaches a certain level, an individual may only consider immediate survival goals. Such observations are supported by the *Inverted-U Hypothesis* and the *Signal Detection Theory* [54]. The *Inverted-U Hypothesis* states that as stress increases and the resulting arousal rises, human ability in decision-making performs well until the stress reaches certain "optimum" point, but thereafter one's decision-making ability declines. According to the *Signal Detection Theory*, stress level increases as signal and "noise" increase and that the ability in decision making varies with the level of useful signals perceived by the individual. It should be recognized that although individuals in a crowd may experience a similar level of stress during an emergency, their behavior could be different from one another. For those whose optimum levels of stress are higher than others, they would behave more rationally (e.g., altruistic and adaptive behaviors) while others may behave nonadaptively.

In summary, at the individual level, a person may demonstrate nonadaptive behaviors when he/she is under severe stress. Nonadaptive behaviors are driven primarily by human instincts to pursue immediate survival goals. A high level of stress happens when an individual perceives a situation as highly important, highly uncertain, and highly urgent. Mediating any of the three factors would help to decrease stress and, in turn, prevent the occurrence of nonadaptive behaviors.

3.2 Interactions among Individuals

From the perspectives of social interaction, an individual's social behaviors are shaped by social structures through the following social identities [55]. Other crucial factors that also strongly influence human social interaction include the respect of personal space [56] and the principle of social proof [57].

- *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 [58]. An individual is also a social being and 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, culture 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 [55], "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. 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. Decision-making as rule-following offers an effective means to explain an individual's behaviors in a social setting. However, during an emergency, an individual who demonstrates nonadaptive behaviors often appears to be highly individualistic and nonsocial [21]. Nevertheless, 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.

- *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 [56], "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." Even though the actual definition of personal space varies among different cultures, gender 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). The respect of personal space functions as a social rule to keep safe distances among individuals. This rule, however, may become invalid in a crowded environment, and the involved individuals are likely to experience a higher level of stress and agitation than in a non-crowded environment. Even so, people still make efforts to regain their personal spaces and avoid physical contact with others [38].
- *Social proof:* The dominant factor that leads people to seek social proof is the perceived uncertainty of a situation. When an individual encounters a 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 [57], "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 blockages of some exits even though other exits are not fully utilized. Other instances in this category include social inhibition and diffusion of responsibility [38,59]. 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 [60, 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. Initial reactors in an emergency have significant influences in a crowd.

From the perspective of social interaction, nonadaptive crowd behaviors likely occur if: (1) individuals fail to comply with their social identities and act non-socially because of severe stress; (2) individuals lose their personal spaces and perceive a necessity to move urgently; and/or (3) individuals seek social proof to guide their actions under uncertain situation; in particular, they follow some initial reactors who demonstrate non-social behaviors.

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 nonadaptive 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 [23,38]. People movement can be highly restricted in a dense and crowded environment. As pointed out by Chertkoff and Kushigian [21], “[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, as discussed earlier, 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, 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 [21]. 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, nonadaptive 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 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.

4. A COMPUTATIONAL MODEL FOR SIMULATION OF CROWD DYNAMICS

One main purpose of this paper is to present a crowd simulation model that takes into account human and social behavior. There are three main reasons for developing computer simulation for crowd behaviors: (1) to test scientific theories and hypotheses; (2) to test design strategies; and (3) to create phenomena about which to theorize [61]. Each crowd setting (i.e., crowd attributes and physical environment) is unique. A full understanding of nonadaptive 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, help the planning process and deal with emergencies.

Human behaviors are complex emergent phenomena, which are difficult to capture into computers as mathematical equations. One common shortcoming among most egress simulation systems is that they oversimplify the representation of human behaviors. Even though these systems can demonstrate some aspects of human and social behaviors, they are inherently constrained by the representation of crowd behaviors. 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 behavior 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 [62,63].

In the framework, we simulate each human individual as an autonomous agent who interacts with a virtual environment and other agents according to an *Individual Behavior Model*, which contains the rules derived at the levels of individual, interaction among individuals and group (as discussed in Section 3). 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, 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 process, a "perception-action" model is adopted in that an agent continually 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.

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 environments (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 virtual agents to represent a crowd based on the distribution of age, mobility, physical size and type of facility (hospital, office building, train station, stadium, etc.) to be investigated. The population and its composition for each type of facility would be different. 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 are maintained. This database is also needed to support 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 to display the simulated results. We have developed a simple visualization environment that is able to receive the positions of the agents, and then generates and displays 2D/3D visual images.
- *The Crowd Simulation Engine.* This module is the core module of the multi-agent simulation system. Each agent is assigned with an "individual behavior model" based on the data generated from population generator. The Individual Behavior Model is designed to represent an individual human's decision-making process. Each agent responds to its environment using the decision rules and initiates actions and reactions accordingly. The internal mechanism of *the Individual Behavior Model* consists of the following *iterative* steps: (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; and (4) conduct collision check and execute the decision. Each autonomous agent will proceed to the (exit) goal subjected to the constraints imposed, select appropriate actions, interact with and update the Global Database as simulations proceed over time.

In addition to the simulation of crowd behaviors, the outputs of the system will also include overall and individual evacuation time, individual paths and blockage locations. The simulation system is designed with sufficient modularity to allow further investigation of crowd dynamics and incorporation of new behavior patterns and rules as they are discovered.

5. A PROTOTYPE MULTI-AGENT SYSTEM

A proof-of-concept multi-agent based computational system has been prototyped, which is able to demonstrate some emergent human social behaviors, such as competitive behavior, queuing behavior, herding behavior and bi-directional crowd flow through simulating the behavior of human agents at a microscopic level. This section describes how human and social behaviors are implemented in the prototype.

5.1 Representations

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.

5.1.1 Virtual Environment

A virtual environment imposes 'environmental constraint' (as discussed in Section 3) to agents, and it consists of 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. The extracted geometric information include:

- *Obstacles*. Obstacles refer to walls, furniture and any objects that are inaccessible. Each obstacle has definitive boundaries. Agents detect obstacles through their sensors.
- *Spaces*. Spaces are the areas where agents may maneuver freely. Examples are corridors, lobbies, rooms, and exterior openings. 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 there are no obstacles between the eyes of the agent and the sign and 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.

5.1.2 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 [64]: Median, Adult Male, Adult Female, Child and Elderly. Each categorization represents a typical type of human population. We envision further categorization and individual attributes will be defined in a latter prototype system.

- *Sensors*. The prototype system includes a visual sensor so that an agent can analyze the environment. The visual sensor of an agent is developed using a ray tracing method [65]. By casting laser rays from the eye position of an agent within a visual angle, 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 (this visual sensing procedure is briefly described in Figure 2). 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 sensors is utilized by an agent to make decisions.
- *Decision rules.* Decision rules represent the mind of an agent, and they are fundamental to an agent's behaviors. 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 above form the basis of the 'perception-action' model of an agent, and the psychological and sociological factors and principles – that are dominant in driving an individual's behavior in emergencies – are represented as an agent's decision rules. The system can simulate not only simple behaviors (e.g., finding an exit), but also complex social behaviors (e.g., queuing and herding behaviors).

5.2 Simulation of Agent Behavior

In the prototype system, each agent maneuvers in the virtual envrionment by continuously executing an "egress algorithm" (the basic steps of this algorithm is given in Figure 3). As the algorithm has indicated, the behavior of an agent is primarily driven by its decision rules. Through structuring decision rules, we divide an agent's behaviors into three hierarchical layers (from simple to complex): locomotion, steering and social. 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; and (3) exiting a door in an orderly manner as a type of social behavior that involves several steering behaviors.

5.2.1 Locomotion and Steering Behavior

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.

The concept of steering behavior has been widely used in robotics [66] and artificial life [67,68]. 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 [69], 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.
- *Seek.* 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 an agent moves forward in a queue by following another agent who is in front.

These steering behaviors serve as 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).*

5.2.2 Social Behavior

Social behaviors are complex phenomena emerging 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, 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 and bi-directional crowd flow.

Figure 4a illustrates an initial setting of a crowd. During multiple runs, when different individual behaviors are activated at a microscopic level, the crowd demonstrates very different social behaviors, such as competitive behavior (Figure 4b), queuing behavior (Figure 4c) and herding behavior (Figure 4d).

Competitive behavior is often observed in emergency situations, when human individuals compete for their own chances of exiting. 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: (1) *walk randomly* until a goal is determined; (2) *seek* the goal with maximum velocity if possible and do not *negotiate* with other agents; and, (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 but often leads to more effective evacuations. Our 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.

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. 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; herding behavior contradicts such an assumption. Our 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 crowds, (3) *seek* the goal.

Bi-directional crowd flow happens in places (e.g., a subway station) where people need to pass each other to reach different goals, which can be difficult to model using fluid or particle system. Our system demonstrates that a bi-directional crowd can be realistically simulated if: (1) a crowd is composed of individuals who have different goals; (2) individuals constantly steer toward the goals; and (3) individuals anticipate potential collisions and take actions to avoid them (see Figure 5).

The social behaviors described above are not independent from each other. It is possible to combine different social behaviors to construct more complex behaviors. For example, the simulation shown in Figure 4d demonstrates herding behavior as well as competitive behavior.

6. CONCLUSIONS AND FUTURE WORKS

Although there have been many 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, particularly the so-called non-adaptive crowd behaviors. In this paper, we discussed nonadaptive crowd behaviors from three different levels – the individual, the interactions among individuals, and the groups – and presented a computational framework for incorporating human and social behaviors during emergency evacuations. For demonstration purposes, we have prototyped a multi-agent system based on the framework. The system is able to model emergent human social behaviors, such as competitive behavior, queuing behavior, herding behavior, and bi-directional crowd flow 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: (1) 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; and (2) validating the model through both replicating some historical overcrowding incidents and working together with the field experts in the areas of crowd management, building design and emergency planning. The computational framework will allow pre-defined deterministic or random assignments of individuals and groups in the design space. 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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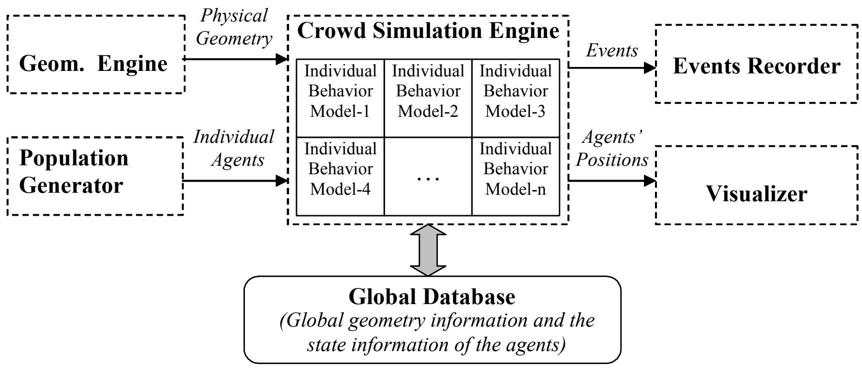


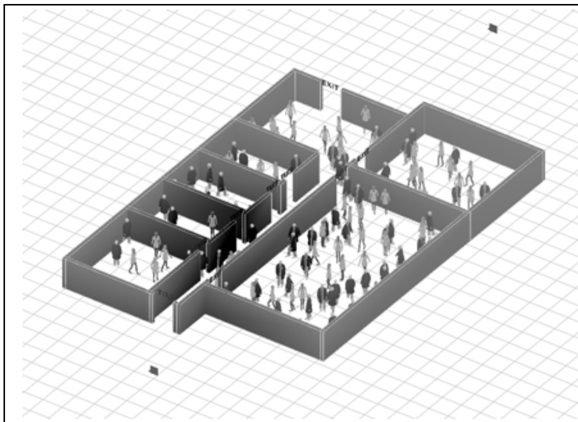
Figure 1: System Architecture.

1. ***cast three rays (left, middle, and right);***	//with the middle ray casting along the orientation of the agent
2. ***compute sensory matrix;***	//representing the distances and intersecting objects
3. ***apply cognition vector to sensory matrix;***	//a predefined vector that provides interpretation to the matrix
4. ***return result;***	//a numeric value that represents a situation

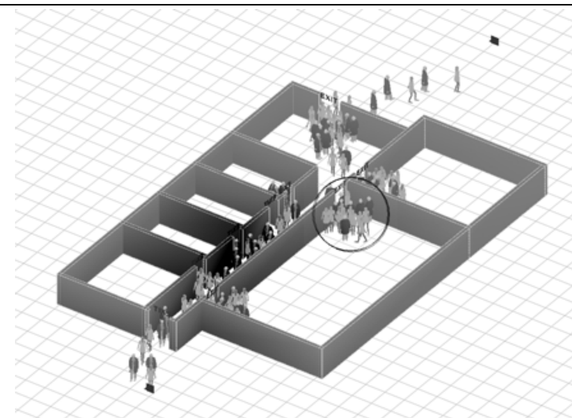
Figure 2: Sensory algorithm using ray tracing.

1. ***WHILE the assembly point is not reached, DO:***	
2. ***detect goal and update sensor;***	//perceive the surrounding
3. ***make a decision;***	//select appropriate rule and action
4. ***anticipate a move;***	//compute new position to move
5. ***execute the move;***	//check collision and update agent's location
6. ***END WHILE;***	

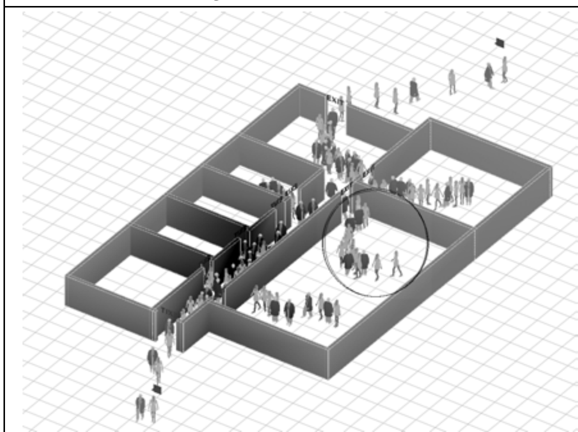
Figure 3: Egress algorithm



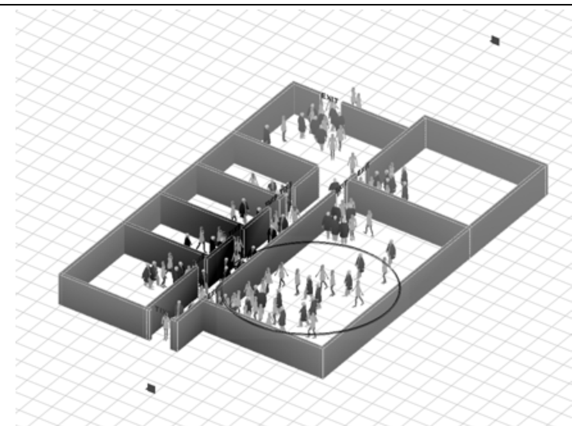
a. Initial setting of a crowd



b. Competitive behavior



c. Queuing behavior



d. Herding behavior

Figure 4: Simulation of human social behaviors

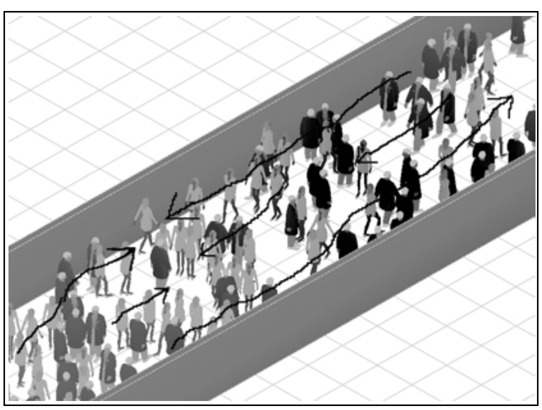


Figure 5: Bi-directional crowd flow