Effective Robot Evacuation Strategies in Emergencies

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Abstract— **Recent efforts in human-robot interaction research has shed some light on the impact of human-robot interactions on human decisions during emergencies. It has been shown that presence of crowds during emergencies can influence evacuees to follow the crowd to find an exit. Research has shown that robots can be effective in guiding humans during emergencies and can reduce this 'follow the crowd' behavior potentially providing life-saving benefit. These findings make robot guided evacuation methodologies an important area to explore further. In this paper we propose techniques that can be used to design effective evacuation methods. We explore the different strategies that can be employed to help evacuees find an exit sooner and avoid over-crowding to increase their chances of survival. We study two primary strategies, 1) shepherding method and 2) handoff method. Simulated experiments are performed to study the effectiveness of each strategy. The results show that shepherding method is more effective in directing people to the exit.**

I. INTRODUCTION

We envision robots that will instantly react to an emergency alarm by positioning themselves along critical evacuation pathway decision points to guide evacuees to the nearest, safe exit. The potential use of robots offers important advantages for evacuees. For example, robots stationed within a building whether for the purpose of evacuation or not could serve as instantaneous first responders during an emergency. Alternatively, a single robot might act to shepherd individuals or groups of people to nearby exits. Either way, robots may offer adaptable instantaneous guidance during an emergency.

Evacuation research has shown that evacuation decisions are strongly affected by crowd behavior [30]. Moreover, the people in these crowds tend to move to the same exit, causing deadly choke points. If evacuation robots could be used to guide even just a portion of the crowd to a different exit, researchers have shown that choke points are less likely to develop and much less deadly [29], [24]. Yet, a human may be more likely to follow other humans during an evacuation than the evacuation directions of a robot. It therefore becomes critical to evaluate how people respond to the directions and guidance offered by evacuation robots, how their behavior is influenced by the behavior of a human crowd, and the robot.

We seek to test and then deploy real robots for the purpose of emergency evacuation in the near-term. This paper therefore focuses on several fundamental questions associated with robot-guided evacuation. Specifically we examine two different types of robot-guided evacuation behavior: shepherding and handoffs. Shepherding is when a single robot leads evacuees to a particular exit by moving through the environment during an emergency. Shepherding requires the robot to navigate the evacuation environment, both avoiding obstacles and yet making sure that the evacuees continue to follow the robot. Evacuation handoffs, on the other hand, describe a situation in which a stationary robot uses gestures or verbal commands to direct the evacuee either to a visible exit or to another robot. The evacuee is thus 'handed off' from one robot to the next until they arrive at an unblocked exit. Because evacuation handoffs only require the robot to move to a predefined location to provide directions, we believe that this type of robot evacuation guidance will be easier to implement in real situations but are uncertain as to whether people will follow the robot.

This paper focuses on several fundamental questions that must be answered if we are to develop evacuation robots. First, during an emergency evacuation, when faced with a group of people exiting in a direction opposite the directions of an evacuation robot, which direction will the evacuee choose? In other words, do people trust the robot to provide guidance to the exit or the crowd of people? The answer to this question may provide insight into how people evaluate the authority of a robot and how group behavior influences a persons decision. Second, how do mistakes by the robot influence an evacuee's decision to follow the robot? Finally, how does the robot guided evacuation method impact an evacuee's decision to follow. Specifically, are people equally likely to follow robots that handoff versus those that shepherd?

The remainder of this paper begins by presenting related work. Because this work is exploratory, we then present our experimental setup and several initial experiments. The paper then concludes with an examination of the results from these experiments and discussion of those results, including avenues for future work.

II. RELATED WORK

There has been substantial work on the mathematical modeling of large-scale evacuations of a populace, (see [27], [29] for examples) and the references therein. However, the study of robot assisted evacuation is only very recent [23]. For example, in [34] robots were employed as dynamic obstacles near exits to improve evacuation efficiency while [4] modeled human-crowd interaction via the dynamic floor field under cellular automata and tested it by having a

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robot provide guidance to human participants in a simulated evacuation. The existing work clearly demonstrates that robots are able to speed the evacuation process. This prior research only considers single robots, while the investigation of multiple robots is still quite limited. A cooperative exit-seeking algorithm for robots is designed in [35] to guide evacuees.

A similar idea is implemented in [36] where an algorithm was developed to help pedestrians find the best exit with the shortest escape time. However, current multi-robot evacuation systems are only validated in simulation and lacking detailed coordinated motion planning strategies and human-robot interaction studies [37]. Hence, we are motivated to derive systematic methods of designing coordinated robot decision making and motion planning in human crowded environments to achieve an efficient evacuation, investigate the human-robot interaction issues associated with evacuation through real human-robotic experimental studies, and evaluate the effectiveness of our theoretical and experimental results by creating a coordinated multi-robot evacuation system and conducting field tests.

Researchers have studied human evacuations extensively to understand human behaviors in high-stress situations [20], [27], [14], [19], [30], [13]. Interestingly, Kuligowski [30] found that panic rarely occurs during emergencies. Instead people tend to form and follow crowds in a calm orderly fashion which goes against common belief.

Following a persons (or a robots) instructions during a high-risk situation such as an emergency evacuation requires trust [31], [33], [9], [25]. Many different factors can influence a persons trust in a robot [28]. It has been shown that robots exhibiting human-like features such as politeness, human-like facial features and speech tend to increase trust from humans operators[10], [11]. Moreover, in spite a lack of experience with an automated system, humans tend to exhibit trust in such systems [1], [18], [32]. Trust is also influenced by the performance of the system [32]. While some studies highlight the role of the robot's performance with respect to increasing or decreasing trust [28], others have observed that humans come to quickly overtrust automated systems [12], [23], [3], [2].

A. *Crowd Behavior*

Evacuations typically involves more than one individual, hence groups and group dynamics can play a significant role in the evacuation decisions of an individual. Understanding how people will act in the presence of other people therefore, becomes important in evaluating a robot's performance if robotic evacuations are to become a reality. The psychology of group behavior is vast [26], [22], [6], [21]. Some recent research has examined the emergence of group behaviors in simulated emergency environments [8]. Others have created animated tools for communicating evacuation directions to groups [7]. Still others have focused on simulating the conditions that cause group panic during an emergency [29]. As far as we know, our work is the first to examine how people respond to when the directions offered by a robot conflict with the behavior of groups of people during an emergency. This work uses crowds as a secondary stimulus during emergencies to find the evacuation strategy with the highest impact on the evacuees behavior and human-robot trust.

III. Experimental Setup

Physical robot evacuation experiments are costly and difficult to conduct. Such experiments typically require deception in that, in order to capture a natural response, the subject cannot be told about the true nature of the experiment. Moreover, although robot guided evacuation experiments may be deemed minimal risk, often one must demonstrate that the research can be conducted safely. With these challenges in mind, we conduct large number of robot guided evacuation experiments in simulation prior to testing the most promising hypotheses on a physical system [23]. Our prior research in this area has demonstrated that exploratory simulation experiments can help inform the development of testable research hypotheses.

For this paper we used the Unity engine to create 3D simulations of an office environment, the robot, and virtual emergency bystanders. These simulations provide a realistic rendering of an office environment complete with office furniture and lighting. The Unity environment allows us to conduct human subject experiments online in reasonably realistic environments. Moreover, online experiments allow us to test a larger, more diverse population of human subjects quickly.

Participants were recruited from Amazon Mechanical Turk and self-selected by picking the Mechanical Turk task we offered. Four hundred and eighty subjects participated in the experiment. IRB approval was obtained prior to experimentation. Subjects were only allowed to participate once. They were paid $3.00 for the experiment and were removed from the pool of participants for future experiments. The study only involved participants from the USA.

Over the course of the experiment, the subject answered several survey questions. In addition to the survey data, the participant's movements in the environment, the time taken, and exit route selected were recorded. The dependent variable for this study was the percentage of study participants that followed the robot. To measure whether participants followed the robot we used the participant's motion data and final location. Participants that ended up in the corridor that the robot was directing toward were considered as following the robot. Similarly, the participants that ended up at the corridor that the avatars were running to were considered to be following the crowd. All other cases where the the intent of the participant could not be determined at the end of the emergency timer were classified under as 'other.'

This study utilized a 3-way between subjects factorial design. The variables tested were: the robot-guided evacuation method used (shepherding versus handoffs), the presence of a crowd of human avatars moving towards a different exit (true versus false), and whether or not the robot made a prior mistake (true versus false). The experimental procedure was

Fig. 1. The emergency phase with a handoff robot is depicted. The human avatars can be seen running towards an exit on the left. The guidance robot can be seen pointing towards another robot in the distance to the right. The countdown timer can be seen at the top of the image.

Fig. 2. The emergency phase with a shepherding robot is depicted. The human avatars can again be seen running towards an exit on the left. The guidance robot can be seen pointing towards a corridor leading to an exit on the right. The countdown timer can be seen at the top of the image.

divided into several phases. The following sections describe each phase in detail.

A. Introduction Phase

The experiment began with an on-screen introduction to the experiment. Next, participants were offered a practice session in which they could move around a different environment in order to familiarize themselves with the simulation's controls. Once comfortable, they proceeded to the navigation phase of the experiment.

B. Navigation Phase

In this phase, participants are placed outside a simulated office environment and offered a guidance robot to aid them in navigating to a particular meeting room. The robot used two arms attached to a mobile based to signal guidance directions. We have demonstrated the effectiveness of this approach in prior work [25]. No other method of interaction was used to influence the behavior of the participant (e.g. verbal commands). In the 'robot makes a mistake' conditions, the robot makes obvious mistakes leading the participant in a circuitous route to the meeting room. This circuitous route involves the robot moving in a figure eight around an office on the way to the meeting room. In pilot studies we asked participants to rate the robot's performance after taking the circuitous route and the majority (64 %) of the subjects rated its performance as a guide as bad in this condition. In the 'robot does not make a mistake' condition the robot guides the participant directly to the meeting room.

C. Task Phase

After reaching the meeting room the participants are told to move to a conference table in the room. Once there, the simulation presents them with an on-screen mid-simulation survey which is composed of a Yes-No question regarding the robot's performance and a paragraph space for the participants to provide reasons in support of their answer. Once they complete the mid-simulation survey and click next, they move into the emergency phase of the experiment.

D. Emergency Phase

During the emergency phase a screen is presented to the participants alerting them of the emergency (Fig. 1). A timer, initial set to 40 seconds, is also displayed. The timer counts down the amount of time that the participant has to find an exit. Depending on the evacuation strategy employed (shepherding versus handoffs), the robot's position and actions differed. In the case of shepherding the robot moves towards the person and gestures for the subject to move to an unseen exit on the right (Fig. 2). For the handoff strategy, the robot gestures in the direction of the next robot some distance away (Fig. 1).

In the crowd condition, during the emergency phase the participants also witnessed human avatars running to an unseen hallway in the opposite direction of the robot's guidance. In the condition with the avatars, they appeared as soon as the emergency occurred and always ran in a direction to the participant's left. Neither the exit to the left nor the exit to the right were visible to the participant without moving a significant distance. Both exits were equidistant from the participant's location at the time when the emergency occurs.

1) Shepherding Method: The emergency occurs while the participant is in a meeting room. When using shepherding method, the robot initially waits at the doorway of the meeting room for the participant. If the robot detects that the participants is not following, it will either stop or move closer to the participant in case the participant changes their mind and decides to follow (see Fig. 3).

2) Handoff Method: When the robot uses the handoff method, three clones of the robot are spawned at waypoints along the path to the exit. Each robot is located at different junction points leading to the exit. The first robot is in front of the meeting room looking and pointing towards the next robot on the far end of the corridor on the participants right (opposite to the directions of the crowd's exit)(see Fig. 4).

The simulation stops when the time runs out or the participant reaches an exit. The participants are then presented with a final survey.

E. Post-Simulation Survey Phase

The post-simulation survey consists of questions regarding the participant's decisions in the simulation. The questions

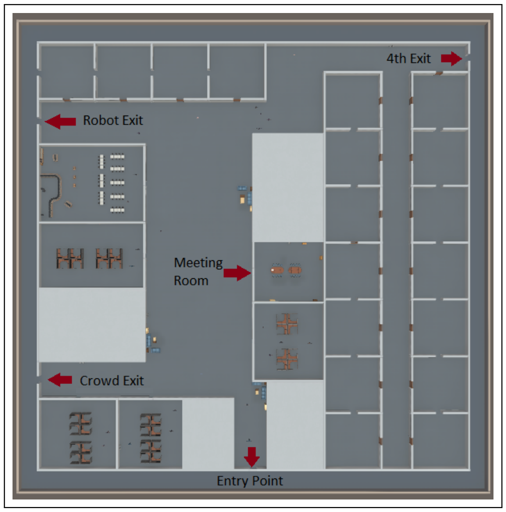

Fig. 3. A map of the environment during the shepherding condition.

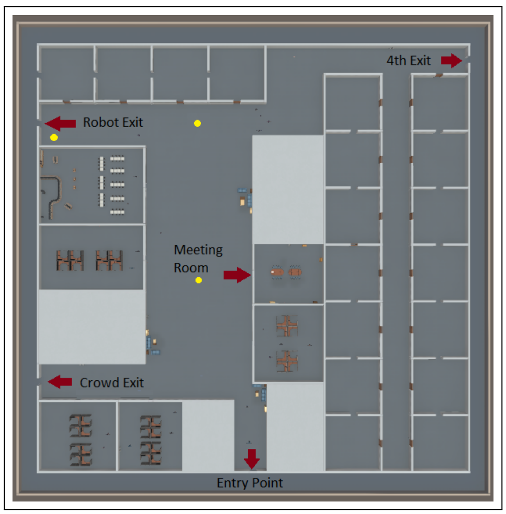

Fig. 4. A map of the environment during the handoff condition. The yellow dots denote the position of the three guidance robots.

are designed as binary Yes/No questions along with a paragraph response space allowing them to provide reasons for their responses. This is followed by a demographics survey and payment information.

IV. Results

A total of 480 participants performed the experiment with 60 participants per condition and a total of 8 conditions. The independent variables were robot-guided evacuation method used, the presence of a crowd, and whether or not the robot made a prior mistake. The data from two participants was excluded from the results because they were unable to complete the experiment. Figures 5 and 6 depict sample motion data from two of the conditions. The results from the experiment are presented in the Fig. 7 and Fig. 8.

Considering the cases where the crowd was present (Fig. 7), in the shepherding condition, with a mistake free robot, we see that majority of the participants prefer to use the robot's guidance (M=45.00, SD =6.42). When the robot makes mistakes the fewer people follow the robot (M=11.86,

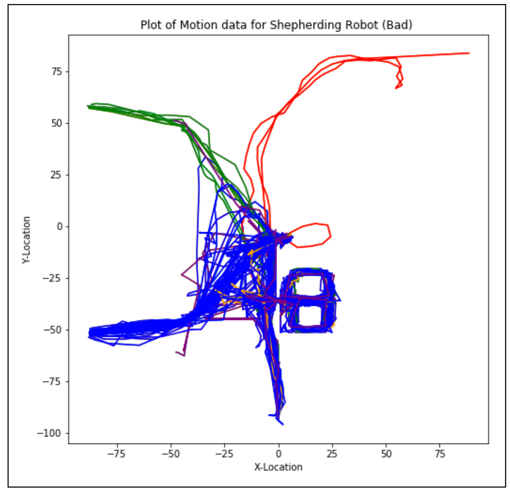

Fig. 5. The figure depict the motion data for the shepherding evacuation method, a robot that makes mistake, and a crowd of avatars moving in the opposite direction. More participants follow the robot, yet many still follow the crowd.

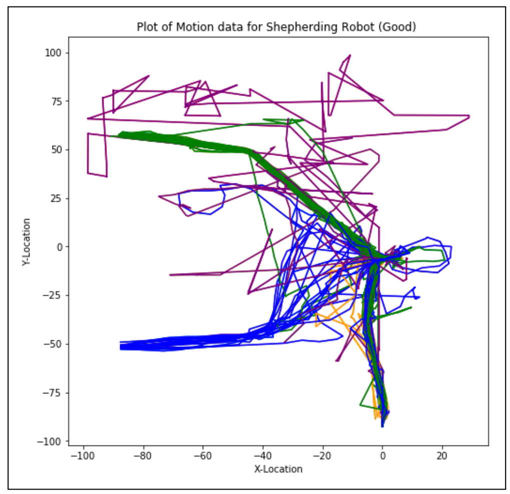

Fig. 6. The motion data for the shepherding evacuation method, a robot that does not make mistakes, and a crowd of avatars moving in the opposite direction. A significant number of people follow the robot towards the exit (green).

SD=4.2). The guidance strategy also has a large impact on the participant's decision to follow with few people following the robot in the handoff condition (M=1.67, SD=1.65 no mistake, M=3.33, SD=2.3 mistake). In fact, when the handoff strategy was used most participants followed the crowd (M=86.67, SD=4.3 no mistake, M=90.00, SD=3.87 mistake). Comparing the shepherding vs handoff conditions, the significantly more participants followed the robot in the mistake free condition ($\chi^2(2,120) = 40.16, p < 0.001$) and ($\chi^2(2,119) = 3.80, p = 0.148$) in the mistake robot case.

Since the presence of crowd may be an influencing factor in the behavior of the participant, the same experiment was run again but without crowds during the emergency. These results are summarized in the Fig. 8. For the handoff strategy, while there is a general increase in the number of people following the robot, compared to shepherding robot, fewer people follow when the handoff method is used (M=75.00

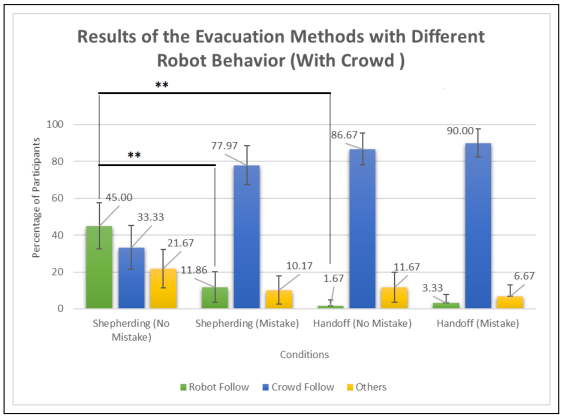

Fig. 7. Results from the influence of evacuation strategy with crowds. The four conditions are divided as groups of shepherding strategy with an efficient and inefficient robot and handoff strategy with an efficient and inefficient robot. The error bars indicate a 95% confidence interval and the asterisk indicates the significance values after running a pair-wise χ^2 test: $^{*}p < 0.01, ^{**}p < 0.001$.

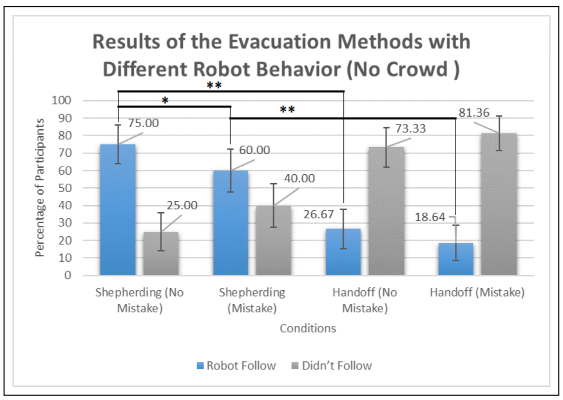

Fig. 8. Results from the evacuation experiment in the absence of a crowd. The results show participants that followed the robot versus did not follow the robot. All four conditions are presented. The error bars indicate a 95% confidence interval and the asterisk indicates the significance values after running a pair-wise χ^2 test: $^{*}p < 0.01, ^{**}p < 0.001$.

versus M=26.67 mistake free, M=60.00 versus M=18.64 mistake). These differences are significant ($\chi^2(1, 120) = 29.28, p < 0.001$, $\chi^2(1, 119) = 21.29, p < 0.001$ respectively).

We can also consider the change in following behavior caused by the crowd. In this case, the movement of the crowd provides information that is not available to the participants in the no crowd experiment. For this reason we provide only descriptive statistics. Across all conditions (mistake free robot versus mistake and handoff versus sheperd) the presence of the crowd reduces the participants tendency to follow the robot (M=75.00 versus M=45.0 mistake free/shepherd; M=60.00 versus M=11.86 mistake/shepherd; M=26.67 versus M=1.67 mistake free/handoff; M=18.64 versus M=3.33 mistake/handoff). These results demonstrate that the presence of crowds moving in a different direction than the robot's guidance decreases the tendency to follow the robot across all conditions. Not surprisingly mistakes by the robot decrease the tendency to follow its guidance. More importantly, the results suggest that the shepherding method results in

Fig. 9. Image of the guide robot prototypes. These robots are currently being built for future use in physical experiments. The arms of the robot gesture to communicate guidance directions.

significantly greater compliance with the robot's guidance compared to the handoff method.

V. Physical Experiment

These simulation experiments are used to shape our upcoming physical robot experiments. We are currently in the process of building several guidance robots (Fig. 9). The design of these prototypes has been informed by our prior work [25]. Because of the algorithmic and perceptual challenges associated with shepherding, our initial physical experiments will examine if and how groups of evacuees are guided to exits using robot handoffs. Our initial conditions will not include crowds of people moving in the other direction or robot mistakes. We intend to measure both the percent of human subjects evacuated and the mean evacuation time. Experiments focused towards different interaction modalities such as digital screens and sounds may be conducted. Ultimately our goal is to develop a system that increases the number of people evacuated while also reducing the evacuation time.

VI. Conclusions

This research has investigated several situational and methodological factors that influence a person's decision to follow or to not follow an emergency guidance robot. Our results show that groups of humans evacuating in a particular direction may dissuade people from following an evacuation robot. Among the two strategies considered, shepherding is more effective and if the robot performs well, a sizable portion of evacuees will follow the robot, potentially decreasing congestion at exit choke points and saving lives.

Additional experiments are required to establish the generalizability of our results to other situations. Our experiments were limited to an emergency evacuation situation in an office environment. Humans may act differently during real evacuations. Simulations were conducted in order to better understand the which factors to investigate in physical experiments. If robots are to contribute to the safe evacuation of people during an emergency, we must understand the interplay of different factors that influence the decision to follow the robot's directions. Future research will focus conducting physical robot experiments and quantifying the potential impact of these robots to save lives.

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