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CS7633 – Human-Robot Interaction

Written Case Study #2

I. Relevant Literature and Key Insights

Within the past decade or so, there have been numerous studies related to the issue of robotic technology intended for planning and assistance in evacuation during various emergency situations. In this section, we will highlight the insights afforded by some of these studies and discuss their relevance to and/or differences with our current experiment.

One study by Ferranti and Trigoni[1] examined the discovery of optimal evacuation routes via Agent-to-Tag (the interplay between mobile robots and stationary sensors or "tags" located throughout a building) in comparison with Tag-to-Tag (inter-tag communications that perform independently of the presence of robots nearby), finding that the latter tends to be more robust and efficient. While these systems have been shown to be beneficial, we cannot assume for purposes of our research (as well as in general) that buildings are pre-installed with stationary tags, and thus the system we propose will rely instead on Agent-to-Agent communication among robots that largely act autonomously.

Another study by Kim et. al.[2] focused exclusively on fire evacuation and explored the design of small, disposable and affordable robots that help address issues unique to the situation. Although our experiment has to do with evacuation scenarios in general and our robots will consist of the Willow Garage PR2 platform, some of the insights in the aforementioned study are nonetheless worth considering, such as the need for robots to possess high temperature and impact resistance, waterproofing, and sensors that detect environmental hazards.

A paper by Shell and Mataric[3] demonstrated in part that robots equipped with directional audio beacon technology significantly help reduce the length of time taken for crowds to evacuate, by alleviating bottlenecks, optimizing escape routes, and deploying the beacons to key strategic locations for maximum visibility and auditory exposure. In the present experiment, our robots have speakers and text-to-speech capabilities; as such, it may be interesting to compare their performance to that of beacons (which produce melodic, non-textual sounds).

Mobile robots cannot function in a chaotic, crowded evacuation setting without intelligent navigation / localization. Many studies have touched upon various algorithms for this purpose, some of which have been discussed in the context of evacuation scenarios: Ants[4], Multiple Depth-First Search (MDFS)[5], Brick & Mortar[6], Cellular Automata[7], and VFH+[8] among others. In the next section, we will briefly discuss the algorithm we are considering adopting for use in our robots.

Finally, some studies have tackled the question of trust between robot guides and human evacuees. For instance, it has been found that when a minimum of 30% of evacuees trust and follow the directions of a robot, there is a statistically significant increase in survival rates by virtue of information propagation, and that in general, survivability rate has a positive correlation to the percentage of people who trust the robot.[9] However, there have been conflicting studies on the issue of over-trust of robots: some studies[10] found that after witnessing a guide robot perform poorly, humans were less likely to trust the robot in a subsequent (simulated) emergency scenario, whereas a more recent study[11] (conducted in real-life settings) found that the trust largely remained intact after the robot's prior poor performance, or after the

[1] Ferranti, et. al. "Robot-Assisted Discovery of Evacuation Routes in Emergency Scenarios" (2008).
[2] Kim, et. al. "Portable Fire Evacuation Guide Robot System" (2009).
[3] Shell, et. al. "Insights toward Robot-Assisted Evacuation" (2005).
[4] Svennebring, et. al. "Building Terrain-Covering Ant Robots: a Feasibility Study" (2004).
[5] Ghoul, et. al. "A Modified Multiple Depth First Search Algorithm for Grid Mapping Using Mini-Robots Khepera" (2008).
[6] Ferranti, et. al. "Brick & Mortar: an On-Line Multi-Agent Exploration Algorithm" (2007).
[7] Schadschneider. "Cellular Automation Approach to Pedestrian Dynamics – Applications" (2001).
[8] Ulrich, et. al. "VFH+: Reliable Obstacle Avoidance for Fast Mobile Robots" (1998).
[9] Robinette, et. al. "Information Propagation Applied to Robot-Assisted Evacuation" (2012).
[10] *See, e.g.*, Robinette, et. al. "The effect of Robot Performance on Human-Robot Trust in Time-Critical Situations" (2015).
[11] Robinette, et. al. "Overtrust of Robots in Emergency Evacuation Scenarios" (2016).

robot was broken down or immobilized, or even when the robot was leading people to an obviously questionable location (i.e. a darkened room with no visible exit). While we will not be running experiments specifically related to over-trust for our project, we do plan to gather post-experiment data involving levels of human subjects' trust in our robots; further, we mention these studies as they raise awareness as to the dangers associated with robots' malfunction during an emergency and the potentially disastrous consequences of blind trust.

Overall, we anticipate our series of experiments to be unique in that they will not only gather relevant metrics (discussed in subsequent sections) in both simulation and real-life settings, but be conducted with certain variations in the environment (see e.g. Sec. III(4)) in a way that, to our knowledge, has not been performed in other studies.

II. Design Approach

We now proceed to discuss some of the modifications we are considering making to our baseline robot system in light of the setting and purpose of the experiment. These proposals are tentative and subject to a feasibility and cost-benefit analysis prior to actual implementation.

First, evacuation scenarios span various types ranging from flood, fire, earthquake and other natural hazards to human-made hazards such as terrorist attacks and bomb threats. The robots should be physically robust enough to stand a reasonable chance of withstanding these elements. Hence, we propose that the robots be equipped with water and thermal resistance (preferably up to approximately 500° C, the point at which flashover typically occurs). A thick aluminum compound (or similar) outer casing, combined with Teflon wiring and waterproof adhesive, may assist in this regard. To help protect against physical impact, the robots should be outfitted with shock absorption plates. Additionally, it would be advisable for the robots to possess sensors that detect temperature changes, carbon dioxide and oxygen levels in the atmosphere, as well as hidden metal objects; this may assist the robots in cordoning off certain dangerous areas as unnavigable (even if there are no physical obstacles there) and protecting the crowd from harm.

Second, it is crucial for evacuation robots to attract the attention of crowds. Of the typical reasons that evacuations take longer than they should is the congestion factor,[12] exacerbated by the general chaos and disarray common during an emergency. In light of the finding that audio beacons help shorten the evacuation time,[13] we should consider adding these on top of the speakers and text-to-speech capability that our robots already have. It would be worthwhile to explore if non-textual, melodic sounds emitted by beacons stand out more than spoken words, or whether a certain combination of beacon sounds and speech is more efficient than either one in isolation. Furthermore, we suggest outfitting the robots with light emitters to be used in conjunction with sounds, which should be of added help especially during a blackout or similar incident.

Third, while the robots possess baseline navigation and obstacle avoidance, it is unclear which precise algorithm they currently employ. At a minimum, we should verify that they use both global (discretized) and local (continuous) pathfinding schemes, perhaps with an exploration algorithm such as Brick & Mortar which has been found to be more efficient than Ants or MDFS due to the reduced overall number of traversals needed.[14] Moreover, although the robots are given a (likely static) map of the aquatic building and are able to track people's movements, we would like to ensure that they can use this information to execute dynamic path re-planning. To this end, we are considering giving the robots continuous localization capability that makes use of a visual odometry algorithm known to have a rate of error less than 2%[15]. We are also planning to endow the robots with Cellular Automata (CA) algorithms to model crowd movement and discover solutions to bottlenecks during evacuation in order to minimize evacuation time (CA has been found to have reduced computational costs by exploiting high parallelism, while still

[12] Lovas. "Models of Wayfinding in Emergency Evacuations" (1998).
[13] Shell. "Insights" (See footnote 3).
[14] Ferranti. "Robot-Assisted Discovery" (See footnote 1).
[15] Kostavelis, et. al. "Visual Odometry for Autonomous Robot Navigation through Efficient Outlier Rejection" (2013).

being able to represent complex emergent crowd phenomena[16]). When combined with the ability to detect temperature changes and other dangers in the environment (mentioned at the beginning of this section), these implementations would result in a more complete level of protection against the vicissitudes that can occur in an emergency.

Fourth, it is our current view that all of the five robots should be equally kitted out as opposed to each robot having different roles. Our reasoning is as follows: 1) in a building as large as the aquatic center, giving specialized roles to each robot might result in their being spread too thin, resulting in the "right" robot being at the "wrong" place at a crucial time; 2) equally kitting the robots can maximize the efficiency of their pathfinding and localization schemes, among others, through parallel processing; 3) the impact of one robot's malfunction can be softened through redundancy; 4) it would allow for a lower learning curve for human users, as well as easier upkeep and maintenance; and 5) agent-to-agent communication can be made simpler and more streamlined (we will ensure that each robot has dedicated communication channels so as to allow them to run localization algorithms in parallel and continuously merge their findings into dynamically updated maps of the area).

Fifth, we believe that expending significant resources on improving the robots' manipulation skills should not be the top priority at this time, given their purpose is to assist people during evacuation through alerting them to the best ways of egress, and not to perform disaster recovery or urban search and rescue (in which victims are generally assumed to be immobilized as opposed to able-bodied). Likewise, the speech recognition and communication capabilities will remain fairly basic, as the primary role of the robots have little to do with sociability (though it is well-known that humans respond better to polite robots[17], it is an open question – one which we do not answer here – how an emergency might affect that disposition).

III. Preliminary Evaluation

We now proceed by assuming for purposes of this section that most or all of the design proposals in the previous section have been implemented. The robot design will then be evaluated prior to field testing for the following:

1. Resistance to elements and forces: We will test the durability of the robots with respect to their ability to withstand high temperature, moisture, and physical impact. Instead of subjecting the robots themselves to these (which could become very expensive), we will perform stress tests on certain key robot fragments or miniature replicas encasing sufficient circuitry and/or control boards for us to know when they have been damaged. We will perform several iterations of each test, and document the mean temperature, moisture level and force of impact at which the robots' defenses break down (using one-sample t-statistic for each of the three continuous variables).

2. Ability to attract attention: Having equipped the robots with speech, audio beacon and light emitters, we will attempt to gauge their relative effectiveness at grabbing people's attention in a loud and distracting setting. Although we realize that the best way to measure this would be through a live field test of a mock emergency scenario, preliminary tests in simulated settings may yet prove useful. The experiment will involve human subjects (we have no particular restrictions on qualifying subjects, as long as they are not vision- or hearing-impaired[18]) traversing through a large 3-D, multi-story, virtual building filled with people, obstacles and loud noise, in which they will attempt to find the exit with help from several strategically-placed robots that use one or more methods of guidance: 1) speech (e.g. "This way!" or "Follow me!"), 2) melodic beacon, and/or 3) light emitter. Since there are three methods, there are a total of seven possible combinations thereof that can be tested. Afterwards, we

[16] Boukas, et. al. "Robot Guided Crowd Evacuation" (2015).
[17] *See, e.g.,* Parasuraman, et. al. "Trust and etiquette in high-criticality automated systems" (2004).
[18] We acknowledge that measuring the efficacy of different visual or auditory robotic cues on the vision- or hearing-impaired in an evacuation scenario would be an interesting study in its own right, but one we do not undertake here as it is too situational.

will tabulate the results to see which combination leads to the fastest time of egress overall. (For the sake of simplicity, we will fix the type, volume and/or intensity of the sounds and light, and will defer a more detailed study of the possible interactions that may exist amongst them.)

3. Performance of evacuation algorithm: We wish to compare at least three factors through an evacuation simulation with and without the presence of guidance robots: 1) the length of time taken for all people to evacuate; 2) the length of time needed to evacuate per person; and 3) the ratio of evacuees per exit (to identify whether one exit is disproportionately congested). At a high level, we plan to use cellular automata to simulate crowd movement, where each particle (representing an evacuee) is attracted by default toward the nearest exit from its current location and traverses there, maneuvering and stopping to avoid collisions as necessary. We will use five guidance robots which will be represented as "special" particles, each of which will navigate toward a juncture near an available exit, attracting nearby crowd particles along the way and redirecting them so as to ease bottlenecks and increase efficiency. For greater realism (and to model the presence of "true believers" who do not follow others' instructions during an emergency[19]), we may stipulate that each evacuee has a certain probability of not following a nearby robot. We will also assign slightly different velocities to each evacuee to simulate different walking speeds (the robot velocity, on the other hand, will be fixed at a slow speed). We will execute the simulation on a building layout similar to the aquatic center, and run numerous tests with evacuees in various initial configurations, and identify whether the presence of guidance robots has a statistically significant impact on the above-mentioned metrics. Our expectation is that the usage of robots will result in a more uniform distribution of people over all of the exits, leading to faster evacuation times both overall as well as per evacuee on average.

4. Hazardous conditions and changes in the environment: We plan to run another series of tests in which modify the simulation mentioned in the previous paragraph to account for changing conditions in the environment. For example, in the event of fire, flooding or similar, a formerly viable exit or navigable passageway may become inaccessible, requiring the robots to dynamically re-calculate alternate routes and reposition themselves accordingly. As such, the experiment and the metrics will be identical to the aforementioned except that, at certain intervals during the simulation, certain areas and/or exits will be rendered impassable.

IV. Concept Validation

In real-life emergencies, there is a plethora of physiological and psychological factors that affect people's decision-making process. For instance, a study has found that people during a fire emergency tended to ignore nearby exit doors and preferred to go out the front door, except that if they could see an open exit door (with a view to the outside), they were more likely to head that way irrespective of distance.[20] Information about best evacuation routes can filter through crowds in sometimes unexpected ways; just ten percent of committed true believers can hold sway over an entire population.[21] Although not even full-scale field tests can accurately capture the chaos of a genuine evacuation scenario, we will perform a series of them at the aquatic center with an emphasis on verifying the results of the simulation as referenced in Secs. III(3) and III(4) (for the sake of saving resources and in consideration of opportunity costs, we plan to defer field tests pertaining to Secs. III(1) and III(2)). As in the simulation, the dependent variables we wish to measure are the length of time for all evacuees to exit the building, the length of time taken per evacuee, and the ratio of evacuees per exit. The independent variable is the presence or non-presence of the robots.

[19] *See* Robinette. "Information Propagation" (See footnote 9).
[20] Benthorn, et. al. "Fire Alarm in a Public Building: How Do People Evaluate Information and Choose an Evacuation Exit?" (1999).
[21] Xie, et. al. "Social Consensus through the Influence of Committed Minorities" (2011).

All of the five available robots will be deployed on site for the experiment. They will be equipped with optimized localization and navigation algorithms, agent-to-agent communication for parallel processing and redundancy, light emitters and audio beacons for use in combination with built-in speech, and other identical capabilities as mentioned in Sec. II. Their navigation will be capped at a speed comparable to that of a slowly walking human, to minimize the likelihood and impact of inadvertent collisions.

We plan to recruit several different groups of subjects, each consisting of 50 or more able-bodied persons. Several iterations of the experiment will be run with one group participating in each, in order to help ascertain reproducibility and reliability of results. In each iteration of the experiment where the robots will be present, the subjects will be introduced to the robots ahead of time to help ease the novelty factor; they will be informed that the experiment involves an emergency evacuation drill, and be asked not merely to follow the robots (unless they wish to do so) but to feel free to disregard or even overtake them in heading toward the exits deemed most suitable assuming this were an actual emergency. In experiments where the robots will not be present, the subjects will simply be advised to evacuate as they would in an actual emergency. Afterwards, we may present the subjects with a post-experiment survey with questions such as, “Did you choose follow the directions of a guidance robot?”, “How willing were you to trust the directions of the robot?”, and “Which feature(s) of the robot most captured your attention during the evacuation?”, in an effort to gather their subjective experiences and reasoning behind their decision-making process (the survey questions will differ depending on whether or not the experiment in which the subjects participated involved the robots’ presence).

Finally, as time permits, we will run a second series of experiments similar to that depicted in Sec. III(4), in which certain exits and/or corridors are cordoned off in the middle of an evacuation, forcing some of the subjects to take detours with or without the assistance of a robot. The experiment setup and metrics will otherwise be identical to those mentioned above. Our expectation is that this second set of experiments will help cement the findings of the first set, while further testing the robots’ ability to share information on the dynamically changing environment, re-deploy themselves in a coordinated fashion, and re-direct portions of the crowd toward optimal exits.