A COMPUTATIONAL FRAMEWORK FOR EGRESS ANALYSIS WITH REALISTIC HUMAN BEHAVIORS

1. MOTIVATING ENGINEERING/BUSINESS PROBLEM

The goal of this proposed research is to develop a computational framework that is capable of incorporating human and social behaviors for virtual egress analysis and design simulation. Although building codes provide basic guidelines for egress design (ICBO 2009), it has long been recognized code provisions alone are not sufficient for design of safe egress, particularly for complex floor plans where local geometry and local environmental constraints can greatly affect crowd behavior and movement (Still 2000, Helbing et al. 2000). Since the 9/11 World Trade Center incident, the 2003 Station Nightclub fire in Rhode Island, and many recent events, there have been a surge of studies by social scientists and fire professionals to gain better understanding of human behavior and crowd dynamics during emergency evacuations (Averill et al. 2005, Cocking and Drury 2008, Mawson 2005, Proulx et al. 2004). From these studies, researchers and experts in disaster management have concluded that environmental and social factors such as crowd density, group relationships, people's familiarity with the place, authority figures, and initial delays to form group consensus, can have significant impacts to the overall evacuation process. However, most computational tools, which have been developed over the years and are now routinely being used in practice, focus on crowd animation and oversimplify human and social behavior assumptions (Kuligowski and Peacock 2005, Santos and Aguirres 2004). This deficiency of incorporating social behaviors into current egress simulations has been echoed by the authorities in fire engineering and social science (Still 2000, Galea 2003). In a recent report to the UK Cabinet Office, Challenger et al. (2009) concluded that *there is a dire need to "improve the realism and accuracy of crowd behavior movement, in addition to improvising visual aesthetics [in existing commercial tools]."*

The objective of this research is twofold: (1) study current theories regarding human and social behaviors in emergencies, and (2) develop an agent-based computational framework that can flexibly incorporate formal social theories in egress simulation. From the theoretical perspective, integrating social science theories into engineering simulation models, which currently are largely based on quantitative models, represents a fundamental and novel research endeavor. Furthermore, the research can have significant impact in enhancing performance evaluation of egress design, providing safer public environment, advancing the state of practice in facility engineering and knowledge transfer between technology and social science research.

2. THEORETICAL AND PRACTICAL POINT OF DEPARTURE

The proposed research will build upon the current understanding of social theories on crowd behavior in emergencies. The study of crowd, crowd behavior and dynamics has a long history in sociology (Durkheim 1995[1912], Kelley et al. 1965). A comprehensive review of various social theories about crowd behaviors has recently been compiled by Challenger et al. (2009). Examples of prevalent theories on crowd behaviors include the self-organization theory (Helbing et al. 2005), the social identity theory (Cocking & Drury 2008), the affiliation model (Mawson 2005), the normative theory (Aguirre et al. 2011), the panic theory (Chertkoff & Kushigian 1999) and the decision-making theory (Mintz 1951). Earlier theories of crowd behavior suggest that people tend to behave individualistically and exhibit non-adaptive behaviors in dangerous situations. For example, the **panic theory** suggests that people become panicked in an emergency situation and act irrationally upon perceiving danger. In contrast, the **decision-making theory** argues that people act rationally to achieve a better outcome in the situation. Recent theories, on the other hand, emphasize the sociality of the crowd (such as pre-existing social relationships or emerging identity during an emergency) in explaining the occupants' behavior during evacuation. For example, the **affiliation model** suggests that people are typically motivated to move towards familiar people or locations and show increased social attachment behavior in an emergency situation. The **normative theory** stresses that the same social rules and roles that govern human behavior in everyday life are also observed in emergency situations. According to these recent theories, evacuating crowds retain their sociality and behave in a socially structured manner. Generally speaking, there is no unified theory which fully explains human behavior in different situations. A simulation tool that is able to incorporate social theories into simulation and test their assumptions can greatly enhance safe egress design.

There have been a wide variety of computational tools commercially available for egress simulation and design of exits. These programs can be categorized into fluid or **particle systems, matrix-based systems, and agent-based systems**:

- *Particle systems* consider each individual in the crowd as self-driven particle subject to social and physical forces. The BuildingEXODUS system (Fire Safety Engineering Group 2009) and the panic simulation system (Helbing et al. 2000) are typical examples. This method, despite being computationally efficient, overlooks the fundamental differences between human behavior and particle physics. 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."
- In a *matrix-based system*, the environment is divided into a uniform grid of discrete cells, representing floor areas, obstacles, areas occupied by people, or other relevant attributes, such as exits and doors. Agent moves to unoccupied neighboring cells based on defined rules. Egress (Keenan et al. 1994) and Pedroute (Halcrow Group Limited 2010), which have been used in buildings and train stations emergency evacuation simulation, are two examples. Although being computationally efficient, matrix-based tools suffer drawbacks in simulating cross flows and can produce results contradictory to field observations (Still 2000).
- *Agent-based systems,* such as the Legion system (Berrou et al. 2005), model the crowd as a collection of autonomous entities known as "agents". Indeed, the term "agent-based" model has been widely adopted and loosely used by many commercial egress tools that were developed originally as particle and matrix-based systems. However, current "agent-based systems" typically oversimplify the behavioral representation of individuals by assuming simple decision rule (such as least efforts) and ignoring many important social behaviors (such as herding and leader influence).

There has been an increasing interest in the agent-based modeling approach to incorporate human behaviors in egress simulation. This approach is particularly attractive as crowd and emergent phenomena are the result of the interactions of virtual agents. Aguirre et al. (2010) described the use of an agent-based model to incorporate the pro social theory (Aguirre et al. 2009) and discussed the difficulties and issues involved in implementation. There is also an ongoing effort at Disney R&D, using an agent-based simulation platform called Spirops, to simulate people movement patterns at the park (Huerre 2010). Preliminary results from both of these efforts show that agent-based modeling is a promising approach in developing an egress simulation tool. Both research activities, however, appear lacking a system architecture that systematically models individual, group and crowd behaviors and interactions.

Our research will build upon our prior research prototype, MASSEgress, which adopts a multi-agent modeling paradigm as the basic scheme to develop an egress simulation system (Pan 2006, Pan et al. 2007). The underlying principle in the design of MASSEgress is to incorporate human individual cognitive processes and behavior such that 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) can be explored. To simulate human cognitive process, a "perception-interpretation-action" model is proposed in that an agent continuously assesses the surrounding environment and makes decisions based on its individual and social behaviors and decision model in a proactive fashion. Even as a demonstration prototype, MASSEgress has been recognized as a pioneering effort for bridging the gap between observed social behavioral phenomena and computational egress simulation; the effort has been highlighted in the recent report commissioned by the UK Cabinet Office (Challenger et al. 2009) and received favorable reviews by researchers in social science (Aguirre et al. 2010).

3. PROPOSED RESEARCH

Theoretical Framework

In order to design a simulation tool that can flexibly incorporate human and social behaviors, we will continue to conduct a systematic study on crowd behavior in emergency situations. Features and rules governing decision-making process will be extracted from social science literature and disaster studies. The information will then be used as the basis for the design and implementation of the prototype platform.

Individual decision, group norm and crowd mood

We conjecture that the process of human decision-making in emergency situations is affected by three basic factors: individual decision, the group's pre-existing and emergent norm, and crowd characteristics. Figure 1 depicts a simplified organizational view of the features that define the occupants and their characteristics in an evacuation situation. Based on this three-level organization, features and behavioral rules are extracted from different human and social theories and are systematically classified into these three categories.

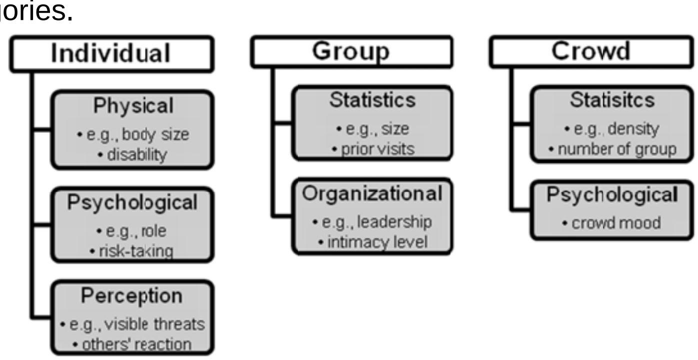

Figure 1: A simplified organization defining occupants' behaviors and the environment

Generalization of different social theories

Simulating human behaviors in emergencies is a complex task that involves psychological, social, physical and environmental factors. By categorizing different behavior features at the individual, group, and crowd level, a general framework can be established. This staged representation would allow us to assume different levels of group and crowd effects on evacuating individuals and test the impact of these effects on the overall evacuation patterns. As shown in Figure 2, an occupant's action is a result of individual preference, group norm, and crowd mood. The group and crowd behavior can affect individual decision, depending on the occupants and the situation.

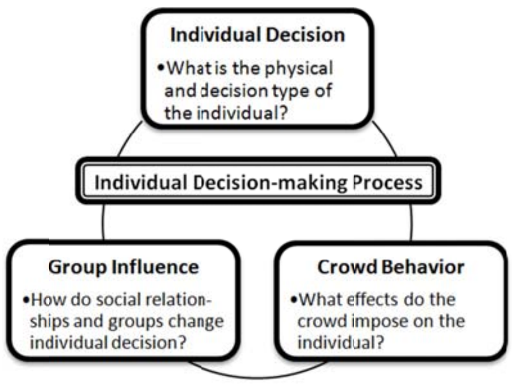

Figure 2: An illustration of individual decision-making process

Computational Implementation

This research will extend the MASSEgress to allow group influence and social behavior models to be defined and incorporated for simulation. Furthermore, extensive validation tests will be conducted to examine the features implemented and to test the behavioral theories based on real scenarios and collected data.

System Architecture

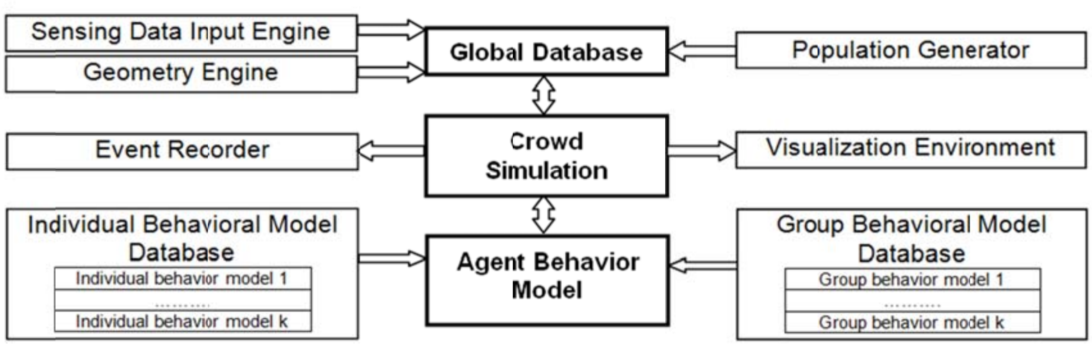

Figure 3: Overall architecture of the framework

Figure 3 schematically depicts the system architecture of the multi-agent simulation framework. The Global Database, Crowd Simulation Engine and Agent Behavior Model constitute the key modules of the framework. The **Global Database** maintains all the information about the physical environment and the agent population during a simulation. It obtains physical geometries from the **Geometric Engine** and sensing information from the **Sensing Data Input Engine**, as well as the agent population distribution and physical parameters from the **Population Generator**. The **Agent Behavior Model** contains the agent decision profiles and agent group information. The

Global Database and the Agent Behavior Model interact with each other through the **Crowd Simulation Engine**, which generates visual output and event logs.

Validation and Testing

The simulation platform is designed to simulate egress patterns both in emergency situations and under normal circumstances. We plan to validate and test our framework with statistical and archived data of prior disaster events based on historical records and with real life data on people movements from industrial collaborators. Many of historical accidents in office buildings and facilities have been studied by social scientists and disaster management researchers. Many of such reports and videos are now publicly available, for example, the ESRC research project on past emergency events (Cocking and Drury 2008) and the NIST investigation of the World Trade Center disaster (Averill et al. 2005). Furthermore, researchers at Disney R&D have agreed to collaborate on this research, particularly in validation data sharing. Through this collaboration (which also has a strong partnership with the GAMMA program at the University of North Carolina), we will make use of the state-of-the-art technology in Disney R&D to record real-life data about occupants' trajectories and group interactions that are particularly useful to our validation tests about group behavior.

Figure 4 shows the proposed validation process. First, demographic data and group statistics are collected as model input. Defining different social behavior models and environmental conditions, simulations will be conducted to produce visual outputs and to facilitate analysis (such as statistical clustering patterns and evacuation routes). The results will then be compared with observed crowd patterns.

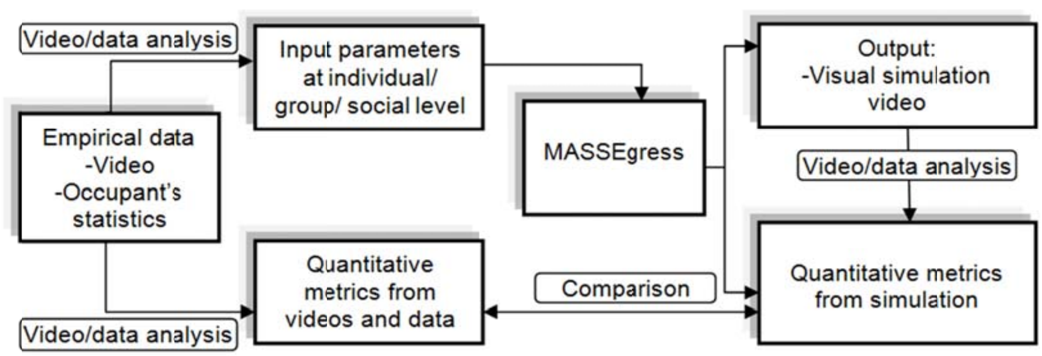

Figure 4: Proposed validation process

Summary of Current Research and Proposed Investigations

A preliminary research effort has been conducted to establish collaborative partnerships and to assess the feasibility of the proposed research. The progress of our research in preparing this proposed research includes:

- *Establishing a theoretical framework to study human and social behavior in emergencies.* We have conducted an extensive review of social theories, historical incidents and human behaviors studies in relation to emergency evacuations. Specifically, some fundamental features and the governing crowd behavior are identified and formalized into the three levels, individual, group and crowd, as shown in Figure 1. In addition, a knowledge database is being constructed to systematically represent the different social behavior theories.

- *Collaboration with industry partners and research groups.* We have established collaboration with an industry partner, Disney R&D, and researchers at UNC, particularly as a joint effort in sharing validation data. Ongoing regular teleconferences are being held to discuss validation issues. Reliable validation datasets in the form of statistical data and videos have been shared among the collaborating parties. Ongoing collaborations include the use of advanced devices to track occupants, and to generate reliable validation data.
- *Extending MASSEgress to incorporate group behavior.* Besides improving the basic functions of MASSEgress, such as agent's locomotion and visual sensing abilities, we have incorporated selected group behaviors, such as leader-following, group-following, group norm formation and communication among group members, which are commonly observed behaviors in crowd evacuation as identified by social scientists. Figure 5 illustrates the differences in evacuation patterns for group-following agents and non group-following (individual) agents in the same physical environment.

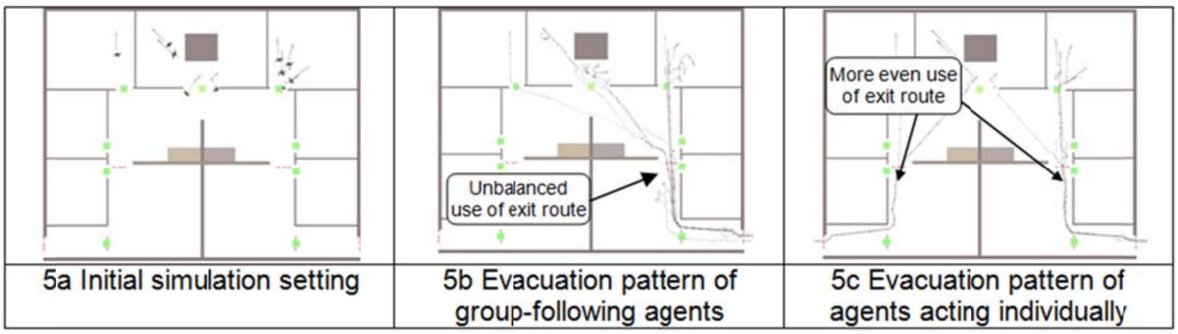

Figure 5: Simulation results with (5b) and without (5c) group-following behavior

Significant research tasks planned for the first year of the seed project will include:

- *Continuing the development of a comprehensive knowledge database and computational framework*. We plan to systematically establish a representational scheme that is able to capture the different social behavior theories. Examples are the effect of sounds and fire alarms (Averill et al. 2005) on human behaviors and reactions. The design of the knowledge database and behavior representation schemes will form the basis of a comprehensive computational framework such that current and future theories can be implemented in a flexible manner.
- *Investigating methods to analyze validation data*. As data are being collected, we anticipate the need to develop systematic data analysis procedures to extract useful information, particularly from videos and images. We plan to investigate advanced algorithms developed in the AI field to aid data extraction and parameter prediction.
- *Increasing program modularity for incorporating other engineering analysis.* We plan to re-design our framework to increase modularity of the program so that egress analysis can be integrated with other engineering analyses, such as performance-based assessments of facilities and spaces, sprinkler layout designs, smoke and fire simulations, and safety/emergency plans.

Research Impact

Human and social behaviors have been largely ignored in current egress tools. By adopting an innovative approach considering crucial social factors, our research will produce egress analysis results which can potentially reduce injuries and loss of lives, and the accompanying post-disaster psychological suffering, financial loss, and adverse publicity of individuals and organizations. From the safety perspective, the outcome of the proposed research can be used to evaluate both existing and new egress design. From the crowd management and facilities operations perspective, the tools can assist event organizers and building managers in developing a wider range of possible solutions to crowd problems and designs specific evacuation plans under different scenarios. Last but not least, this research will bring social science research to enhance virtual design simulation.

4. RELATIONSHIP TO CIFE GOALS

This research supports the “function” and “globalization” areas of this year’s Call for Proposal. Firstly, this computational framework for egress analysis, upon completion, provides relevant stakeholders a reliable tool to assess the design conformability with the explicitly stated project development objectives from the safety engineering perspective. Our proposed framework also serves as a reliable assessment tool to ensure the quality of “highly reliable and ultimately highly resilient facilities”, especially during the design process. In addition, this project will subsequently lead to significant contributions to the field of crowd safety, which is an increasingly important issue in facility design due to recent natural and man-made events occurred globally.

In sum, this highly interdisciplinary research will have significant impact to design practice and can lead to immediate industrial applications with characteristics that satisfy CIFE’s missions.

5. INDUSTRY INVOLVEMENT

This project has received significant feedback from industry and other agencies. We have established an ongoing collaboration with researchers at Disney R&D, and UNC on crowd simulation, with special interest in exploring the social effect on crowd movement pattern. Specifically, we have established connection with Stephanie Huerre, the developer of the crowd simulation program at Walt Disney Imagineering, for the exchange of data as the collaboration develops. We will work with any organizations that have an interest in involving with our research effort.

6. RESEARCH PLAN, SCHEDULE AND RISKS

The research plan for the proposed first year research period is as follows:

- By the end of Fall Quarter 2011 – we plan to conduct a series of benchmark simulations which aim to (1) verify the ability of the framework in showing the desired social and behaviors in simulations, and (2) test the simulation scalability. Additionally, we will continue to gather data and construct a database for validation purpose.
- By the end of Winter Quarter 2011 – we plan to develop the methodology to analyze the collected data and extract input parameters from the selected validation data for simulations. We anticipate modifying the decision module to incorporate additional behavioral rules observed in these data.
- By the end of Spring Quarter 2011 – we plan to replicate occupants’ movement patterns observed in the validation data. A systematic analysis of the simulation results from MASSEgress (and comparison with Spirops, Disney R&D’s simulation program, if necessary) will be conducted.

- By the end of Summer Quarter 2011 – we plan to complete a detailed report on the findings of this study. Furthermore, we anticipate that we will produce a range of experimental results by generating benchmark simulations and replicating both emergency and non-emergency real-life egress scenarios, and identify further developments.

This interdisciplinary research is a high-risk, high-payoff project involving participants from Civil Engineering and Computer Science, with significant input from social science research. Collaborating with industry and academic researchers, we hope to gain better understanding of people movements, especially during emergencies. We anticipate the following risks:

- *Complex human behavior in emergencies.* Due to the high complexity of human behavior, especially in emergencies, an agent-based simulation paradigm with a three-stage decision-making process is employed to mimic crowd interaction. This approach provides high modularity and flexibility so that new modules can be added to account for new theories and observations.
- *Source of validation data.* We are highly aware of the challenge in obtaining useful real-life validation data; therefore, we have established collaboration with the industry partner and the interested research group in sharing data and exchanging knowledge. We will expand our collaboration with relevant research groups (such as Prof. Aguirre at University of Delaware) who study historical disasters from the human and social behavior perspective. We will also refer to online archives of past events to obtain useful data.
- *Computational demand.* To overcome the computational demand in simulating large crowds and to ensure system scalability, we will develop and seek efficient algorithms, particularly from AI and Robotics research, to efficiently and realistically simulate crowd movement.

7. NEXT STEPS

This research will provide insights into egress designs and emergency responses due to natural and man-made disasters. We plan to pursue government funding opportunities such as NSF, NIST, FEMA, DHS, etc.. To test our result with industry, we will seek feedback from our industry partner through continuous collaboration. Successful demonstration of this research may lead to practical products needed by the industry.

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