MULTI-AGENT CROWD BEHAVIOR SIMULATION FOR TSUNAMI EVACUATION

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We certify that we have read this report and that, in our opinion, it is satisfactory in scope and quality for the degree of Master of Science in Computer Science.

COMMITTEE CHAIRPERSON

To my partner Eric,

through all our adventures,

he’s always at my side.

Acknowledgements

I want to thank Dr. Nancy Reed whose instruction and guidance made this project both possible and successful.

ABSTRACT

Tsunamis pose an imminent threat to human life with little advanced warning. In the threat of such events, people act outside of their usual societal patterns and may make critical decisions with uncertain information, under emotional duress, and with limited time. As such, people are susceptible to information cascades, whereby many people will make the same decision based upon observations of others. Social force models based upon particle dynamics such as Helbing's model have shown behavior similar to observed crowd phenomena. In this paper we describe a simulation of tsunami evacuation using a modified form of Helbing's social-force model applied to agents designed in the Repast Simphony agent framework.

We believe that by simulating a tsunami evacuation of a beach community that city administrators can improve evacuation plans and thus reduce casualties during a tsunami. Thus, we hope that lessons will be learned by simulation and not firsthand experience. The beach communities of Hawaii are chosen as a focus area due to their highly dense population of tourists and residents, and susceptibility for tsunamis. We have used the simulation to refine a model for crowd behavior. We found that a designated buddy system would result in a more efficient evacuation. We noted that it is important to encourage helping both people within and outside one's family to improve the rate of evacuation.

There are several avenues for future work including advanced evacuation path discovery and applying the simulation to GIS maps of local beaches.

Contents

Chapter 1

Introduction

Hawaii is the highest risk area in the world for a tsunami [1]. The Hawaii Civil Defence Agency notes that both distant and local seismic events can generate tsunamis. Although a distant tsunami may take hours to reach Hawaii, it may not be detected until it is within minutes or hours of Hawaiian shores. Locally generated tsunamis can reach land within minutes. Poor evacuation coordination, emergent crowd behavior, and physical obstructions can result in greater casualties. We hope that through simulation, these factors can be mitigated.

The characteristics of tsunamis make them a more complex threat than simple flooding or an advancing fire. Since a tsunami involves multiple waves, where the second wave may be much larger than the first wave, people may be lulled into a false sense of safety once the first wave has passed. A tsunami can occur at any time of day and during perfect weather, giving few natural cues to the impending disaster. The receding water can expose vast stretches of the sea floor, luring curious people into the danger zone. Also, the roaring wall of incoming water from a tsunami differs starkly from normal breaking waves that people enjoy surfing upon. Chiefly, a tsunami's power reaches down to the sea floor, pushing along copious amounts of heavy rocks and debris. The debris-laden waves of the 1960 tsunami that struck Hilo, Hawaii bent parking meters to the ground and crushed framed buildings [4].

Historical accounts of the devastating 1960 tsunami that hit Hilo showed public confusion over what the warning sirens meant, people returning before it was safe, and a report of dangerous misinformation from a public official [2]. Survey reports in 2005 found that although there was a general awareness of the tsunami siren tests, the residents surveyed lacked an even understanding of the siren's meaning [7]. We can likely assume that the extensive nonresident tourist population would have an overall lesser degree of understanding of the dangers and mitigating actions for surviving a tsunami event.

In 2008, 6.8 million people visited Oahu with 563 thousand visitors during the month of December alone [5]. With that volume of people, crowd dynamics during an evacuation could result in casualties. Helbing provides an extensive summary of evacuations at stadiums, theaters, night clubs, and other areas people congregate [8]. In these areas, casualties have resulted from people being crushed into barriers, and trampled or blocked at exits.

In this paper we describe the development of a multi-agent system capable of simulating the evacuation of a Hawaiian beach for a tsunami event. The simulation includes a modified particle based social force model that governs movement. The awareness, mobility, and altruism of individual agents are used to determine the agent's action. An agent may choose to help other agents at a cost of reducing their own mobility.

Chapter 2

Related Work

Particle based approaches to modeling behavior often use rules and forces to elicit complex behaviors from simple assumptions. Reynolds [15] applied a particle system to model the flight of bird flocks. The individual bird decisions would result in flocking behaviors. Helbing [9] proposed a particle system for crowd behavior where agents reacted to several social forces. The model supported both individual and collective-based behaviors. Helbing applied the model to crowd panic situations where exits become congested, people become injured, and individuals exhibit mass behaviors.

In 2002, Helbing [8] discussed the observable phenomena of crowds, and presented social force models for normal and panicked pedestrian dynamics. During simulation, a parameter for nervousness caused the switch between the normal and panic models. One such simulation featured a linear fire front approaching and injuring an evacuating population. Fire and smoke were used as ”socio-psychological” effects that affect the nervousness parameter. Braun [3] generalized the Helbing model to allow for individual agents’ characteristics to impact their efficiency and decisions in a simplified evacuation scenario. The model supported familial altruism and dependency.

Koh [11] found middle ground between social particle-based and behavioral focused simulations and proposed a two-tiered approach to pedestrian modeling. The macro level governed the path coordination, while the micro level handled sub-goals such as avoiding other agents. Agents were endowed with the ability to remember a map, have limited range of vision, and have a limited memory of events such as encountering obstructions. Simulations demonstrated following, overtaking, and congestion avoidance behaviors.

In order to simulate realistic crowd behavior, Hu [10] used ”psycho-socio-physical” factors to define the context in which the agents make their decisions. A ”behavioral context” level, such as an emergency, changed the probability of actions at the behavior level. Actions were predominantly chosen by mutual inhibition between the available options. Hu noted that this method is intuitive and more computationally tractable than cognitive models for simulating large populations.

Sabino [16] used a cellular based Repast model to simulate the evacuation for a dam break and emergency response for the Alqueva dam in Portugal. In his proposal, Sabino hoped to use the simulation to validate the proposed Dam Break Emergency Plans (DBEP). In his research, he found a lack of published works on emergency plan simulation. Physical drills are noted to be difficult, costly, time-consuming, and lacking realism. In the simulation, an event triggers agents toward self-evacuation. Civil protection later renders support to these agents.

Murakami [12] demonstrated the benefits of simulating agents where certain agents filled the role of leaders. Leaders could either gather and lead or direct other agents during an evacuation. He enumerated many roles and actions that leaders fulfill in ensuring the safety of others. Some simulations showed that the overlap of instructions from too many leaders could hinder group formation and an efficient evacuation. Murakami noted that simulation results paralleled real-life fire drill exercises performed with multiple leaders.

Pelechano [14] applied Helbing's crowd behavior model to building evacuation simulations including trained leaders, untrained leaders, trained non-leaders, and followers. Trained leaders had complete knowledge of the office map and would lead people out. Untrained leaders tended to help others and found alternate paths themselves. Followers could panic requiring leaders to guide them out. Through the Helbing model, agents are attracted to exits and repulsed by obstacles. Simulations showed that the introduction of trained leaders rapidly increased the percent of people evacuated. A ten percent population of trained leaders was found to be optimal. Pelechano concluded that room for improvement remained via adding individualism to Helbing's model to produce role-based local motions.

Chapter 3

Implementation

An agent simulator was developed using the Repast Simphony agent toolkit [6]. Repast is a free and open source agent simulation toolkit available for use under a New BSD style license. Repast provides an Eclipse IDE editor for editing the model as well as a run-time user interface. The developers noted [13] that Repast has been applied to producer/consumer problems, evolutionary emergence, social norm emergence, national border development, and archeology.

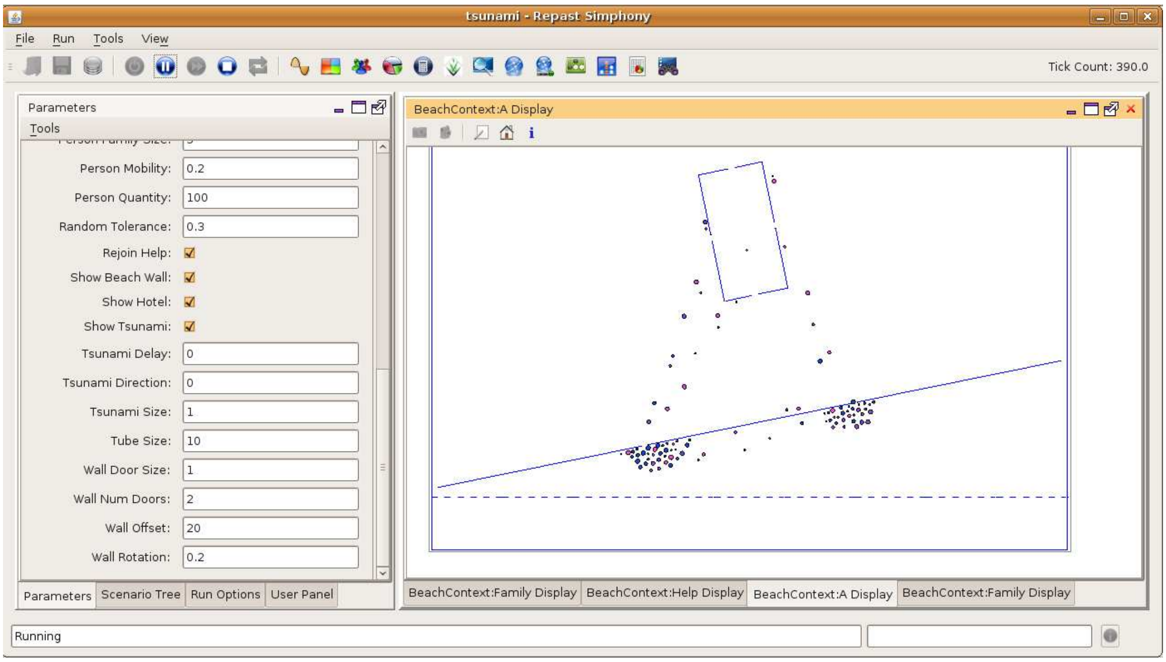

Figure 3.1: Repast simphony run-time GUI

This project primarily uses the JAVA modeling, 2D visual displays, chart plotting, and data set recording capabilities. The agents exist within a 2D continuous space. Several scenarios have been hard coded into the simulator. Many of the parameters governing these scenarios can be adjusted through the run-time user interface. At runtime, a user of the simulator can set the magnitude of the tsunami, population size, family size, hotel configuration, seawall configuration, agent behavior, and average values for the agent attributes. Once the desired parameters are set, a user can start the simulation and observe the effects. Figure 3.1 shows the run-time interface of our simulations involving a hotel and seawall.

The crowd behavior is controlled by a modified form of Helbing's social force model [8] which treats agents as particles reacting to attractive and repulsive forces around them. Equation 3.01 shows the core of Helbing's force model. This equation represents the sum of forces operating on the i^{th} agent.

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_W \mathbf{f}_{iW} \tag{3.0.1}$$

For the i^{th} agent, m_i is the mass, $\frac{d\mathbf{v}_i}{dt}$ is the acceleration, $v_i^0(t)$ is the desired velocity at time t, $e_i^0(t)$ is the desired direction at time t, $\mathbf{v}_i(t)$ is the velocity at time t, and τ_i is the acceleration time constant. Helbing defines the repelling force of person j on person i as an exponential function, $\mathbf{f}_{ij}$. Similarly, he defines the repelling force of walls on the i^{th} person as an exponential function, $\mathbf{f}_{iW}$.

In our case, we add additional forces to the model for the tsunami. The approaching wave front presents a repulsive force similar to a wall. Waypoints along an exit path provide attractive forces. The attractive force of waypoints is incorporated into the first term on the right hand side of the equation where v_i^0 is the desired velocity and $\mathbf{e}_i^0$ is the desired direction. Repulsive forces among agents, and between an agent and a wall are accounted for in the second term and third terms respectively. The repulsive forces of people and walls are intended to prevent agents from overlapping or going through physical obstructions. In addition to the exponential repulsive force based upon distance, the equations for the force between agents and other agents or walls includes "body force" and "sliding friction force" as defined by Helbing [8]. While we are not making use of trampling detection in this simulation, we still include these forces in our model to aid in keeping agents apart. For the exponential coefficients, friction constants, and acceleration time constant τ we use the values derived by Helbing[8].

One main modification to Helbing's model that we made is to account for the effects of some forces that are insufficient or inappropriate for modeling human behavior. For example, initial simulations showed that the repulsive force of walls was insufficient to overcome either a fast moving agent or the cumulative force from many agents pushing on an agent near a wall. The result was that the agent moved through the wall. String theory notwithstanding, this behavior is undesirable. Therefore, additional measures were made to ensure that it is impossible for an agent to go through a wall. When an agent tries to move through a wall, their position is adjusted to being close to the wall allowing the normal exponentially increasing repulsive force of the wall to exert its influence. Additionally, the simulation prevents agents who are on opposite sides of a wall from exerting repulsive forces on each other.

Still noted [17] that such fluid dynamic models overlook crowd phenomena such as pedestrians starting or stopping suddenly or the faster movement possible at the edges of columns of people. The simulation uses the natural mass control of the particle-based system for handling gross movements. However, based upon the agent's character, in our model an agent may ignore the repulsive force of the tsunami or the attractive force of the path to the safe zone. The agent may choose do to so, for example, if they have a low awareness value, or if they are en route to helping another agent. Additionally, initial simulations showed that strict limits on maximum velocity and acceleration were needed to keep movements more in line with humans than particles. We have set the maximum velocity at 3 m/s, which is roughly 6.7 mph. Although humans can undoubtedly run much faster, the domain of this experiment is on beach evacuations. We believe that the dry sand on beaches inhibits the maximum speed a person can run.

Chapter 4

Enhanced Agent Model

4.1 Initialization

To set up a simulation, the user must specify both the parameters for the map as well as the agent population attributes that influence crowd behavior. It is not the goal of this project to provide a tsunami forecasting or water inundation model. For the experiments presented in this paper, we tracked the evacuation rate without the introduction or interference of a tsunami. However, we built a hard-coded tsunami event into the simulator that is based upon an approximation of measurements for the tsunami that devastated Hilo, Hawaii in 1960. The run-up of the tsunami onto land is calculated by assuming that the land has a constant slope. A user may adjust the presence, land slope, arrival time, and scale factor of this tsunami through the run-time user interface. If selected, the tsunami appears as a blue dashed line during the simulation that moves up and down the screen depending on the height of the water and the slope of the land.

Based upon the simulation parameters specified, the agents are initialized with appropriate values for awareness, altruism, mobility, and family connections. The values for the parameters are assumed to be uniformly distributed with the specified random tolerance value for the parameters. For example, we might specify that on a certain day, Waikiki beach goers are 5% aware, 15% altruistic, 80% mobile, and have an average of 3 family members present within a radius of 5 meters.

The initializing code places the agents randomly in clusters representing their family. Agents within a family are placed within the specified maximum radius. This clustering placement plan correlates closely to observable behavior of family and friends congregating on the beach.

4.2 Agent Attributes

The agents in the simulation are defined by various attributes that affect their decisions. These include awareness, altruism, mobility, and family connections.

4.2.1 Awareness and Evacuation

Educating the population what to do in the event of a tsunami is an important step in preventing casualties. However, the messages do not uniformly reach the population. For example, phone book inserts probably don't reach people who only own a cell phone. Additionally, the high prevalence of tourists in Hawaii means that there is a large population of people who are not familiar with the local disasters and mitigating actions for survival. In our simulation, the awareness factor defines the likelihood that at a given time, the agent will enter evacuation mode and move toward the safe zone. Since this decision is calculated at each time unit, the initial awareness value must be quite low to prevent all of the agents from evacuating within a few units of time.

If the decision is not to evacuate, then the agent's action depends on what the tsunami is doing. If the tsunami is receding, then the agent moves towards it. This behavior corresponds to people moving toward the exposed seabed out of curiosity only to endanger themselves further. If the tsunami is advancing, the agent will react solely to the forces of other agents and walls. Thus, their movement will be somewhat erratic. Should the tsunami rise to a level that the endangers the agent, the awareness value is dispensed with and the agent goes into evacuation mode. We assumed that once a tsunami hits a person, they will know to evacuate.

We believe that one could obtain average values for the awareness factor by observing the reaction time of people being drilled for an evacuation. Thus, we assume that a person's awareness of tsunami evacuation procedures affects their reaction time.

4.2.2 Altruism and Help

Personal behavior can vary from entirely selfish to entirely selfless. Lifeguards, for example, are on the selfless side of the spectrum. An altruism measure for the agent will represent how what percent of the time the agent is willing to help another agent.

If an agent chooses to help evacuate another agent, the choice of which agent to help is based mostly upon need. Need is calculated according to the product of the reciprocal of mobility, reciprocal of distance from the normal sea level, and the reciprocal of the distance from the helper to the agent. Thus, the need is greatest for an agent with a very low mobility value that is close to the ocean and is nearby the helper.

Agents are selective about who they choose to help. They will only choose to help another agent that has a mobility value that exceeds a specified difference from their own. This type of agent will also ignore agents beyond a certain distance and agents with a larger mass than themselves. Additionally, if the agent has any family members, they will always help a family member before helping someone else even if the need is greater for a non-family member.

When an agent is helping another agent, their mobility value is averaged between the two agents. Thus, a person being helped slows down the helper. An agent will not help an agent that is already being helped, is safe, is dead, or is helping another agent. If the agents are separated for a specified distance, then the helping link is broken. If the agent is not set to resume the link, then the helping agent will continue toward the safe zone while the other agent is left behind.

4.2.3 Mobility

Children, the elderly, and several other types of persons are at an increased risk of casualty owing to their limited mobility. In our simulation, the mobility factor limits the maximum speed that the agents can attain. An agent with a low mobility factor can still evacuate themselves, but at a slower rate.

4.2.4 Family

Connections between people vary from solitary people to entire families. Agents are placed in clusters together on the map close to others in their family. Agents will choose to help family members over non-family members in an evacuation.

4.2.5 Exit Path

We assume that all agents know of one path to a safe zone. That path may not be the most optimal or safest. Helbing notes [8] that alternative exits are often overlooked in panic situations. We believe that one reason for this is that people remember their most used path and fail to look for or use alternative paths. For our simulation, all agents are given a path to safety. Each agent family is given the same path. Paths are built based upon known bottlenecks.

For the hotel simulation, an agent's first waypoint on their path to safety consists of a series of three lines around a gap in the seawall dividing the beach from the hotel area. The three lines are used to guide the agent through and away from the bottleneck. Thus, if the agent is right up against a wall, they will move for the first line which is offset slightly from the gap in the wall. This prevents wasted efforts from an agent attempting to go through a wall.

Since the particle motion results in occasional erratic movements, it is sometimes difficult for the agents to get through small apertures. Thus, when an agent approaches a waypoint, they are set to slow down so that they can go through the waypoint and not miss it.

Chapter 5

Experimental Design

5.1 Tube Test

In this experiment we tested various configurations of tubes to test what the velocity profile is for agents moving through a constrained space. Since we are using a modified particle physics based approach to simulating the agents, then we should expect to see the parabolic velocity curve for the velocity about the middle of the tube. Under normal particle fluid flows, particles along the walls encounter friction resulting in a slower velocity.

A narrow tube is constructed with specified width and fixed walls. The agents are created and placed randomly within a small section of one end of the tube. Each agent is assigned a single waypoint at the opposite side of the tube. When an agent reaches the other side of the tube, they are considered safe, colored white, and removed from further calculations of forces. Thus, in effect, safe agents are removed from the simulation.

5.2 Aperture Test

In this experiment we test the effects of the size of an opening in a wall with the time needed to evacuate the map. Constricted openings result in bottlenecks. When people crowd an exit, the phenomena of arching is observable. That is, a human semi-circle forms around the exit that inhibits progress through the door. The contention for this exit results in fewer people escaping than if they had not crowded the doorway.

We initialize the map to have a seawall with one exit. No other obstructions are present and the tsunami is deactivated. One hundred uniform agents are created with a random position beneath the sea wall. Each agent is given the same exit path consisting of going through the doorway and traveling a short distance to safety. The agents are set to have no family, no altruism, and maximum awareness. For each run of the simulator, we increase the size of the door by one meter. For comparison, an additional run is made with no seawall.

5.3 Designated Buddy

Public information campaigns are one way that city administrators can attempt to reduce casualties before a disaster strikes. One campaign that could be developed is for families and friends to adopt a buddy system for beach trips. In such a system, persons with low mobility would be paired with buddies that have higher mobility and greater awareness of how to act during a disaster. If the tsunami sirens sound, the more mobile and aware buddy would meet his buddy and they would evacuate together. For these simulations we track the total number of saved people over time.

For the buddy system, each pair of sequentially numbered agents is paired together in a helping relationship. That is, the helper agent is set to move toward the agent that needs help. The agent needing help proceeds normally based upon his characteristic values until the helper is within two meters. At that point, the helping bond is formed and the agent being helped follows the helper to the safe zone. The buddy being helped will have a mobility value of one tenth of the helping buddy's value. We used a simple map for these simulations including a seawall twenty meters from the sea level with four openings that are two-meters in length each. The safe point is centered horizontally and 50 m away from sea level. Once either agent is safe, the helping link is broken.

The first run of the simulation is without the buddy system being active. The second run of the system is with the designated buddy pairing and random map placement. The third simulation run is with the designated buddy pairing but with placement of the buddies within two meters of each other.

5.4 Buddy Discovery

Another possible campaign that a city can promote is to encourage people to provide evacuation assistance to those with lower mobility or awareness. This idea differs from the buddy system mentioned above in that the person being helped is not predesignated, but discovered at the time of the evacuation.

For this set of simulations we look at how buddy discovery affects evacuation time and the number of people being helped. The agents chose whether or not to help an agent within a specified radius based upon their altruism value and the other agent's character. For the agent to choose to help another agent, the other agent must have a smaller mass and a lower mobility value. The mobility value of the agent needing help must differ from the helping agent's mobility value by a specified threshold. Half of the agents are set to have a mobility value of 0.6, whereas the other half receive a mobility value of 0.06. The agents with higher mobility are set to be helpers and the agents with low mobility are set to be non-helpers. The help threshold for mobility is set such that the difference between the two possible mobility values is sufficient to warrant help. We used a more complex map for these simulations. The map included a seawall twenty meters from the sea level with four openings that are two-meters in length each. Additionally, we placed a hotel structure on the map with length 20 meters and width 10 meters having a slight rotation. The hotel structure has a 2 meter opening center along the length of each side of the structure. The entrances to the hotel are assigned randomly to the agents as waypoints on their way to the safe point. The safe point is centered horizontally and 50 m away from sea level, in the center of the hotel structure.

In our simulation runs, we incrementally lower the altruism value. The altruism value corresponds to how likely a person is willing to help an agent around him. For the first set of runs we establish a population with no families to prevent family preemption in helping. By design, if a person has any family, they will help their family members first even if there is a greater need from another person. For the agent to choose to help another agent, the other agent must have a smaller mass and a lower mobility value of which the difference must exceed a specified threshold. In a subsequent set of runs, we allow family preemption by establishing families of three agents apiece.

Chapter 6

Experimental Results

6.1 Tube Test

In this experiment, we observed that the speed across the width of the tube was nearly uniform. Figure 6.1 shows a section of the tube populated with agents. The agents are moving toward a waypoint on the right end. The color represents the ratio of the velocity magnitude to the maximum velocity of the agents with pure blue being the slowest, and pure red being the fastest. Initially, the leading edge of the crowd of agents did have a slight speed advantage at first. However, as the simulation progressed the velocity became uniform across most cross-sections of the tube. This simulation diverges from the expectations of particle physics in that the agents have a cap on their velocity which is quickly reached. Subsequent attempts to set an extremely high cap for the velocity of agents did allow for faster movement through the tube. However, aside from a few outliers, the speed remained uniform.

Additionally, whereas a tube with liquid may have many millions of molecules, this simulation only dealt with up to a few hundred agents. Thus, there may have been insufficient population density to exert the desired effect in the tube. It is also likely that the constants governing the repulsion of agents diverges greatly from the corresponding electromagnetic constants for molecules. Given the overhead of simulating each agent, it would be impractical to extend the simulation beyond a few thousand agents.

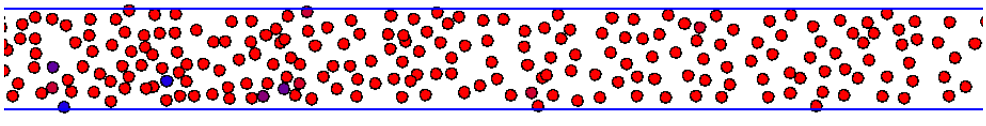

Figure 6.1: Agents traveling through a tube.

6.2 Aperture Test

The case with the one meter door proved to be extraordinarily slower than the other test cases. Contention for the exit was fierce. After 20,000 time units, there were still two agents who had not yet evacuated. These two would not let each other through the door. In addition to inter-agent forces, we suspect that the edges of the walls in the doorway were exerting a repulsive force that contributed to keeping the agents out of the door aperture.

Surprisingly, even with an aperture of ten meters wide, arching was observed. We conclude that the arching phenomenon was exacerbated by our slowing down the agents when they are approaching their waypoint. While this makes attaining waypoints easier, it also means that the agents are slowing down right at the bottlenecks. In effect, they are making the bottlenecks worse and extending the arching beyond what one would predict.

As the size of the aperture increased, the rate of evacuation steadily improved. One thing we did observe was that after successfully passing through the door, there was still opportunity for contention at the safe point. In this experiment a relatively short line served as the safe point. The final simulations ended up with dozens of agents fighting to get into the safe zone. As before, the slowing down of the agents made this waypoint a bottleneck as well. Thus, the completion times of the larger aperture tests were skewed by having not one, but two potential bottlenecks. It was noted, however, that the speed of agents between bottlenecks appeared to be virtually uniform, similar to the tube experiment.

To test the theory that the waypoint slowdown was causing excessive arching and contention at waypoints, we ran the simulations again with the slowdown disabled. The simulations used the same random number seed and all initialization parameters were identical to those in the case with the slowdown enabled.

As shown in figure 6.2, the elimination of the slowdown expedited the evacuation. The average factor of reduction was 3.42. However, in the two meter case, the value does not take into account two agents who had reached a steady state at either side of the doorway. Had we introduced slight random variations in the values for radius or mass, it is likely that this would not have occurred.

Arch formation of consequence was noted for up to the four meter door size. Figure 6.3 shows arch formation in the simulations with a 1-meter, 2-meter, and 3-meter doorway respectively. Each screen capture was taken at roughly sixty time units. For the simulation with a 6-meter door-

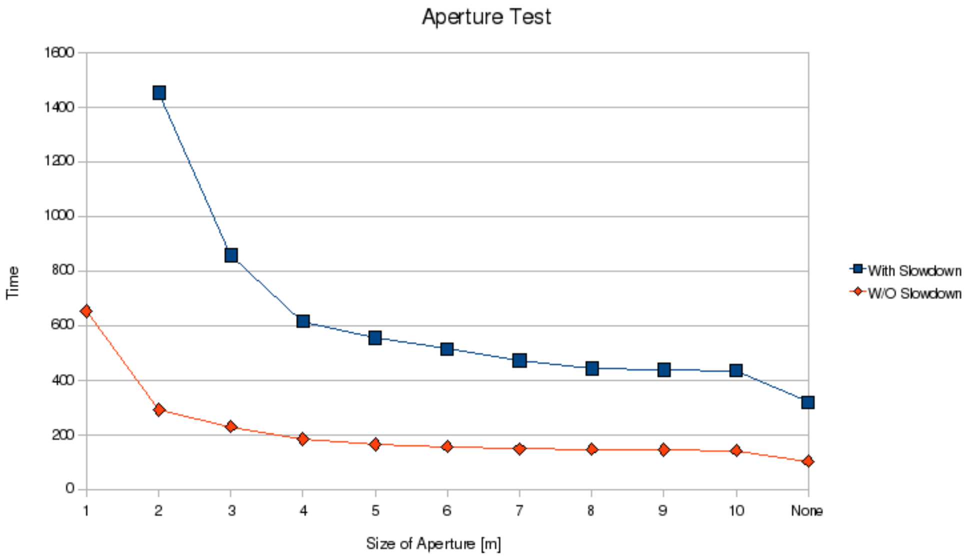

Figure 6.2: Effects of increasing door size

way, arching was not evident. However, it is likely that had there been more than 100 agents to evacuate, arching would still have occurred.

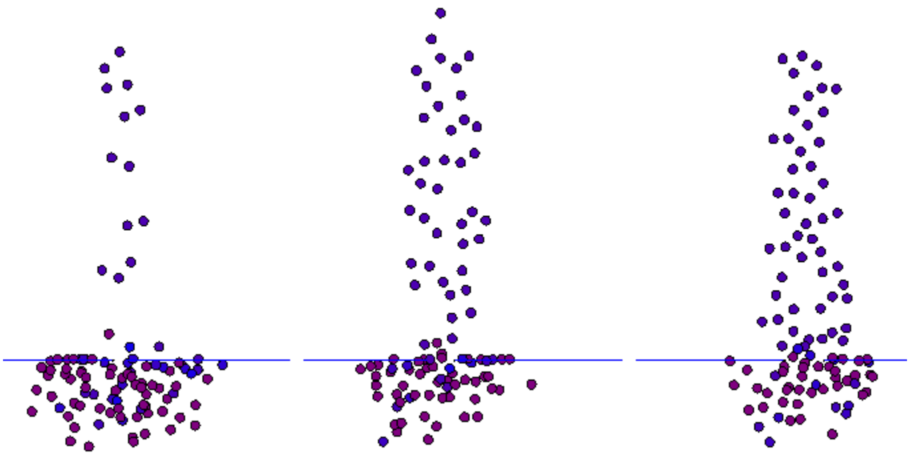

Figure 6.3: Arch forming in 1m, 2m, and 3m doors respectively

6.3 Designated Buddy

In the test runs of this experiment, we observed an interesting behavior for some pairs of agents. For most pairs of agents, they traveled, as expected, at the same speed. However, for certain pairs, the person being helped lagged behind causing the helper to continually travel back to help. After much investigation, we found that the helping person had a desired velocity of 5.0 meters per second, whereas the agent being helped had a desired velocity of about 0.5 meters per second. Thus, even though the agents' mobility values were averaged, one agent merely didn't want to go faster. The cause for this bug is that the help pairing occurred when the agent was slowing down for a waypoint. After the pairing, the agent was no longer following waypoints, but an agent's position. Thus, the agent never reset its desired velocity to 5.0 meters per second. We corrected the bug, but the behavior of the agents is somewhat reminiscent of an observable human behavior. If a person becomes tired, he may not want or be able to travel as fast as the person that is helping him. While we have been treating mobility and desired velocity as separate variables, their interaction suggests that combining the two would be possible. However, we could instead keep the variables separate using mobility in a physical sense, and desired velocity in a mental sense. Thus, mobility would represent the proportion of the maximum velocity that the agent is physically capable. Desired velocity would then represent the velocity that the agent is willing to perform.

For the formal runs of the experiment, figure 6.4 shows the cumulative number of agents that are saved up to each time step. With no buddy system in effect, the more mobile agents saved themselves within 175 time steps. The rest of the agents, aside from a few that had became stuck, arrived at a much slower rate to safety. The first agent with low mobility didn't arrive at the exit until time step 483, and the last didn't arrive until time 1232. In stark contrast, the simulations with active buddy systems had evacuated an average of 90% of their populations by time step 483. Random placement, instead of close placement, did not appear to add considerably to the time to evacuate. Although the agents saved some time by having each other close, the important fact is that they always knew where each other were and could reach them quickly.

Unfortunately, some agents still managed to get stuck. When an agent is en route to help another agent but is blocked by a wall, currently their only option is to wait for the agent they're pursuing to come out from behind the wall. In the mean time, they continually try to move through the wall or bounce around an find a doorway by luck. On the other side of the wall, the agent needing help is, by design, unaware of a nearby helper and continues their normal course of action. A better method would be to calculate which waypoint that the helping agent knows about is the closest one, and then create a path of waypoints to follow, guiding the agent from its current position, closer to the agent needing help.

Additionally, a helper agent and the agent being helped could still maintain a helping relationship with a wall between them. Thus, neither of the agents would be able to move away

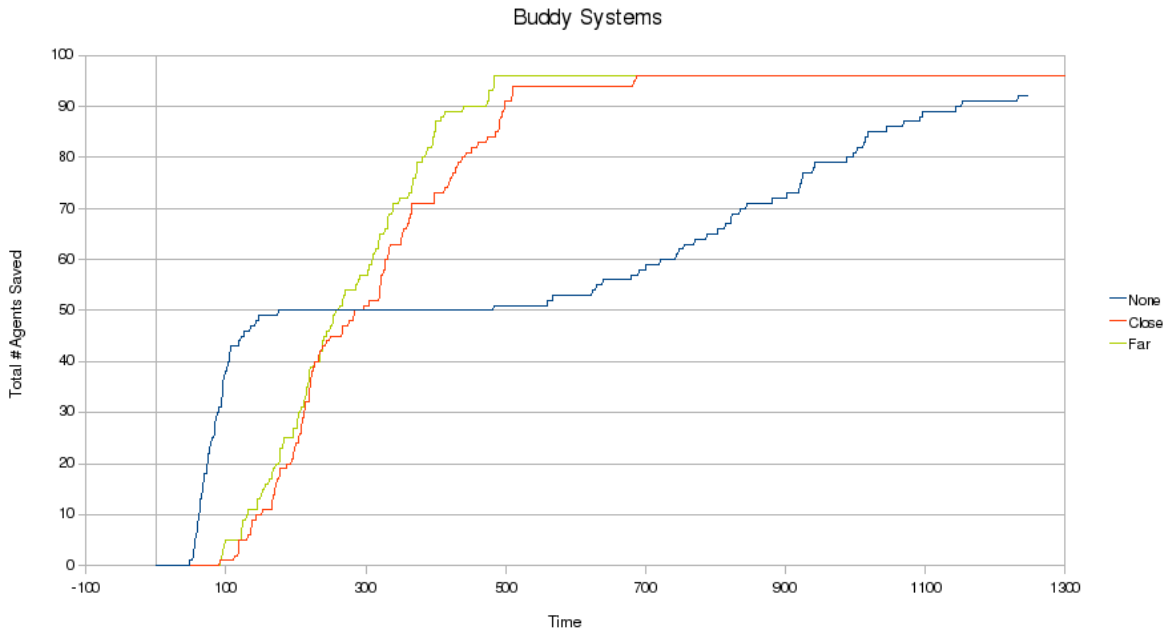

Figure 6.4: The effects of designated buddy systems.

from the wall. This rare effect occurs when a pair is attempting to navigate through a doorway. The agent being helped makes it through the door, but the helping agent doesn't. In most cases, the helping agent, who leads the other agent, passes through the door first. However, if the agent needing help is already at the door when the helping bond is formed, then this problem is more likely to occur.

This set of simulations revealed another problem. It is possible that contention around a waypoint can lead to an agent fulfilling a waypoint only to be pushed back into a position where they cannot reach their subsequent waypoint. One solution to this problem might be to periodically recalculate which waypoint the agent should be using. However, we suggest that this calculation should only be done if the agent's position has not changed substantially after a specified number of time units.

6.4 Buddy Discovery

As figure 6.5 shows, the number of pairings decreases relatively slowly with decreases in the value for altruism. The number of pairings includes both original helping relationships formed as well as helping relationships resumed when agents became too far apart. Each line shows a reduction in altruism of a factor of ten, while the resulting number of pairings between the lines varies from 21% and 74%. The reason for this behavior is that for each time step, and for each agent, a random number is chosen in the interval $[0, 1]$. The number is compared to the agent's altruism value. If the random number is less than the altruism value, then the agent chooses to help another agent if one is available that meets the specified criteria. Thus, even a relatively low value for altruism is likely to result in the agent providing help. To prevent an agent from merely being a designated helper, the agent must have a very low value for altruism to overcome the large number of random choices being compared.

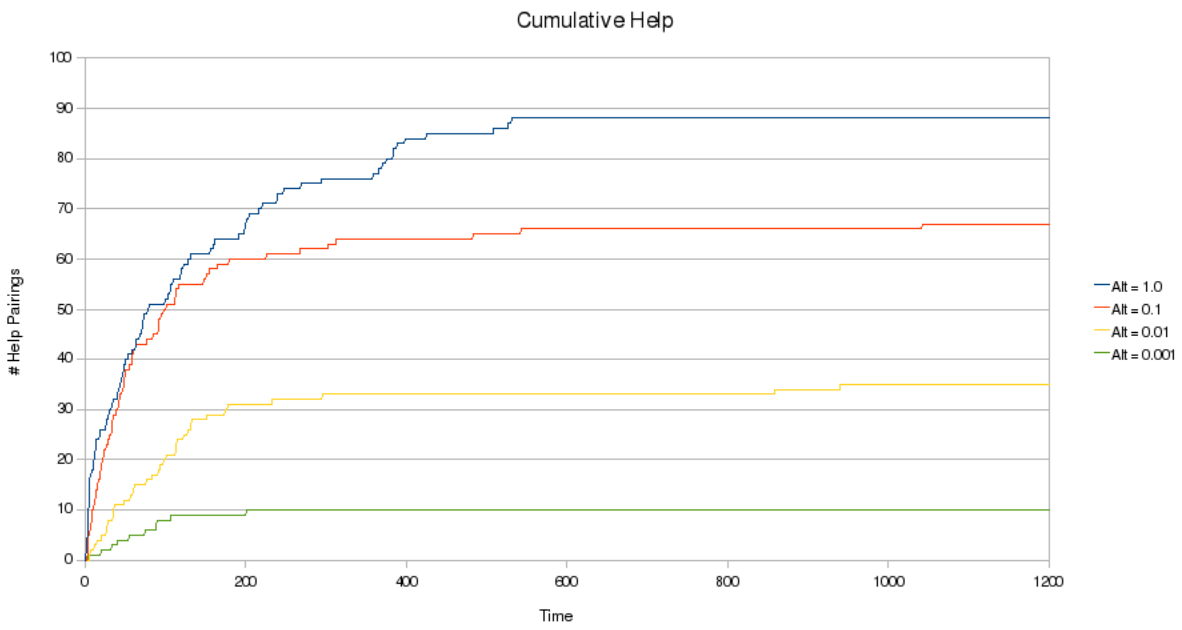

Figure 6.5: The effects of altruism on the number of help pairings

Figure 6.6 shows the effects of family preemption on the rate of evacuation. We expected that people helping their family members instead of a more needy person would contribute to a slower rate of people attaining safety. For both values of altruism, the lack of families did appear to contribute to a higher number of agents becoming safe. However, even though the agents favored their family members first in choosing a needy person to help, we did not notice a significant difference between the the non-family runs and the family-based runs.

When compared to the case of no agents being helped at all, the only run to perform on average worse at most time steps was the case where we had an altruism value of 0.001 and people were prioritizing their family members. The rate of family members fleeing in pairs mirrored the single people fleeing. However, since the altruism value was low, people only rarely chose to help someone outside their family even if they had no family members needing help. Thus, this shows that it is important to encourage both helping family members as well as helping those people outside one's family.

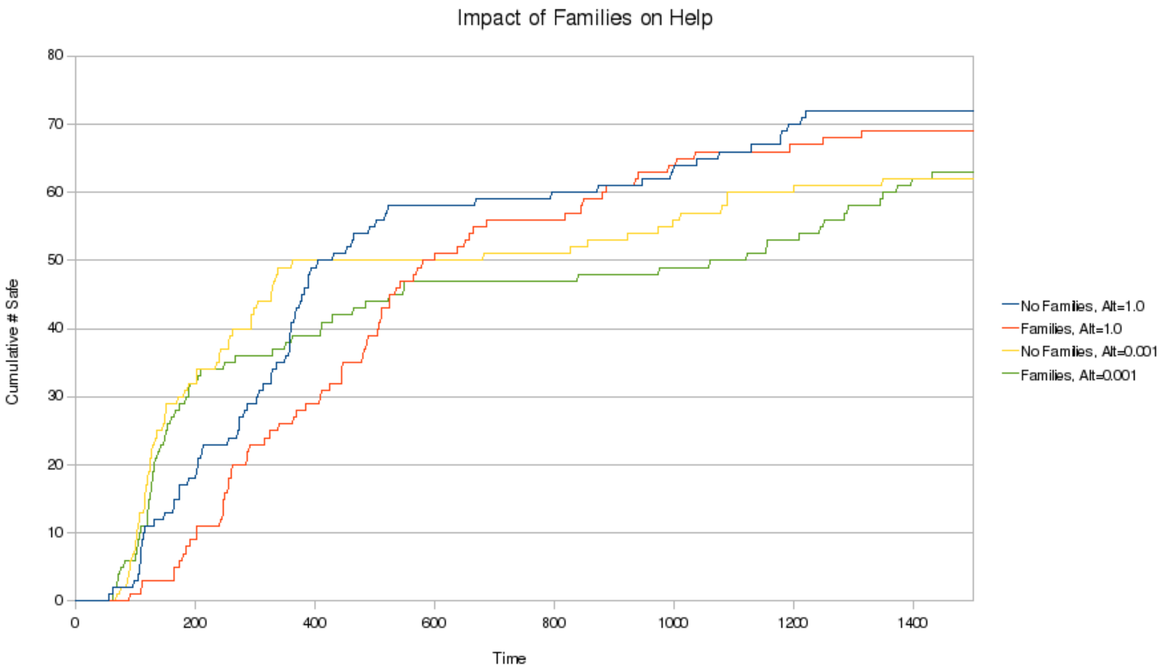

Figure 6.6: The effects of family preemption on help

Agents in all runs occasionally produced some undesirable behavior. The new such behavior that became evident in this group came from the introduction of the rotated hotel structure. Without waypoints to guide the agents around the sharp rotated edges of the structure, some agents became stuck when moving along the wall towards the entrance at the top of the hotel. Also, agents moving down the wall could encounter an equilibrium with agents trying to move up the wall. Furthermore, we witnessed agents passing through an entrance that they did not know about only to travel to the interior side of the entrance of which they were aware. We think that by performing a periodic calculation for the nearest waypoint may lead the agents to find safety quicker.

One disturbing behavior that we noticed is that agents would often pass a valid entrance to the hotel, and thus the safe zone, in favor of pursuing their designated entrance. This is not a bug. We designed the agents to move along a single set of waypoints. We did not enable the agents with any path discovery capabilities. However, the reason we find this behavior disturbing is that it mirrors some forms of human behavior. In panic situations, people are not always capable of thinking rationally and exploring their alternative paths to safety.

Chapter 7

Emergent Behavior

At various stages of development and during certain input values, the simulator exhibits some undesirable emergent behavior. If the agents are not set to slow down for waypoints, they occasionally enter into stable planetary orbits around a waypoint. For the orbits involving multiple agents, these orbits are even apparently stable with different masses, radii, and trajectories. It is possible that the timing, speed, and positions of the agent orbits prevents significant disruption from the repulsive forces between the agents which are based upon distance. The waypoint where orbiting usually occurs is at the one that designates reaching safety. Point and line waypoints have been used with similar results. Having an area waypoint might alleviate this problem.

An additional problem involves agents becoming stuck behind obstructions on the map. Without any path knowledge, the agents frequently became stuck at a simple wall. Drawn only by the attractive force of a destination beyond the wall, the agents merely kept bumping against the wall. With the introduction of waypoints to guide agents through the bottlenecks on the map, agents moved toward their waypoints in the order specified. If the waypoints were specified correctly, then the agents did not get stuck behind a simple walls with exits that can be approached directly. Rotated walls, such as those on a hotel structure, provided more of a problem. Some agents were designated to use the entrance on the far side of the rectangular shape and had to navigate clumsily around the shape. More complex maps would likely result in other similar behaviors. Under the waypoint system, the burden of specifying useful waypoints falls upon the simulation designer. If the agents had a more intelligent path-finding algorithm, much of that burden could be eliminated and the results might be more interesting.

Occasionally, agents would also enter into steady state relationships around bottlenecks in the map. This occurred more often around small doorways with agents of similar size, radius, and mass. A pair of agents would end up on either side of the doorway, each trying to get through, but being repelled by the other agent. Similarly, if two similar agents were moving slowly along a wall in opposite directions, they could prevent each other from passing. In a particle-based system, the forces can become balanced resulted in a relative equilibrium.

Lastly, altruistic agents could enter into problems trying to help other agents. This occurred in two forms. First, multiple agents with identical values for mobility would try to help each other resulting in a help cycle. The first agent would follow the second who would be following the third. This resulted in an orbiting following motion. The second type of help problem occurs if an agent had the lowest mobility value, and the helper agents were set to help the neediest person first regardless of distance. Naturally, all of the helping agents would navigate toward the neediest person, contending to be the person who gets to help. However, by design, only one agent is allowed to help. Thus, the remaining agents are left to navigate to the second most needy person and so forth. Adding a strict distance limit on people to help improves the situation. However, this change has the potential to filter out needy agents that are not nearby.

One benefit of particle-based simulation is that complex behavior can be produced through specifying only a handful of forces. However, while it is acceptable for actual particles to reach equilibrium or exhibit orbiting behavior, we do not find such actions generally desirable in simulating evacuations. As such, we added additional code to the agents to make their movements more realistic. For example, we set a limit on the maximum velocity possible for the agents. Additionally, we made improvements that added individuality to the agents resulting in behavior that is quite different than particles. For example, an agent could choose to be attracted to or repulsed from the tsunami. We believe that such hybrid approaches, including both particle and individual influenced behaviors, show promise for evacuation simulations.

By adhering solely to their one known exit path, agents increased contention at some doorways while ignoring alternative exits. While we believe that a person is more likely to use the path to safety that they are most familiar with, the algorithm should be improved with path discovery capabilities. We believe that through drills with real people, that one could calculate how often a person uses their known path versus how often he engages in path discovery activity. Such an exercise might involve having the people navigate through a maze with monetary prizes at various locations. The users could be given the choice between using a known path to a small amount of money, or finding a path that leads to a potentially much larger amount of money. A time limit would give the people a sense of urgency in completing their task.

Chapter 8

Conclusions

Human behavior is an exceptionally complex phenomena. However, under certain circumstances crowd behavior can be somewhat predictable. Helbing [8] noted that low density crowds dynamics bore similarity to gases whereas high density crowd dynamics shared similarities with fluid motion. As such, a particle-based system for simulating agents can be a useful tool for modeling the interactions of a large number of agents.

We used a modified form of Helbing's social force model [8] treating agents as particles reacting to attractive and repulsive forces around them. We applied this model to the problem of evacuating agents from a beach in preparation for tsunami inundation. Our simulations showed that instituting a buddy system can greatly improve the efficiency of evacuations. This result requires that the helping agent must know where their buddy is and that he should evacuate when a tsunami warning is issued. We presume that if the location of their buddy is not known, then the time spent in locating the buddy would result in a slower evacuation.

If a person has the choice between helping a family member and helping a stranger, we believe that the person would choose to help the family member. In our simulations where agents faced this choice, the altruism of the agents played a significant role in the rate of people reaching safety. When the altruism value was low, people only rarely chose to help someone outside their family even if they had no family members needing help. For agents with a high altruism value, this resulted in a greater number of people being evacuated. We found that the best result occurred when people found someone near them needing help regardless of whether they were a family member or not. However, we believe that the best practical solution would be to encourage people to not only help their family members but also community members in an evacuation.

In conclusion, we believe that an honest appraisal of human behavior would show that casualty in such disasters as a tsunami is inevitable and must be expected and planned for. That is not to say that the amount of injuries cannot be mitigated. What we are saying is that people are well known for being in the wrong place at the wrong time.

Chapter 9

Future Work

In the future we hope to include more advanced path planning and path discovery. Currently, exit paths are built from successive choices of waypoints that represent key bottlenecks on the map. For example, at initialization, an agent may receive the waypoints for a door in the seawall, then a door for the hotel, then a safe spot within the hotel. The seawall and the hotel represent two distinct tiers of waypoints. Our current implementation assigns each agent a single path through to safe zone. We assume that each person is capable of figuring out one path to safety in fleeing a tsunami. However, as some of our simulations have shown, the paths known are not always the most efficient.

By path planning, we mean developing an algorithm that will run at initialization to provide agents with a waypoints to guide the agent past both bottlenecks and obstructions. These would represent known paths. One avenue that we could look at for path planning is to assign agents to waypoints according to the frequency of use for the exits of a particular structure. For example, most people are familiar with the main entrance to a location. It is likely that far fewer people know where the emergency exits are located. For path discovery, the agents should be enhanced to be able to find their own paths to safety if they become stuck. We believe that by adding these capabilities to the simulator agents will take more efficient paths and become stuck less frequently.

Another area of possible future work would involve observing the effects of dedicated helpers. These helpers would continually guide agents from the danger zone to the safe area. Actually, the code for this has already been implemented. However, this class of agents requires more advanced path planning than the regular agents. We have not yet developed the path planning capability for the dedicated helper agents to continually navigate back and forth past obstructions on the map.

Additionally, this simulation would benefit from the realism provided by GIS map data. Combined with some projected tsunami run up data, the GIS data could be used to initialize the tsunami event in our simulator. If city administrators conducted studies, they could determine the appropriate values for the agent attributes such as altruism, awareness, and mobility. These values could be obtained by psychological testing, canvassing of neighborhoods, and through evacuation drills. All of these additional data sources would likely improve the accuracy of the simulation.

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