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Emergency Evacuation Robot Design

Paul Robinette and Ayanna M. Howard
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332
probinette3@gatech.edu; ayanna.howard@ece.gatech.edu

ABSTRACT

In this paper, we discuss an initial design of a multi-robot emergency evacuation system inspired by current emergency notification standards. It is intended for these robots to be stored in large buildings that are unfamiliar to a majority of their occupants, such as malls and convention centers. In the system design, robots are designed with a heterogeneous set of capabilities, depending on their role. The system of robots as a whole will take input from a human operator so that evacuees are guided to the best exit. Behaviors include tasks such as searching for an injured person or circling around the environment to catch “stragglers”. The robot gives both audio and visual instructions to any humans in the area. The four roles in the multi-robot evacuation system include rescuer, leader, aider, and notifier. Two possible robot designs have been created.

In our design, we have augmented methods developed for emergency personnel to create rules and standard notification protocols to help emergency evacuation robots maintain trust and safely evacuate people in emergency situations. This results in minimizing the risk to emergency personnel, while successfully increasing the safety of individuals. The robot models and behaviors will be tested by placing users in a simulated emergency environment and recording their actions.

Key Words: emergency evacuation robot, alarm, guidance

INTRODUCTION

When the ground is shaking from an earthquake or the roof is torn off by a tornado it can be difficult to know the safest route to evacuate a building. Emergency personnel are rigorously trained to recognize dangers and safely guide people to an exit, but they can take several critical minutes to arrive on the scene. Signs and alarms can alert people of danger and guide them to an exit, but these static devices have no current knowledge of the safest exit. Most buildings do not even have the ability to differentiate between an evacuation emergency and an emergency where it is better to shelter in place.

Emergency evacuation robots, however, can be stored in buildings and activated along with traditional guidance and notification techniques. This project has designed methods that such robots would use to direct humans. Specifically, the research focuses on how evacuation robots indicate direction of travel for humans and how the robots should behave in order to attract human attention and trust. Individual robots use simple rules inspired by swarm intelligence to determine to what extent they follow operator commands and to what extent they exhibit other behavior.

BACKGROUND

We begin by discussing four components related to emergency notification standards. Understanding of these features were used to create the robot models and behavior, as discussed later.

2.1 Exit Sign Design Constraints

There is considerable debate about the ideal design of exit signs. A NIST report [5] exhaustively covered several experiments on exit sign visibility, especially during smoky conditions. They then performed their own experiment using twelve signs consisting of varying levels of luminosity, different colors (red and green), different backgrounds, and different font styles tested by twenty-one observers. Their experiment confirmed some previous studies which found that luminosity is a large factor in visibility (some of their observers suggested it is the largest factor). Most of the results were inconclusive, with some observers preferring one particular style and others preferring another. Some recommendations were possible. Signs should have a luminance of 70 cd/m^2 and should be actively lighted as glowing material was insufficient to penetrate smoke. Signs with illuminated, stenciled letters and a solid background were preferred over those with a lighted background. The color red was preferred to green, however the authors mention that this could be due to a variety of reasons, including familiarity with the color and differing brightness. The color is in conflict with some of the sources cited in the NIST study, so more research is necessary here.

The NIST study also pointed out considerable variations among various national and international standards bodies. Some have specific minimum and maximum luminosity requirements while others have no such requirement. There is considerable variety in the sizes required for the letters and the spacing between the letters. Different countries also have different color standards, with some preferring white on green, some green on white and some red on white. This project conforms as closely as possible to US guidelines and de facto standards for the purposes of familiarity.

A 1985 study evaluated several different exit signs in use at the time, but did not reach many conclusions despite testing in normal conditions and smoke [11]. They determined that color, brightness and size of the sign mattered, but could only recommend that signs be as large and bright as possible. They found that exit signs in North America were usually red while those in Europe were usually green. Green signs typically allow for a greater luminosity, but easy recognition is also important, so the study could not give a firm recommendation on color.

Exit signs also must consider individuals with disabilities. This is one area where robots could be a great benefit as they can approach those with sight problems. A study was performed [3] where people with disabilities in an assisted living environment rated the visibility of various exit signs. A sizable minority of these people had vision problems. This paper had some surprising results as it shows that there is a small difference between the distance at which people with visual impairments can recognize an exit sign (mean of 13.9-14.6 meters depending on the sign) versus those without seeing disabilities (14.5-14.7 meters). The study found that people can recognize an exit sign at a point several meters past where they can read the word. This confirms that the robots should use a familiar sign to guide people.

2.2 Panic Models

Several studies have been performed on how people react in emergency situations. One of the most interesting studies interviewed 128 survivors from a fire in the Solarium of the Summerland Leisure Complex in 1973 [14]. Sime found that individuals with strong ties to a group were less likely to panic and try to escape in a selfish way than previously thought. He found that families and groups of friends were more likely to make escape choices that were optimal for the group as a whole. Sometimes, particularly tight groups would exhibit this behavior at great personal risk. One example of this would be a parent refusing to leave a burning building without his/her child. This study showed that some families that were not together at the onset of the emergency still found each other and were grouped at their exit. The affiliate behavior was greatly dependent on the closeness of the group. Families were much more likely to stay together, close friends somewhat less and casual acquaintances (such as those who met at the resort) were unlikely to stay together at all. This research can help in determining how robots should behave in order to evacuate affiliate groups together.

Another study analyzed video of crowds panicking during the 2006 Hajj in Mecca, Saudi Arabia [7]. The researchers plotted the position and velocity of each person in the area immediately in front of a bridge entrance. From this, they determined when the crowd transitioned from laminar to stop-and-go or turbulent flows. Using this data, they made several recommendations to the Saudi Arabian government to improve the flow of pedestrians and reduce the number of casualties. These recommendations included making certain pathways one-way, discouraging stops on walkways, and tracking the number of people in each area.

A final study experimented with which exit individuals chose in a simulated emergency [1]. Benthorn recruited volunteers and had them test an emergency situation at an IKEA store. Each volunteer was given a headset which played an alarm and gave instructions to evacuate as quickly as possible. The study found that when a volunteer could see closed exit doors nearby the individual still preferred to go out through the front of the store, but when a volunteer could see an open exit door (such that the person could see outdoors) then the individual was more likely to take it regardless of distance.

2.3 Aircraft Evacuation

Several experiments have been run to determine how people evacuate airplanes during emergencies. Muir has performed many tests with over one thousand paid volunteers to discover how people behave during an evacuation. During one test, the researchers tried several different aisle widths in front of the wing exits [8]. They determined that wider aisles (up to approximately 20 inches) allowed more people to evacuate. Greater than 20 inches of width and the aisle became wider than the exit itself, so evacuees assumed that more than one person could leave at a time. This was not possible due to the width of the exit itself, so this caused a bottleneck in the exit row. Muir also examined what happened when volunteers were given extra incentive to evacuate quickly. This incentive was an additional $7.75 over their pay as volunteers if they could be among the first 50% to evacuate. For over the wing exits, this actually increased the mean time for evacuation. Some volunteers would push through bottlenecks to get out faster, which only delayed the group as a whole. Volunteers would also climb over seats (the authors note that not all seats were empty) to jump ahead in the line. This selfish and somewhat irrational behavior complements Sime's work in determining when groups work together to evacuate.

2.4 Search and Rescue Robots

Considerable research has been done on using robots for search and rescue applications. Bethel and Murphy studied how volunteers reacted to rescue robots in a simulated urban disaster [2][9]. They created several recommendations for how robots should approach, contact and interact with the victims. For the approach and other motions, the researchers suggest using smooth acceleration and deceleration. In contrast, typical robots are usually jerky when moving in an unknown environment. The researchers also suggested using blue lighting around the robot to convey a sense of calm. For interaction, they note that there are several different “zones” where the robot can be: the intimate zone (0 to 0.46 meters), the personal zone (0.46 to 1.22 meters), the social zone (1.22 to 3.66 meters) and the public zone (further than 3.66 meters). Robots are assumed to stay in the social zone or closer. To communicate, the researchers assumed that the robots would have to be in the intimate or personal zones. They suggested using voice communication to reassure the victim and music when there is no information to communicate.

EXISTING SYSTEMS

Mass evacuations of buildings are rare, so it is impossible (as well as unwise) to study one as it happens. It is possible to observe fire drills, but it is unlikely that people respond to a drill in the same way as they would to a real emergency. As such, existing work has focused on how humans act in emergency situations. Recently, there has been a considerable effort by government and private organizations to improve emergency evacuation plans [12]. Some robots have been designed to guide visitors in museums, but their lessons are unlikely to apply to emergency robots [4].

3.1 Existing Emergency Systems

In a fire emergency, evacuations are usually triggered by alarms. These alarms have an audible component (usually a horn or a voice) and a strobe light. The functional purpose of the system is to provide notification and guidance to facilitate an evacuation in a fire emergency. The measures of this is the time it takes to respond to the notification and the time it takes to evacuate. The goal of the system is to minimize both of those measures. To do this, the system must provide notification and guidance. Currently, guidance is only provided visually through exit signs, but notification is provided visually and audibly using fire alarms. According to the Boyce study [3], the exit signs have a maximum visibility of approximately fifteen meters and, according to the NIST review [5], this is greatly reduced as smoke fills the room.

3.2 Evacuation Plans

Due to increased disaster preparedness, most organizations have published guidelines for evacuation. Georgia Tech's guidelines (Figure 1) are a good example [6]. On the surface, it appears that these recommendations are simply common sense. The first step is to remain calm, the evacuation step is in the middle and at the end the evacuee is told to wait for further instructions from a safe location. This sequence is clearly tailored to engineers, however, because step two is to safely stop work. This accounts for situations where a researcher is running an experiment that may be more dangerous if left unattended than the potential for being trapped in a fire. The evacuee is also told to gather belongings if possible. At the end, the evacuee is told to wait at a predefined staging area. Most of the evacuees will be familiar with the area, so they should have some knowledge of the location of exits and staging areas.

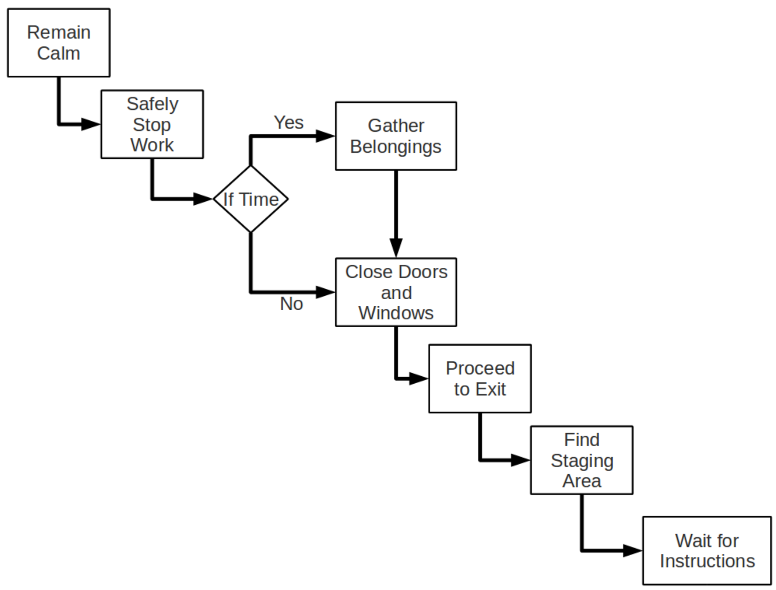

Figure 1: Georgia Tech Evacuation Procedure

We have modified this sequence to become more generic (Figure 2). Assuming that the evacuees can easily see an exit sign when the fire alarm sounds (or if they happen to know the building well) then this is an easy process to follow. If they cannot easily find the exit then they must look for one. This has the potential to form a loop where the evacuee is continuously looking for an exit sign. Too many iterations of this loop and the evacuee will panic.

3.3 First Responder Model

A sequence model for first responders can be created (Figure 3) based on guidelines issued for evacuating individuals with disabilities [10]. The responder must first search the building for people to evacuate. If the immediate danger is low, then these people can simply be directed to an exit. If the danger is high, then the responder must either guide people to the exit or, if they are not able to move easily, the responder must carry the individuals to safety. It can take several minutes for any responders to arrive at an emergency and even longer for them to search the building. During this time, the situation can become very dangerous, for both the individuals inside of the building and for the responders.

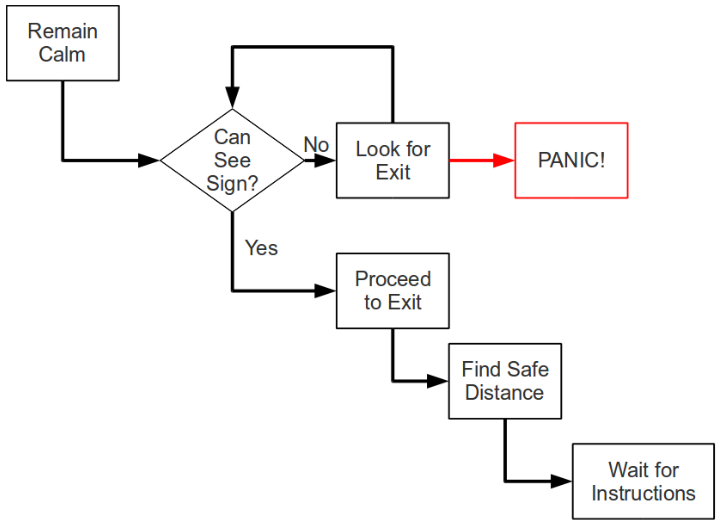

Figure 2: Generic Evacuation Procedure

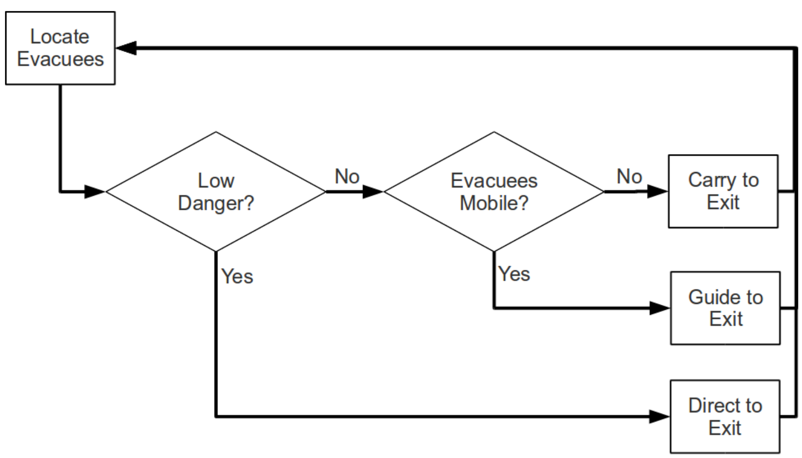

Figure 3: Emergency Personnel Procedure

ROBOT DESIGN

Using the analysis and reviews above, a new system has been designed to notify and guide people out of buildings during an evacuation. The robot adds an audio guidance component and supplements all other guidance and notification components. Using this robot, people do not have to rely on a clear line of sight to the nearest exit sign. The notification components are also improved by giving more information about the situation to confused evacuees.

4.1 Notification Methods Prototypes

Based on the literature review and a work domain analysis, two prototypes were developed for the exterior of the robot. The first robot (Figure 4) is designed with three sides. The rear side is designed to be noticeably narrower than the other two so that the robot's forward direction is clear. The three sides of the robot are nearly identical, except for directional arrows. The robot is at least as tall as an adult human so that it can be seen in a crowd. Each of the top three corners have a downward facing light to illuminate the area around the robot. These are very bright to help evacuees see where the robot is and where they are going. Flashing lights and strobes have been avoided as the evacuees are expected to look at the robot as they follow it to an exit.

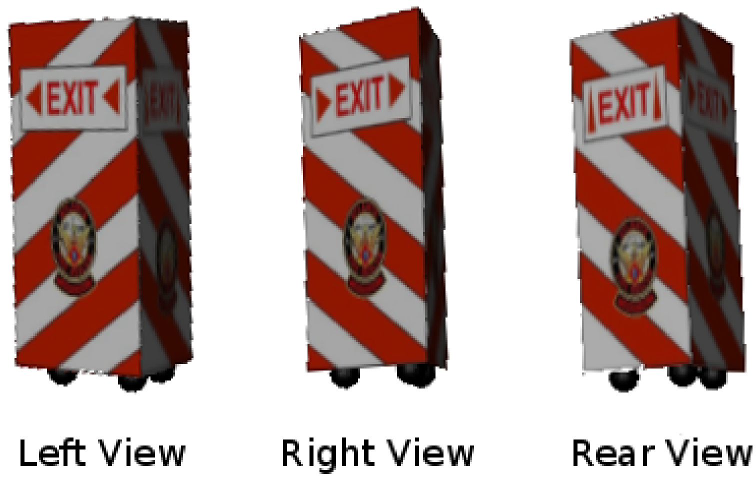

Figure 4: First Robot Model

The most important aspect of the design is the static display featured prominently towards the top of each side of the robot. This is shown in the diagram as a standard North American exit sign. The color and style of the sign should be changed based on the location of the robot. In Europe, this should be a green sign with a figure heading towards the front of the robot. All signs, regardless of style, have directional arrows pointing towards the front of the robot. It is assumed that the front of the robot will always be pointing towards the best exit path. The exit signs are illuminated brightly from behind, but not so brightly as to blind people within a meter of the robot.

To encourage trust, the robot is designed with red stripes to make it resemble a fire truck. The robot will need approval from national and local fire safety organizations, so showing their logos as big as possible will show evacuees that the robot is an approved evacuation device. If possible, the local fire department should put their logo on it as a seal of approval.

A second robot model (Figure 5) was created after receiving reviews from other researchers. The changes in this robot were motivated by concerns that the first robot looked like a static sign when it was still, rather than a dynamic robot. The same white and red colors are used, although the stripes were not included in this model. The robot has “EXIT” written twice on either side of its cylindrical body with arrows pointed towards the front. There is a three dimensional arrow on top also pointing towards the front of the robot. This arrow is in response to comments that the first robot model's forward direction is somewhat ambiguous. “Emergency Evacuation Robot” is written along the back to make the robot's purpose very obvious.

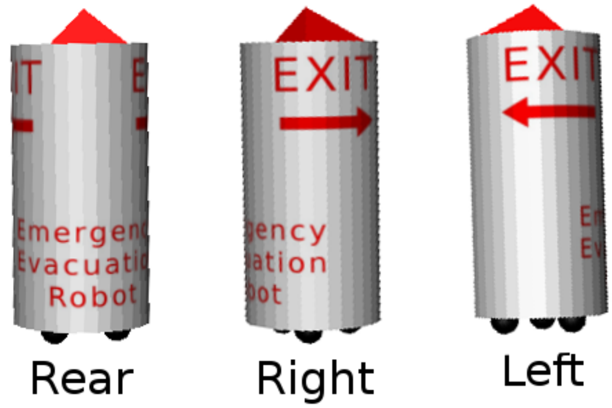

Figure 5: Second Robot Model

4.2 Robot Behaviors

Robot behaviors are broken into four different modes: rescuer, leader, aider, and notifier. The robots switch between modes as the needs of the situation change. All robots, regardless of mode, must behave in a way that encourages people to accept and follow them during an emergency. All robots will make audio announcements to notify people of the emergency, instruct people on the best course of action, and inform people of any changes in the current situation. When they move, they must move in a way that reminds people of emergency workers. As Murphy and Bethel [2][9] found, jerky, unpredictable motions can scare people. The robot will accelerate and decelerate smoothly.

4.2.1 Rescuer behavior

The rescuer robots are tasked to search for evacuees. All robots start in rescuer mode and transition to the three other modes as needed. When a rescuer robot encounters a group of people, it will transition to leader behavior. When a rescuer robot finds an injured person, it marks that position for emergency personnel. If a sufficient number of robots are available for search, guidance and notification, it transitions into aider mode and waits with the victim to act as a communication device. If all incapacitated victims have aider robots, all groups have leader robots and the search is being handled by sufficient rescuer robots, then the robot will move to a strategic point and transition to a notifier robot. If a dangerous area or an area with great uncertainty of safe direction is found, the robot will transition to notifier behavior.

4.2.2 Leader behavior

The leader robots focuses on utilizing models of human behavior to enable the robots to indicate the travel direction for dispersed crowds of people and allow it to attract human attention and trust. The leader attempts to stay within the social zone of nearby people and direct them to the best exit. Once the group following the robot exits safely, the leader converts to rescuer mode to search for more evacuees. If multiple groups join together, some of the leader robots will transition to notifier robots so that those further down the line can know the safe direction of travel. In [13] it was found that this behavior greatly improved survival rates over no robotic assistance in simulation.

4.2.3 Aider behavior

The aider robots wait with injured evacuees and attempt to render what aid they can. At the current state of robotic technology they simply act as a communications conduit. An aider robot also keeps track of the victim it is tasked to help and communicates his or her current position to emergency personnel. In the future, they may be able to exhibit more complex behavior, such as carrying a victim to safety or rendering first aid. This robot will attempt to stay in the personal zone of the victim to allow easy communication and possibly even comfort. It will only transition back to rescuer mode when the victim is successfully retrieved by emergency personnel.

4.2.4 Notifier behavior

The notifier robots are left in large, open areas to function as stationary exit signs. These robots are most helpful in smoky situations where wall mounted signs cannot be seen. They audibly tell nearby people the nature of the emergency and the best course of travel. They point towards the best exit for evacuees to follow. They are also used to block exits that are unsafe due to situational danger or overcrowding.

CONCLUSIONS

By using standard notification methods, emergency evacuation robots can attract attention and gain trust of evacuees during emergency situations. Methods developed by human-robot interaction researchers as well as those developed for emergency personnel have been used to create rules to help the robots maintain trust and safely evacuate people. These robots can be stored in malls and convention centers where people are not familiar with the exits and can be deployed as soon as an emergency is detected. Fewer emergency personnel will be needed to risk their lives as these robots can be used to search the building remotely.

The next step in this research is to perform a test to determine how people will react to emergency evacuation robots. This will be accomplished by using a computer program that simulates an emergency by placing the user in a first person three-dimensional environment. The user will have the option of following the robot or attempting to evacuate on their own. The user's actions will be monitored to determine how he or she reacts to different versions of the robot design and behaviors. This simulator is in the final stages of development.

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