Crowd Management and Evacuation Modeling System

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ABSTRACT

From time to time, emergencies occur where pedestrians are required to flee large metropolitan areas. Some of these areas may include: concerts, parades, and stadiums. An urban-based pedestrian modeling system can be developed to take into account the set of interdependencies, or specific repercussions, which may affect the outcome when a large number of individuals are required to quickly evacuate urban settings. A number of simulation models are currently in research and development that deal with crowd pressure and herding movements through a confined space. However, most of these models deal solely with indoor structures and do not focus on the problem of safe unified movement through an undefined space. This paper aims to modify and improve the Helbing model (indoor setting) to simulate the urban settings (outdoor settings) using a cluster computer system for massive numbers of pedestrians in various emotional and physical conditions, as they flee a virtual urban environment.

INTRODUCTION

Mass exodus of large urban settings has occurred throughout world history. But, until recently, those situations were few and far between. Large metropolitan cities are laid-out to handle automotive traffic, with varying degrees of success. But recent major power outages in New York and the attacks of 9-11-01 show that urban cities need to be prepared with an Emergency Pedestrian Modeling System (EPMS) to handle a mass-evacuation of individuals on foot within urban settings. In the current rush to provide safer environments, adapting an existing model to fit another situation has become commonplace.

Formidable challenges are tied to the fact that simulation modeling requires the use of complex algorithms capable of processing large volumes of data. Cluster computers and grid computers, are comprised of a network of personal computers working in parallel to harness the cumulative power of the entire network (Dowd and Severance 1998; Sterling 2000). These clusters are very useful in handling large volumes of simulation data following parallel computing principles. Geographic simulations are one unique application applied to clustered computing systems. In these systems, the cluster simulates the activities playing-out within the spatial boundaries. Within a cluster's virtual environment, a specific spatial area is divided into smaller blocks in a fashion similar to a checkerboard. Each node, or computer, in the cluster monitors one of the small regions. As an entity (such as a virtual pedestrian) moves from one region to the next, it is handed-off from one node's control to the next, allowing for complex interaction in real-time, between large numbers of entities and regions (Gould 1999). This system allows each computer to handle its maximum number of entities; and the entire cluster is able to handle far more entities than otherwise possible.

The author's Emergency Pedestrian Safety System (EPMS) simulation project uses a cluster computer to model pedestrian movements during emergency situations, where massive numbers of pedestrians are fleeing a general area, typically in an urban setting. The EPMS model is suited for outdoor urban environments with large numbers of pedestrians, each having individual characteristics. EPMS modifies and improves the Helbing model (indoor setting) to simulate the urban settings (outdoors) using a cluster computer system to handle massive numbers of pedestrians in various emotional and physical conditions, as they flee a virtual urban environment on foot. The Helbing model deals with indoor scenarios and deals with only relatively small numbers of virtual-pedestrians, up to about two hundred. The author's work proposes modeling the behavior and movement of hundreds of thousands of urban pedestrians. The proposed model will take into account different city sizes, bridges, and roads.

EMERGENCY PREPAREDNESS SIMULATION – LITERATURE REVIEW

Historically, panicking crowd behavior was an important area of research during the cold-war. A literature review reveals much research published throughout the 1950's and 1960's (Mintz, 1951; Quarantelli, 1957; Brown, 1965; Kelly, 1965). Simulations that model human behaviors based upon attributes and crowd dynamic are rare (Helbing, 2000a). There are simulations currently in research and development that deal with crowd pressure and herding movements through a confined space. However, these models deal solely with indoor structures and do not focus on safe unified movement through an undefined space. Studies dealing with placement of structures and safely routing crowds are in their infancy. A direct focus needs to be placed on pedestrian crowd evacuation. Placement of obstacles and crowd management is a concern, as studied at the Notting Hill Carnival (Batty, 2002).

Previous research has focused on pedestrian traffic as it relates to evacuating buildings. Helbing, et al developed a computer program to model the behavior of multiple pedestrians escaping a confined space, and provides a visual depiction of their interaction. The model takes into account many of the socio-psychological characteristic features of panicked escape. Helbing suggests that one area of future research is to add personal characteristics to the simulated individuals within the virtual model (Helbing, 2000b). The Helbing model was used by Braun, et al to develop a model for studying the impact of individual agents' characteristics in emergent groups (Braun, 2003). The Braun model extends the Helbing model by adding personal characteristics to the simulated individuals in four forms: group membership, need for help, tendency to provide help, and speed.

The Helbing and Braun models are arguably two of the best current designs. Like Braun, the author contends that the Helbing model has certain limitations which need to be overcome before it can be applied to urban planning for emergencies. After overcoming these issues, the author's resulting EPMS model will be suited for outdoor urban environments with large numbers of pedestrians having individual characteristics. The Helbing model is designed to simulate human behavior in indoor settings. All of the situations and scenarios in their research are indoors.

There are two important characteristics of an indoor model: the objectives and the obstacles; these are the first two limitations when applying the Helbing model to an outdoor setting. The third and fourth limitations involve personal characteristics, and crowd size.

The first limitation of the Helbing model involves the objectives. The objective of the virtual-crowd in the Helbing model is for everybody in a dispersed crowd to reach a specific location, and in some scenarios to subsequently fit through a small opening such as a doorway. An urban disaster evacuation simulation deals with where the pedestrians will go after exiting the confined space. In this scenario, the pedestrians' objective is not to reach a particular location, but to evacuate a particular location (flee a danger zone).

The second limitation of the Helbing model involves the obstacles in the virtual environment. Indoor scenarios have certain characteristics not found outdoors and vice versa; such as more walls and single-entry/exit locations. An urban disaster evacuation simulation will be carried out in an outdoor urban setting where there are fewer boundaries such as walls, more open spaces for freedom of movement, and small-sized obstacles such as mailboxes, light posts, and parked cars.
The third limitation of the Helbing model involves personal characteristics of the pedestrians. In the Helbing model, the developers state that their model could be improved by adding individual personal characteristics ("individual variation of parameters"). Any improvements on the Helbing model should consider adding personal characteristics to each individual, such as: physical fitness, endurance, speed, etc…

The fourth limitation of the Helbing model involves the sheer quantity of people being modeled. The Helbing model deals with indoor scenarios and is therefore required to deal with only relatively small numbers of virtual-pedestrians. An urban disaster evacuation simulation may be required to model the behavior and movement of hundreds of thousands of pedestrians. Large-scale urban evacuations are occurring on an increasing frequency. Attacks of terrorism and large-scale blackouts have recently caused pedestrian evacuations of large urban cities such as New York, Detroit, and London.

The Helbing model's software is capable of running on a standard personal computer. Efficient and timely operation of the model is not possible given the speed of current personal computers if it is required to track hundreds of thousands of pedestrians using a single workstation.

CLUSTER COMPUTING APPLICATIONS

In recent years, cluster- and grid-computing have proven to be a cost-effective alternative to traditional supercomputers (Sterling, 2000). Cluster computers are comprised of a dedicated network of personal computers working in parallel to harness the cumulative power of the entire network (Dowd, 1998; Sterling, 2000). The resulting system has many advantages over a traditional supercomputer including cost, performance, scalability, and maintenance (VonZandt, 1992). In addition to these benefits, cluster computing systems are capable of performing tasks in new and unique ways, giving additional advantage over traditional supercomputers (Scannell, 2004).

Geographical simulations are one unique application applied to clustered computing systems. In these systems, the cluster simulates the activities playing-out within the spatial boundaries. Simulated complex activities and interactions among large numbers of entities within the spatial constraints become exceedingly computational-intense. Clusters are well suited for these complex applications. Within the virtual environment, a specific spatial area is divided into smaller blocks in a fashion similar to a 'checkerboard'. A single node in the cluster monitors each of the small regions. As an entity moves from one region to the next, it is handed-off from one node's domain, to the next, allowing for complex interaction in real-time between large numbers of entities (Gould, 1999). Applications such as this have been used, for example, in science to simulate the interaction of large numbers of molecules in a spatial area (Maniatty, 2002).

This paper proposes the development of a virtual urban environment using a cluster computer system, to aid in modeling emergency pedestrian evacuation procedures. The system will monitor and track large numbers of virtual-pedestrians as they flee a simulated urban environment. After developing a large database of contingency plans, it will be available to provide advice on the most efficient evacuation routes given an emergency of a particular type, at a particular location, at a particular time.

METHODS

The author's Emergency Pedestrian Safety System (EPMS) model addresses the four limitations of the Helbing model by developing the following modifications: a) the desire to flee rather than converge; b) an outdoor rather than indoor environment; c) personal characteristics for each simulated individual; and d) a much larger population of virtual-pedestrians.

This paper builds on the research of Helbing, Farkas and Vicsek by proposing four modifications to their work in order to develop the author's EPMS model; a simulated environment to model large-scale pedestrian evacuations of major urban environments. The four modifications that are required (objectives, obstacles, personal characteristics, and quantity of people), are discussed in detail.

MODIFICATION ONE: OBJECTIVES

Studies dealing with crowd management need to move in the direction of simulating outdoor activity and modeling interactions between simulated pedestrians. With an understanding of the processes by which individuals make decisions and filter through undefined spaces, we as a society can build improved simulation models to replicate this activity. Based upon mathematical models all individuals have goals and sub goals (Batty, 2002). The interest should point to how we are going to safely evacuate thousands of pedestrians from a city when there is a disaster. Rather than focusing on moving large numbers of pedestrians *to* a location, the author's model focuses on moving a large numbers of pedestrians *away* from a location. This can be accomplished by altering the acceleration model and changing the objectives and sub objectives of the simulated individuals.

MODIFICATION TWO: OBSTACLES

In an outdoor simulation, a pedestrian will have fewer obstacles and barriers than they would likely encounter indoors. This author's model differs greatly from the Helbing model by introducing larger spaces and smaller barriers. Simulated individuals will have 'objectives' and 'sub objectives' directing their movement as they move away from the disaster area. An 'objective' for a simulated individual will be how they would react to a situation depending on their attributes. 'Sub objectives' will only come into place if a simulated individual looses their way, cannot overcome an obstacle, or does not have access to the path they would have naturally chosen first.

MODIFICATION THREE: PERSONAL CHARACTERISTICS

This paper builds on the research of Helbing, Farkas and Vicsek, in which they outline nine characteristic features of escape panic situations (Helbing, 2000a):

1) People move or try to move considerably faster than normal (Predtetschenski, 1971).
2) People start pushing and interactions among people become physical in nature.
3) Moving and in particular, passing of a bottleneck becomes uncoordinated (Mintz, 1951).
4) At exits arcing and clogging are observed (Predtetschenski, 1971).
5) Jams build up (Kelly, 1965).
6) The physical interactions in the jammed crowd add up and cause dangerous pressures up to 4,450 N $m^{(-1)}$ which can bend steel barriers and brake down brick walls.
7) Escape is further slowed by fallen or injured people acting as 'obstacles'
8) People show a tendency toward mass behavior, that is, to do what other people do (Keating, 1982) (Quarantelli, 1957).
9) Alternative exits are often overlooked or not efficiently used in escape situations (Keating, 1982) (Elliott, 1993).

These nine features are incorporated in the Helbing system through mathematical modeling. They work well to predict panic and panic-related behavior, and will be incorporated into the author's EPMS model. In addition, as suggested by Helbing, individual characteristics will be added to each simulated individual.

Each simulated individual will have a list of general personal attributes. These attributes will be classed in 4 general areas; knowledge, skill, ability, and adrenaline. Assigning each simulated pedestrian a scaled value in each of the four general attributes will allow the simulation to exhibit variation between each pedestrian.

(1) Knowledge

By definition, knowledge is the fact or condition of knowing something with familiarity gained through experience or association. Knowledge may also be described as a set of models that describe various properties and behaviors within a domain. In reality, there exist many possible, equally plausible, definitions of knowledge. For purposes of this research, the authors focus on the following definition of knowledge: the idea or understandings which an entity possesses that are used to take effective action to achieve the entity's goal(s).

In essence, knowledge is the act or state of knowing gained through the psychological interaction between experience, learning, cognition, and perception of fact and truth. As such, knowledge activities within a society are largely influenced by the members of the society and their individualities such as cognition, experience, culture, and expertise, which are functions of the chemical and psychological functions of the human brain.

Knowledge is the full utilization of information and data, coupled with the potential of people's skills, competencies, ideas, intuitions, commitments and motivations. A holistic view considers knowledge to be present in ideas, judgments, talents, root causes, perspectives, and concepts. Knowledge is not static; rather it changes and evolves within a panic situation.

Each simulated individual will be assigned an initial knowledge level that may change throughout the simulation through learning, experience, and adrenalin levels.

(2) Skill

Skill is the ability to produce solutions in some problem domain. Simulated pedestrians need an attribute for information problem-solving. This will be accomplished with the skill attribute.

Task definition defines the information problem at hand and identifies the information needed to complete the task. Information-seeking strategies would apply to brainstorming all possible sources. The simulated individuals need to find the necessary information within their environment so they can react accordingly. The pedestrians need to engage in the source, whether it is hearing, sight, touch, or smell. Next, the pedestrian needs to extract relevant information from the sources they find in their environment. Synthesis can be used to gather information from multiple sources (such as other simulated pedestrians or emergency response teams). Finally, simulated pedestrians can use evaluation to judge the effectiveness of their initial decision. Each simulated individual will be assigned an initial skill level when the simulation begins. Skill levels will be modified by adrenaline, and will interact with knowledge levels and ability levels.

(3) Ability

Ability is the quality of being 'able to perform;' a quality that permits or facilitates achievement or accomplishment. Within the simulation, pedestrians will be assigned a value that represents their abilities. The ability-score will take into account a person's speed, strength, endurance, height, dexterity, and vitality (Hyman, 1998).

Each simulated individual will be assigned an initial ability level. Ability levels will be modified by adrenaline, and will interact with knowledge levels and skill levels. Each individual's ability will have direct impact on how the pedestrian moves throughout the virtual urban environment. After the results are analyzed and compared to repeated simulations, the ability factor is expected to be the most important variable to individual safety.

(4) Adrenaline

Adrenaline is a catecholamine secreted by the adrenal medulla in response to stress, which stimulates autonomic nerve action (Fite, 1911). This comes into play during panic and disaster related events. When the simulated individuals are in a panic situation or crowd herding event, their adrenaline factor will directly affect their other attributes in a positive or negative manner. Adrenaline affects the nervous system releasing hormones and sending rapid signals to the brain. A person with high adrenaline levels is at risk of having high panic levels. Individuals with high panic levels will generally not use common sense when reacting to stress or disaster related events. Adrenaline can also benefit an individual as in temporarily bestowing extra abilities or increasing upon abilities they already possess. Adrenaline is a factor often missing in other existing crowd evacuation simulations. In this model, the adrenaline factor will be a change agent acting on the simulated individuals. The adrenaline level of each simulated individual will change throughout the simulation, depending on current conditions. The adrenaline level will then have a positive or negative affect on the levels of the other three personality factors; knowledge, skills, and ability.

MODIFICATION FOUR: QUANTITY

A cluster computer system uses multiple personal computers, networked to harness the combined computing power of all the processors in the network through the use of parallel processing software architecture (Spector, 2000; Sterling, 2000; Smaller, 2002). A cluster computing environment involves two elements, hardware and software. Cluster computing systems and grid systems are found in multiple varieties and complexities. In a cluster's simplest form, a Beowulf-type cluster computer system is managed through a single 'master' computer (node). The master node is networked to the rest of the system through a network switch, cable, and network interface cards, preferably of the fastest affordable variety. The multiple droid nodes are dedicated to the network, performing whatever tasks are passed to them from the master node (Apon, 2000; Baker, 2000; Becker, 2001). Cluster computers of this type are relatively easy and inexpensive to construct (Kitchens, 2002; Childers, 2003b, a).

The author's EPMS model utilizes the multiprocessing power to control the various dynamic variables within the application. Cluster computing software has the ability to brake down processes being executed on the master node of a cluster. Each node in the cluster will receive a process or piece of the overall program being executed. Once the node is finished with the small job it has been assigned, it will return the information back to the master node. With this technology, large applications such as simulations can be executed quickly and efficiently. The EPMS application will use droid nodes to control simulated pedestrians that are in the droid node's virtual space, assigned to each droid node by the master node.

Passing the simulated pedestrians from droid node to droid node as they move around the virtual landscape will take the overall processing volume off the master node and allow for simulations that model hundreds of thousands of pedestrians. Cluster applications are required in order to study crowd management and simulated movement of hundreds of thousands of people in large outdoor settings. The sheer number of individuals being modeled, each with their own individual characteristics, cannot be modeled in a timely and efficient manner by the traditional single-processor personal computer available to most researchers.

The EPMS model will track the locations of hundreds of thousands of simulated pedestrians throughout a virtual urban environment. Due to the quantity of simulated pedestrians and the computational steps required, a cluster or grid-computing environment will be required. Although, the EPMS application can be scaled down to run on a single workstation effectively. The application will be set up to map an urban environment, in a virtual grid system to monitor each simulated pedestrian at all times. This information will be recorded and later used to calculate statistics concerning overall outcomes of multiple simulations.

Figure 1: Simulated individuals running through downtown streets between buildings

Individuals will be tracked by the EPMS from the time they evacuate to the time they reach safety (or when the simulation terminates). As the simulated individuals move through the virtual city they will in essence be moving through a large matrix. Splitting-up the processing of simulated individuals among all the droid nodes in the cluster will permit the application to handle hundreds of thousands of simulated individuals.

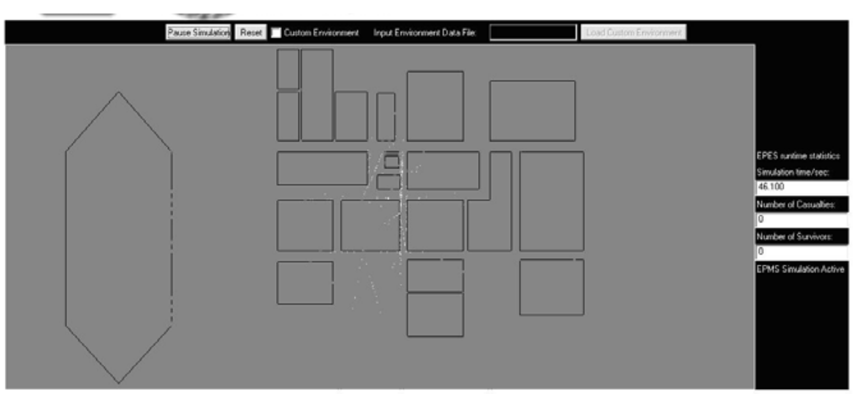

Figure 2: Overview of a typical downtown city environment

In reality, the pedestrians will not be transferred directly from one droid node to the next; they will be passed to the master node which monitor's all intra-cell activity.

RESULTS

The objective of the EPMS model is to provide a simulation that will predict the timing and flow of pedestrians fleeing an emergency situation and arriving at a "safe" location; defined as a certain distance away from the center of the crisis area. The simulation will begin with the occurrence of an event that would cause a large scale evacuation by pedestrians; such as a blackout or terrorist attack in a large metropolitan environment. The simulation will track people as they exit structures, filter onto city streets, and proceed away from the danger zone to a safe area. The program will terminate either at a predefined time specified by the user, or after a certain percentage of simulated pedestrians escape the danger zone.

Data gathered from the EPMS model will consist of the time, location, and personal characteristics of each individual as they cross a threshold into what is considered a "safe" location. This data will be recorded to a file for later analysis. Three basic analyses will be performed using the time and location data, along with further data mining using the personal characteristics data. The results will help to determine the safest and most efficient evacuation procedures for an emergency of a given type, location, and time. Thus, through a series of Monte Carlo simulations, a large set of contingency plans will be developed and will be ready for dissemination to the pedestrian public in case of emergency.

First, *distance to safety*. The question here is how far away from the center of disaster can the majority of people (for example 80%) get within a certain time period (for example 1 hour)? This is important information for officials and emergency personnel when there is a specified time-to disaster, such as bomb-threats and the possibility of a second terrorist attack.

Second, *time to safety*. The question here is how long will it take to get the majority of people (for example 80%) a given safe distance (for example 5 miles) away from the center of disaster? This is important information for officials and emergency personnel when the geographic area affected by immanent disaster is known in advance. For example, when there is a known threat to the population.

Third, *flow of pedestrian traffic*. What is the flow rate of people entering a safe zone? Are there fluctuations? This information is especially important to care-providers such as the Red Cross when food, supplies, medical aid, and shelter are being provided.

Fourth, *other data mining*. Recording the personal characteristics of each person along with the time and location they reach safety will allow data mining to be conducted. This may provide valuable information in two areas. First, are the personal characteristics of the individual people appropriately assigned for this sort of simulation? Second, are there any lessons to be learned from the characteristics of the people who tend to reach safety first?

APPLICATIONS

This model is intended to run Monte Carlo simulations in order to develop a set of contingency plans for pedestrian evacuation of large urban centers. The variables affecting the behavior of the simulated individuals will be randomly generated for each individual; the outcome of each simulation will be slightly different. Running a series of multiple simulations for contingencies based on the type, location, and time, of emergency evacuations will provide a better picture of anticipated results.

In the event of a natural or man-made disaster, emergency preparedness plays a vital role in ensuring the safety and efficiency of pedestrian movements. Emergency preparedness greatly depends on the understanding of the scope and magnitude of potential incidents and the significance of their disruptions to the mobility of people. Preparedness involves anticipating a range of emergency scenarios and developing and testing various response plans. In the case of emergencies that affect pedestrians, response time is a critical factor in minimizing adverse impacts including fatalities and loss of property. Following the events of September 11, 2001 the urban environment recognized the need for better emergency planning and prevention, crisis management, and response to threats and disasters affecting the citizens.

The author's EPMS system will develop contingency plans to handle multiple variables within an emergency situation. The matrix of contingency plans will include the variables representing the Type, Location, and Time of a disaster. This contingency matrix will be used to develop optimal emergency response plans in order to evacuate individuals from a disaster area. *Type* will represent the nature of the disaster being modeled. This will incorporate the size, severity, and duration of the emergency. Some emergencies such as single explosions affect only a small local area, and are short in duration. Other emergencies such as floods and hurricanes affect a large geographic area and may last for hours or even days. *Location* will represent the geographic "ground zero" of the simulated disaster. *Time* will represent the time of day the disaster takes place. It will incorporate the expected number of individuals in a certain area and their distribution in buildings, streets, subways, etc. Within a large urban environment conditions are expected to change throughout the day. The system will be required to run multiple contingency plans to account for these changes.

If and when a real emergency occurs, the EPMS system will search the many emergency contingency models that have already been simulated, analyzed, and stored. Using the location, time, and severity, information, the EPMS program will match the current situation to the most similar contingency plan for routing escape paths. So in essence, the evacuation path will be generated from stored data as well as real-time information that the system is receiving.

DISCUSSION AND FUTURE DIRECTION

When fully developed, the author's EPMS system will be a valuable tool for government officials and emergency response teams. The application will be invaluable for planning for emergency response and communicating the optimal evacuation routes to the public.

A live test of the validity of the EPMS system would be very difficult and unlikely due to the volume of people required, and the difficulty in getting people to demonstrate a realistic reaction during a crisis rehearsal. However, smaller-scale reenactments would help to support the validity of the EPMS system. In addition, using video footage of pedestrian evacuations during past emergencies might help to validate the EPMS system.

Future direction in this line of research should be directed toward refining individual characteristics, altering the topology of the landscape to allow for hills and valleys, allowing for weather conditions that might impede the individuals' progress, signaling the public with some sort of directional devices, communicating in real-time with the public during the emergency situation, and allowing for public transportation systems.

BIBLIOGRAPHY

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