Computational Modeling of Nonadaptive Crowd Behaviors for Egress Analysis

CIFE Seed Research Proposal

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1. Introduction

The objective of this research is to study human and social behavior for emergency exit in buildings and facilities. Among the numerous 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 situation. 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 [14]. In a crowded environment, it has been observed that most victims were injured or killed by the so called "non-adaptive" behaviors of the crowd, rather than the actual cause (such as fire) of the disaster [1,8]. Non-adaptive crowd behaviors refer to the destructive actions that a crowd may experience during a disaster, such as stampede, pushing others out of the way, knocking others down, and trampling on others, etc.; these actions are responsible for a large number of injuries and, even, deaths in crowd disasters. To study the non-adaptive behavior in a crowded environment, we need to carefully study human and behavior in panic situation from both the psychological and sociological perspectives.

There exists a variety of commercially available computational tools for the simulation and design of emergency exits. However, most of the current computational tools focus on the modeling of spaces and occupancy but rarely take into consideration of crowd behavior. On the other hand, the usefulness of a simulation tool is preconditioned by properly and correctly modeling non-adaptive crowd behaviors. Understanding non-adaptive crowd behaviors is essential to the development of effective egress strategies and models for achieving crowd safety. Although a number of computational crowd models have been developed, none could cover a comprehensive range of scenarios suitable for safety engineering purpose [13]. Most of these models either are oversimplified or are based on incorrect assumptions about crowd behaviors. As noted in a recent report by the Society of Fire Protection Engineers [28], "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."

This seed research proposal is to initiate a study of non-adaptive crowd behaviors from the perspectives of human and social interactions and to incorporate such behavior in a dynamic computational model suitable for emergency exit and egress analysis. In doing so, we will then be able to adapt egress analysis suitable for specific design circumstances. Furthermore, the behavior-based model will provide insight to current prescriptive and, often, ambiguous codes and provisions for egress design.

2. Related Works and Developments

2.1. Non-Adaptive Crowd Behaviors

Although the study of crowd behavior can be dated back to the 1800s, relative few studies about non-adaptive crowd behaviors have been reported in the literature; furthermore, most of the behavioral studies were conducted prior to the 1960s and 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 [8]: (1) panic [2, 3, 4, 5], (2) decision-making [6, 7], and (3) urgency levels [9]:

- Panic theories deal primarily with the factors that may make the occurrence of panic during emergencies. The basic premise is that when people perceive danger, their usual conscious personalities are often replaced by the unconscious personalities which 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 human behavior, even under dangerous situation, can still undergo rational decision making process, attempting to achieve good outcomes and objectives in the situation [6]. In a situation such as a theatre fire, cooperating with others and waiting their turn can likely be beneficial to the group and, in turn, increasing the individual's likelihood of exiting. 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 and join the competition; 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 [8].
- One other theory suggests that the occurrence of (human) blockages of exiting space depends on the *levels of urgency* to exit [9]. 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 distribution of the urgency levels contains a large number with a high urgency to leave – 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 [8].

In summary, these theories have provided many insights into human behavior and reactions in an emergency situation. Nevertheless, a comprehensive theory about non-adaptive crowd behaviors has not been developed. Furthermore, the incorporation of these human behaviors in computational egress simulation is difficult and challenging.

2.2. Related Computational Models

There has been a wide variety of computational tools, which are commercially available, for the simulation and design of exits. Most existing models can be categorized into fluid or particle systems, matrix-based systems, and emergent systems:

Fluid or Particle Systems

Many have considered the analogy between fluid and particle motions (including interactions) and crowd movement. Two examples in this category are the Exodus system [15] and the panic simulation system built by Helbing et al. [16]. The development of Exodus was started by the Fire Safety Engineering Group at the University of Greenwich in 1997. The system is able to simulate the evacuation of large numbers of individuals from large multi-floor buildings [17]. Through adopting fluid dynamic models coupled with discrete virtual reality simulation techniques, the model tracks the trajectories of individuals as they make their way out of the building or are overcome by hazards (e.g., fire and smoke). The output of Exodus includes overall evacuation time, individual waiting and evacuation time, and individual paths.

The panic model by Helbing et. al. simulates crowd escape panics using self-driven many-particle systems [16]. Some of the interesting phenomena captured by this model are: (1) crowd transition to incoordination due to clogging, (2) 'faster-is-slower' due to impatience (i.e., moving faster likely causes clogging), and (3) mass queuing/herding behavior (as people tend to follow what others do). Using this simulation model, the results suggest that the best escape strategy is a certain compromise between the following of others and an individualistic search behavior [18].

Recent studies have revealed that the fluid or particle analogies of crowd are untenable. As noted by Still [13], "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." Specifically, fluid or particle analogies 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 from a smoke-filled room with two exits - one exit is clogged while the other is not fully utilized [26]. However, a fluid or particle analogy would likely predict the efficient use of the both exits. Furthermore, it is difficult for fluid or particle systems to properly model bidirectional flows in a very crowded environment [12].

Matrix-Based Systems:

The basic idea of a matrix-based system is to discretize a floor area into cells. Cells can be a free floor area, an obstacle, an area occupied by people, or a region with other attributes [19]. Each cell is equivalent to the minimum area which a person would occupy. People transit from cell to cell based on occupancy rules defined for the cells.

Two examples of the matrix-based systems are Egress [19] and Pedroute [20]. AEA Technology started the development of Egress in 1991, and it has become one of popular commercial software for crowd simulation. The model employs artificial intelligence techniques to determine how a person would react under a variety of circumstances such as fire and smoke. The output of Egress includes evacuation time analysis, comparison between people evacuation and progression of hazard, and potential structural and procedural improvements [19].

Pedroute was originally developed by London Underground Limited, and it has been used extensively to model crowd parameters in underground networks around the world [20]. The model can simulate train and passenger movements going through a station or a building. The performance of the building is assessed using service levels, passenger densities and delays. The output includes passenger density, passenger average delay, and passenger flow rates, which help to identify passenger flow bottlenecks and the emergency evacuation capacity of the building.

It was suggested that the existing matrix-based models suffer from the difficulties of simulating crowd cross flow and concourses and they are based on assumptions which are questionable based on field observations [13].

Emergent Systems:

The concept of emergent systems is that the interactions among simple parts can simulate complex phenomena such as crowd dynamics [21, 22, 23, 24]. One example of the emergent systems is the Legion system [13,25]. 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. The computational model over-simplifies the behavioral representation of individuals. First, the model 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 the social behaviors such as herding and leader influence.

In summary, current computational tools, although they provide some capabilities for simulating evacuations, lack the ability to properly model human and social behavior in emergency situations. It was found that the assumptions employed in current systems have been found inconsistent or incorrect.

3. Proposed Research

This seed research proposal intends to develop a computational "agent"-based tool that would allow the simulation of human and social behavior in an emergency situation. The research is divided into four basic tasks:

1. Establish a framework to study the dynamics of nonadaptive crowd behaviors under emergencies.
2. Develop a multi-agent based computational model as the basis to implement crowd behavior.
3. Incorporate in the computational framework other engineering analyses, such as performance-based assessments of building codes, design of egress and safety/emergency plans.
4. Explore effective safety engineering strategies in the areas of facility design, crowd management, and crowd control.

In the first year, the research will focuses on the first two tasks. Further development of the third and fourth tasks will be pursued in subsequent years.

3.1. Research Approach

Based on our preliminary research investigation, the study of non-adaptive crowd behaviors can be divided into two levels:

- On a macro level, nonadaptive crowd behaviors are essentially emergent phenomena that arise due to weak crowd coordination, high crowd density, severe environmentally imposed constraints, and mental tension (e.g., high emotional arousal) within a crowd.
- On the micro level, nonadaptive crowd behaviors can be modeled as decision-making processes of individual humans influenced by high mental tension.

Based on the crisis model proposed by Billings, Milburn, and Schaalman [31], we hypothesize that the mental tension of an individual is the direct results of his/her perceptions toward a given circumstance. Such perceptions can be quantified by three attributes of the circumstance: importance, uncertainty, and urgency. *Importance* refers to the severity of a situation, and it is measured by the value loss from the decision maker's perspective. The severity of a situation determines how much mental pressure an individual is subjected when pursuing a solution. High importance implies high pressure level and more willingness an individual is to react to the situation. For example, an individual is more likely to react to a situation when he/she perceives it as a real threat. *Uncertainty* deals with the "quality" of the solution for avoiding loss. As for the decision maker, the level of uncertainty of a problem is related to the level of mental pressure. For example, a good solution implies a low degree of uncertainty as well as low mental pressure. *Urgency* refers to the amount of time perceived to be available for making a decision. These three factors thus determine the level mental tension influencing an individual's decision.

Symbolically, the amount of mental tension, F, during an emergency situation can be expressed as:

$$F=f(I,U,T)$$

where I denotes the pressure determined by *IMPORTANCE*, U the pressure released due to *UNCERTAINTY*, and T the perceived available time determined by *URGENCY*. If an emergency is perceived by an individual as highly important, highly uncertain, and highly urgent, then an enormous amount of mental tension will be created to influence the decision process. On the other hand, moderating the three factors may effectively decrease the mental tension level.

The framework to be developed will be to study the mental tension in emergency by varying the parameters.

Individual's decision-making will be based on two categories of decision rules: (1) individualistic rules – experiences, bounded rational thinking, and following instincts; (2) social interactions rules – social identities, respecting/defending personal spaces, and social approvals. The choice of decision rules will be based on patterns. Examples of such patterns may include:

- When there is very little or no mental tension present, an individual tends to follow his/her experiences and social identity rules.
- When under the influence of low level mental tension, an individual tends to provoke bounded rational thinking to pursue solutions while compromising his/her social identity rules.
- When under the influence of high level mental tension, an individual tends to be more individualistic (non-social) and acts on personal instincts.
- A high mental tension level reduces an individual awareness about his/her surroundings. When there remains a minimum awareness by an individual, the individual tends to justify his/her behaviors through seeking social approvals.
- An extremely high level of mental tension may overload an individual's decision ability and cause some temporary (or permanent) psychological disorder.

These patterns will then serve for developing individual behaviors to be incorporated into the computational framework.

3.2. Computational Framework

The design of our computational model is based on a multi-agent simulation paradigm. We simulate each human individual as an agent who interacts with a virtual environment and other agents according to *an Individual Behavior Model* and some *global rules*. Each agent has an imperfect model of the world, which is maintained in *the Individual Database.* The agent's actions occur in another model – the virtual environment, which maintained in *the Global Database*. An agent accesses the virtual environment through simulated sensors, and makes decisions based on its decision model. The nonadaptive crowd behaviors can then be observed *visually* as emergent phenomena.

As shown in Figure 1, the system we envision 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:* We plan to adopt AutoCAD/ADT to model the geometries of physical environments (e.g., a building or a train station, etc..). The tool then sends the results 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 location. This module will also allows the system to perform statistical simulation as well as generating random populations for the study of human behaviors.
- *The Global Database.* It maintains all the information about the physical environment and the agents in the system.

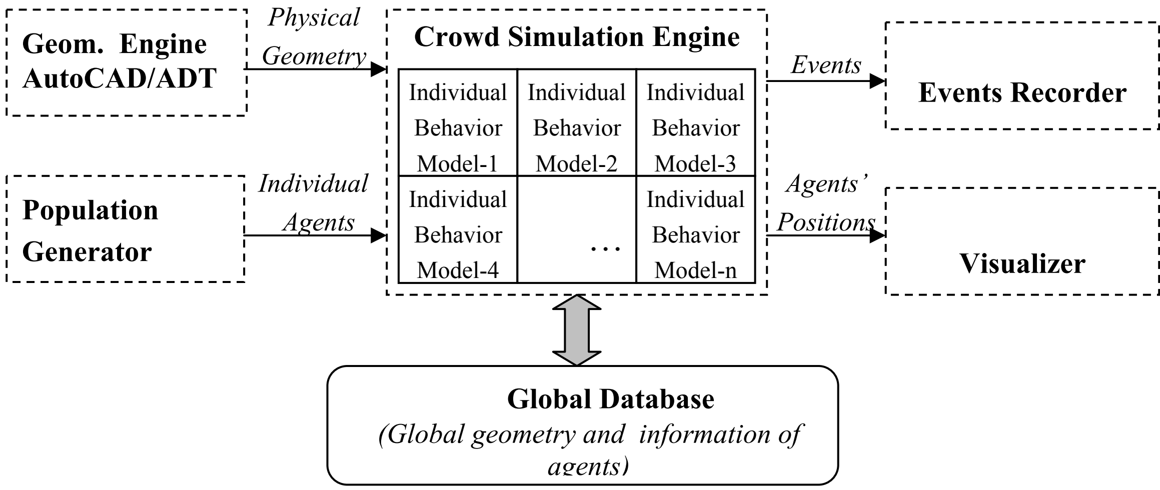

Figure 1: The system architecture.

- *The Crowd Simulation Engine.* Each agent responds to its environment using the patterns and behavior's rules. This module will also serve to update the Global Database through simulations to allow "some" learning process over time.
- *The Events Recorder.* This purpose of this module is to capture the events that have been simulated in the virtual environment for later retrieval.
- *The Visualizer.* This component receives the positions of agents, and then generates 2D/3D visual images in real-time.

As depicted in Figure 1, *the Individual Behavior Model* works as a sub-system residing within *the Crowd simulation Engine*. The Individual Behavior Model is designed to represent an individual human's decision-making process. We envision the internal mechanism of *the Individual Behavior Model* will consist of the following steps (see Figure 2).

1. receives a decision request;
2. collects information about the situation (i.e., crowd density, sensory input, tension level);
3. choose a rule (e.g., instinct, experience, or inference) to make a decision;
4. conduct collision check and execute the decision;
5. repeat step 1.

In addition to the simulation of nonadaptive crowd behaviors, the output of the system will also include overall and individual evacuation time, individual paths, and blockage locations.

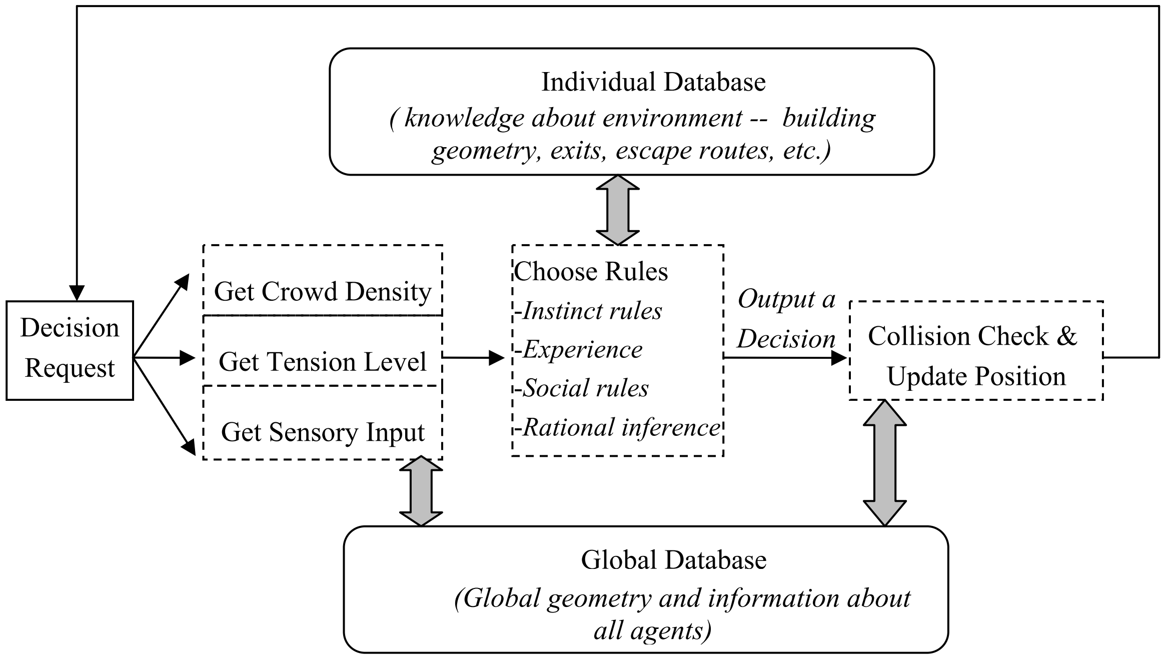

Figure 2: Individual behavior model.

3.3. Anticipated Results

We expect the following results from the proposed research:

- By the end of Summer Quarter, 2004 -- We plan to conduct a thorough literature survey on the subject on crowd dynamics and non-adaptive behavior prior to the beginning of the project. We expect to complete a report summarizing the state of practice in Egress simulation and analysis.
- By the end of Autumn Quarter – We plan to consolidate our survey results and develop a preliminary version of non-adaptive behavior and scenarios and patterns for emergency situation. A preliminary prototype of the simulation framework will begin during the Autumn quarter.
- By the end of Winter Quarter – We plan to begin the prototype of a simulation framework for emergency exit analysis. We will start to incorporate the individual behavior model and investigate the interaction among individuals.
- By the end of Spring Quarter – We plan to complete a working prototype for the simulation of egress environment.
- By the end of Summer Quarter – We anticipate that we will produce a series of prototype demonstrations to include most of the recent crowd simulation techniques in the field.

Validation and calibration of the simulation system will be an ongoing activity, which we do not expect to complete the task by the end of the project calendar year. This task will be the focus of research in the subsequent years.

4. Relationship to CIFE Goals

This research focuses on emergency exits and egress analysis, which is a subject of paramount importance to facility engineering and design. The research presented in this proposal touches upon four of the CIFE research areas and goals:

Organization Modeling:

- Modeling of the complex organizational behaviors of a crowd inside buildings and facilities.

Visualization:

- CAD modeling of building geometries, exiting signs, and escape routes.
- Visualization (2D/3D) of crowd movements.

Facility Management:

- Development of theories and tools for the safety engineering of buildings and facilities.

Management of Technology

- Development of tools for assessing building designs, safety procedures, and crowd management.

5. Industry Member Involvement

Egress is one of the most critical issues in facility design of any public assembly – ranging from office buildings to theme parks. We expect that our work will be of interest to many organizations from industry and government agencies. Specifically, we anticipate feedbacks from facility managers and owners, government agencies and CIFE company members.

6. Milestones

We separate milestones into two categories:

Milestones to be accomplished by the end of the proposedt project year:

- Solidify the theoretical framework about human individual and social behaviors within a crowd from the perspectives of psychology and sociology.
- Develop a detailed implementation plan for the simulation environment
- Develop a proof-of-concept prototype that is able to demonstrate some of the fundamental features of crowd behaviors, such as herding behavior and crowd clogging.

Milestones to be accomplished beyond the end of the proposed project year:

- Calibrate the prototype and complete the crowd simulation system.
- Conduct case studies and validate the system.

7. Risks

This proposed research is a high-risk, high-payoff project that could lead to significant advancement in facility engineering and design. There are two fundamental risks for this project:

- Human individual and social behaviors are complex subjects. The crowd behavior model that we aim to develop may not be sufficiently general for a broad range of scenarios. However, we do expect the simulation system is to be designed with sufficient flexibility and modularity to allow further investigation of crowd dynamics and incorporation of new patterns and rules as they are discovered.
- Since our approach follows closely the emergent approach where a complex environment is made up of a collection individual agents. Simulating large crowded environment may require a significant amount of computations, depending upon the decision model to be developed and implemented. The PIs have significant experience in distributed

computing research and we do expect available computational platforms available to the PIs are sufficient to demonstrate the usability of the simulation systems.

The proposed research is an interdisciplinary research effort involving individuals with different expertise. Dr. Ken Dauber, Deputy Director for Teaching and Learning, is a sociologist with his research and teaching focusing on social organization; he also has been involved in large scale software development at Stanford's Center for Teaching and Learning. Mr. Xiaoshan Pan is a PhD student with MS degrees in Architecture and Computer Science; his research experience includes AI and computational modeling for building design. Prof. Kincho H. Law's research focuses on the computational science and engineering and has led an effort in developing simulation of disabled access. The risks described will further be mitigated through a collaborative effort by the researchers from different background and expertise.

8. Next Steps and Potential External Funding Sources

We plan to continue this research by exploring government funding opportunities such as the National Science Foundation, NIST, FEMA, Office of Homeland Security and others. There has been an increase in emphasizing research related to human and social behaviors and complex engineering systems sponsored by various NSF programs. This research towards the development of a simulation system for emergency exits and egress design could have impacts on current research and development efforts related to emergency responses due to natural or man-made disasters. Last but not least, successful demonstration of this research may lead to practical simulation of egress analysis and design needed by the industry.

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