Concepts of Operations for Robot-Assisted Emergency Response and Implications for Human-robot Interaction

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Abstract—In this paper we discuss a field study at Disaster City, Texas in March 2006. First Responders and robot developers tried out various concepts of operations in a number of disaster scenarios. Observations, video data, and questionnaire data were analyzed and based on these results, we propose some guidelines as well as some future research areas for human-robot interaction. In addition to the guidelines proposed as a result of our observations in this study, we include design implications from other literature, both laboratory and field studies.

Keywords: Human-robot interaction, rescue robots.

I. INTRODUCTION

The exercise at Disaster City is one of a series in a National Institute of Standards and Technology (NIST) program sponsored by the Department of Homeland Security (DHS). The goal of this program is to develop metrics and evaluation methodologies for Urban Search and Rescue (USAR) robots. In initial workshops with the first responder community, NIST developed a number of requirements for USAR robots [http://www.isd.mel.nist.gov/US&R_Robot_Standards/ accessed August 31, 2006]. These requirements were prioritized and[1] several work items are now being developed with the ASTM standards group for emergency response [ASTM E.54.08, http://www.astm.org accessed August 31, 2006]. In order to refine the requirements initially developed, NIST is running a number of "responder meets robots" exercises.

II. DISASTER CITY

Disaster City is a Texas Task Force One (TX-TF1) training facility located at Texas A&M University, College Station, Texas [http://www.teex.com/teex.cfm?pageid=USARprog&area=USAR&templateid=1117 accessed August 31, 2006]. It is part of the Texas Engineering Extension Service (TEEX) at Texas A&M. The TX-TF1 training site features full-sized collapsible structures, including a strip mall, office building, industrial complex, assembly hall/theater, single family dwelling, train derailments, and three rubble piles.

The event took place over three days. There were "scenarios" scheduled for 4- three hour blocks. These scenarios were used to familiarize the responders with the capabilities of the various robots[2]. Scenarios took place on two rubble piles, in

[1] This research was conducted while Dr. Scholtz was at NIST.

[2] Vendors supplied robots for the technology exercise. The mention of these robots in this paper does not constitute an endorsement by the National Institute of Standards and Technology. The robots are described only to help readers understand the capabilities of the different robots.

the strip mall, on the passenger and hazmat trains, in the collapsed house, and in the single family dwelling.

The final three hour block of time was used as a mock incident response. First Responder teams were assigned to one of four scenarios: single family dwelling, collapsed house, passenger train, and rubble pile. In the Data Analysis Section, we explain how these were selected.

Figures 1 – 4 show each of the venues. In addition, a brief description of each type of disaster is given.

Figure 1. Single family dwelling.

The single family dwelling is partially collapsed due to an earthquake. The main entrances are compromised. Responders must enter through either a leaning collapse or through a 24” triangle breach. There is also a basement that is accessible from the outside down some steep stairs. The maze of rooms needs to be mapped and searched for victims.

Figure 2. Rubble Pile.

The rubble pile is a fully collapsed structure with subterranean voids. There are some entrances supported loosely by concrete barriers. There are confined dimensions and problematic rubble that will hamper searching.

Figure 3. The Passenger Train.

The passenger train was hit by the industrial hazmat tanker cars. The sleeper car is evaluated and has curtained alcoves on each side of a narrow aisle that should be searched. The crew car is lying on its side and also needs to be search. The mailroom in this car needs to be searched but is too small for a responder in a level A suit to enter.

Figure 4. The House of Pancakes viewed from inside.

The house of pancakes is a partially collapsed building with the roof almost in contact with the ground on the only accessible side. Robots must enter through the confined space under the metal roof or through a breach. There is a maze of obstacles and debris which will hamper search.

III. ROBOTS

We used both air and ground robots in the initial scenarios. However, because of safety concerns, the grounds had to be cleared when using the aerial vehicles so they were not incorporated into the final mock incident responses. A number of diverse ground robots were used. These included robots with manipulators, extreme mobility robots, and robots that could be thrown or otherwise launched into an area the responders needed to investigate. Some robots had wheels while others had treads. Some robots had the ability to change shape (See figures 5 a and b). Figures 6a-6e show the diversity of ground robots. The robots used in the scenarios were all teleoperated. One constraint in selecting robots for various scenarios was that the bandwidth they operated on had to be compatible. Of course, this was in addition to the physical constraints imposed by the scenario.

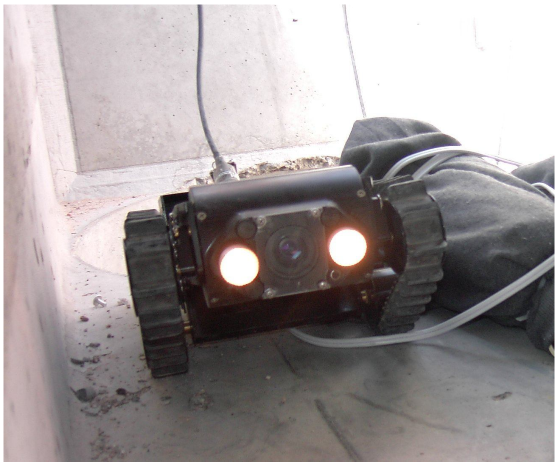

Figure 5a. Shape-shifting robot in lower configuration.

Figure 5b. Shape-shifting robot in raised configuration.

Figure 6a. A robot which navigates using tracks.

Figure 6b. A wedge-shaped track robot with manipulator.

Figure 6c. A small "throwable" robot.

Figure 6d. A robot with articulators.

Figure 6e. A wheeled robot with articulators.

IV. DATA COLLECTION AND ANALYSIS

For each scenario NIST personnel took video data and made observations. In addition, we collected questionnaires from the responders concerning the representativeness of the scenario and the team performance. Figure 7 shows the questionnaire used. Responders were asked to rate each question on a scale of 1 to 7, where 1 was the low end of the scale and 7 was the high end. In general responders gave different ratings to different robots (if there were multiple ones involved in the scenario) for questions 4 and 5.

1. **How representative was the scenario of a possible US&R event?**
2. **Concept of operations used in scenario?**
3. **Assessment of responder team performance**
4. **Capabilities of robot**
5. **Utility of robot in scenario**
6. **Length of time needed to accomplish the scenario**
7. **Overall performance of scenario (responders and robot)**

Figure 7. Questionnaire used to assess the different venues during the first three days

These questionnaires were collected from each member of a responder team during the first three blocks of the exercise.

Table 1 shows the results from these questionnaires

	Passenger Train	Rubble Pile	Strip Mall	Train	Dwelling	Rubble Wood Pile	Pancakes
Representative Scenario	5.38	5.69	5	6	5.5	5.5	5.86
Representative Operations	5.29	6	4.58	5.38	5	5	6
Team Performance	4.67	4.4	5.14	5.25	4.75	4.67	5.17
Bot Capabilities	4.13	3.19	5	5.5	4	5	4.5
Scenario Utility	3.29	3.5	4.86	5.75	4	5	5
Time Required	3.86		4.14	4.43	5.75	4.75	5.5
Robot/Responder Performance	4	3.93	5.29	4.1	3.75	5	4.92
Operator Interface	3.67	4.67	4.57	5.75	5.67	5	5

The scenarios and the operations performed were rated as 5 or over with the exception of the strip mall. That venue was not used in our final portion of the exercise. The Hazmat train was not used as well as that required the use of an aerial vehicle. The four venues selected for use in the final portion of the exercise were the passenger train, the rubble pile, the dwelling and the house of pancakes. All of these were highly rated as representative of situations responders would encounter.

The robot/ responder performance and the operator interfaces for the robots were not as highly rated. There are several reasons for this. First of all, in many cases, the operator interface needs to be improved. One goal of this analysis is to examine the operator interface, not just for usability, but in the concept of operations. The performance of the robots and responders is also due to differences in expectations of responders and the actual capabilities of the robots. Again, using the robots and developing concepts of operations based on a better understanding of capabilities is essential to improving the robot/responder team performance.

V. CONCEPTS OF OPERATIONS

The most interesting data came from observations of emerging concepts of operations from the various venues. We describe these four scenarios in the following paragraphs.

A. Single Family Dwelling

The responder team used three robots primarily in this situation. They used a large robot with a manipulator arm, which we designate as robot A for this document, a smaller shape changing robot, which we designate as robot B, and for a portion of the time they employed a small throwable robot which we designate as robot C. The responders were setup in a tented area with power supplied by generators in front of the single family dwelling as there were no Hazmat concerns. In addition to the three robots, a search dog was also used. The robots were operated by the robot developers under the direction of the responders.

The team leader had the operator of the large robot drive the robot around the building. He watched the video and constructed a map of the exterior of the dwelling based on this information (Figure 8). This also allowed him to determine the entrances to the dwelling. After the exterior had been traversed, the team leader sent the larger robot into the dwelling through the partially collapsed entrance. The smaller, shape changing robot was sent into the basement of the dwelling using the stairs. The two operators were sitting close to each other under the tented area with the team leader watching the video from both. He used this to map out the inside area and to determine that the area was safe enough to send in a dog. A possible victim was identified by the smaller robot in the basement. A dog was sent in to verify this.

There was an issue when robot A was unable to get into a suspected space in the upper floor of the building. According to the map the responder constructed there was an additional space that had not yet been searched. However, there were obstacles (collapsed walls and debris) that prevented the robot from entering this space. Both robot A and B were moved out of the dwelling and the larger robot, robot A, used the manipulator arm to grip the smaller robot, robot B, and move it into the building, assisted by members of the response team. Once it had moved back into the area, the operator was able to place robot B on top of the collapsed wall which allowed the robot B to penetrate farther into the building. In this operation, the two operators moved close together and used cameras from both robots to do the placement.

Several other cooperative efforts were seen. In one instance, robot A dropped robot C through a hole in the main floor. The operator of robot C used both his camera and the camera of the robot A to maneuver through the basement area.

B. Rubble Pile

During the rubble pile scenario a responder operating a larger robot, which we designate as robot D, worked in conjunction with the rescue dog handlers. Using robot D, the responder circumnavigated the rubble pile, accessing possible entry points. The responder identified the existence of a victim using the microphone on the robot. The robot was also equipped with a speaker so the responder and the victim could communicate. This communication enabled the responder to narrow the search area by asking the victim if they could "see the robot". When the victim responded that the robot was in view, the dog handler then sent in the rescue dog to pinpoint the victim's location. Figure 9 shows what the rubble pile looked like.

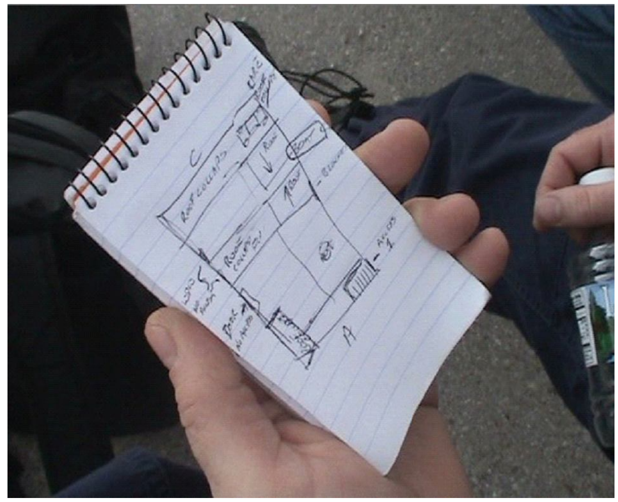

Figure 8. The map created by the responder.

Figure 9. Responders searching the rubble pile

C. Passenger Train Wreck

Two robots were used in this scenario. Each robot was run by an operator under the direction of a First Responder. The responder asked the robot operators to clear the train and look for any signs of life on the slanted wrecked train. The first robot, which we designate as robot E, started at the entrance on the ground and began to clear the train looking for survivors / victims. The other robot, which we designate as robot F, started at the back of an upended train car and worked its way toward the front. A responder dropped robot F in a side window and stayed there to do tether management. The operators were located outside of separate sections of the trains and communicated over the hand-held radios to each other. Figures 10 and 11 show two setups at the passenger train.

Robot F eventually got a piece of cloth wrapped around a tread and was stuck. The operators decided to use robot E's arm/claw to grab and try to remove the cloth from the robot F's tread. Robot E's operator managed to grab the cloth with its manipulator but was unable to free the cloth and instead, dragged robot F a short distance. A second strategy was developed in which robot E stayed stationary and operator for robot F attempted to drive away from robot E to free the cloth. This strategy was successful.

Figure 10. Responders find a place to setup the OCU to search the passenger train

Figure 11. Another group of responders setting up to search the passenger train

In the second part of this scenario, the team was searching a train car that was lying on its side. The same two robots were used, again being driven by their operators under supervision of the First Responder. The responder asked to have them clear the train from opposite ends. This time the operators were set up next to one another. The robots eventually met up with each other in the center of the dark train and used each other's lighting to help see a larger area than they would have been able to see by themselves.

There was another interesting operator event at the trains. The operator for robot E was quite tired after concentrating so heavily and another operator offered to replace him. While turning over control, the original operator gave a verbal description of where he thought the robot was currently positioned in the train and drew an imaginary path on the operator control unit (OCU) using his finger to describe the center hall layout.

D. *House of Pancakes*

The House of Pancakes scenario focused heavily on three robots, which we designate as robots G, H, I, in conjunction with a rescue dog handler. In the scenario, the House of Pancakes was meant to represent a recently collapsed building. The scenario started with the responders tele-operating robot H around the outside of the house to look for the presence of survivors and to determine the best opening to enter the house. An open doorway was found and robot H was navigated through that doorway. Robot H was assumed to have biohazard sensors on it that could detect hazardous gases in the environment. Once robot H traversed all accessible areas of the house, robot H (conceptually) responded that the environment was safe, the rescue dogs entered the site to smell for survivors. In the scenario, there was one survivor near the back of the house which the dog quickly detected.

In parallel with this, robot G, with robot J in its grippers, was tele-operated to drive up on the collapsed roof of the house. Figure 12 shows robot G carrying robot J. The purpose of this part of the scenario was to have robot G drop robot J into a breach near the uppermost portion of the roof to allow it to look around the remaining upper stories of the building to see if any survivors could be detected.

A small piece of plywood (about 1 m by 1 m) was placed near the bottom of the collapsed roof to allow robot G to drive up onto the roof. Once robot G drove up on the plywood and reached the uppermost portion of the roof, the operator aligned robot G with the breach and extended its manipulator to be directly over the breach. The pincher in the manipulator was then released and robot J was dropped into the breach. For this scenario, robot J was not functional (it broke earlier in the week), so the scenario ended here. If robot J was functional, it would have been used to navigate around the upper stories of the building to find survivors.

Figure 12. Robot G with robot J in its gripper.

VI. IMPLICATIONS FOR DESIGN

Based on the emerging concept of operations we can determine some priorities for design – and likewise we can also determine some items that are not as likely to affect design.

In the single family dwelling we did not find a need for operators to be on the move. Moreover, since there was no Hazmat danger, there was not a need for operators to wear protective gear. However, in the train scenario we found that the operators worked outside, sitting on the ground. Therefore, things such as lighting conditions played a big part in being able to see the OCU. Moreover, being able to comfortably set up operations in less than ideal conditions has to be considered when designing the OCU hardware.

The team lead was busy trying to update a map sketched on his field notebook with information given him by the two operators of the robots. A shared electronic notebook might be a good addition when working with teams of robots. Assume that the team lead could sketch in the initial external map as the perimeter is being mapped out. If this were done on a tablet PC, for example, and then used as a shared file both robot operators could add information to it as they searched the building. The team lead could have access to this on the tablet PC and could add information and annotations as well. The notion of maps surfaces again in the train scenario when operators change shifts. Having explicit information for the incoming operator to understand where the robot is and what has already been searched is valuable.

The use of videos from two robots when doing a cooperative task was accomplished by having the operators sit close and leaning over to see the other's OCU. While there is a need to have hardened cases for the OCU, it might be feasible to have hardened display units that could be attached to several OCUs if it is feasible that robots might cooperate. Then the video from one robot could be broadcast to several additional display units. For example, when one operator is picking up or setting down a smaller robot, both operators need to have a good view of what is happening so that the smaller robot can be correctly placed and can move as necessary to enter a void or start up a steep slope. In these scenarios responders positioned the smaller robot in the grippers of the larger robot outside of the buildings. This might not always be the case so it is essential to provide good video to the operators to position both robots to ensure that the smaller robot is not damaged during this operation. Releasing the smaller robot was a delicate operation in many cases. In the case of the robot J, this was not an issue. But in the single family dwelling, for example, it was necessary to place the smaller robot on a rather steep incline. Therefore the smaller robot had to be position so that it could immediately start moving up the incline rather than sliding backwards. This necessitated ensuring the camera view was on the smaller robot while releasing the grippers. The operators had to be closely coordinated to carryout their actions (releasing and starting to move the smaller robot) at the same time.

The team also made use of sharing resources of the robots. In the train scenario using two lights (one on each robot), rather than just a single light helped to speed the search of the train.

Communications need to be provided. In the scenarios we saw communications between robot operators, between robot operators and victims, and between responders and the robot operators. Teams communicated to share robots. Granted that this was due to limitations of the number of robots available but we assume that this will most likely be the case in the future. This would allow teams to know what robots are available should they find a need for a particular capability. In the House of Pancakes and in the Single Family dwelling we saw responders use two robots in parallel. There is a need for communications between the responders in these two efforts. As the goal is to quickly locate victims and to determine how much of the site has been covered, a way to fuse information coming back from both efforts should be provided.

We did not simulate a command and control center in this exercise. This would add another level of communications. Some questions would be whether the raw data such as video footage or sensor data would be available directly to the command and control center on demand. Would it be sufficient to have a dynamically updated map showing where teams are working and where the robotic resources are? Assuming that multiple robots are being used in a scenario, what type of fusion of information should be done and transmitted to command and control? Would it be sufficient to know which robots were currently in use?

A number of awareness issues should also be considered [4]. Knowing which teams are using which robots at any point in time is essential both for command and control and for the responder teams. Responder teams might want to know if the robots being used are "on task", that is actually searching or if there is some sort of robot help situation in progress.

VII. DESIGN IMPLICATIONS FROM THE LITERATURE

Murphy and her team have done much work on field studies that can be added to this analysis. For example, Burke et al. found that a good percentage of operators' time in US&R missions was consumed with gathering information about the state of the robot and that state of the environment [2]. This time was significantly greater than the time they spent navigating. They also found that operators had difficulty incorporating their small view (through the robot camera) into the overall picture. Displaying dynamically constructed maps of the overall area and the actual search areas of the various teams might help with overall situation awareness.

Burke and Murphy found similar issues in another field study when over 50% of the robot operator communications dealt with situation awareness concerns [1].

Murphy also found that two humans working together are nine times more likely to find a victim than one operator alone. This was not directly incorporated into our scenarios especially when there was more than one robot involved. The First Responder moved between robots and did look at the video but there as not a concern attempt to dedicate another responder to watching the robot video. If there are multiple robots involved, must a dedicated responder watch the video sent back from each robot? Or would it be feasible for a responder to watch video from several robots, assuming it could be viewed on a single display [5].

Drury et al. formulated a framework for awareness in human-robot interactions [4]. As noted in this framework there is a need for human-human awareness, robot-human awareness, robot-robot awareness, and humans' overall mission awareness. As the robots in our field study were tele-operated we did not see instances of robot-human awareness. The robot-robot awareness was also mediated by the human operators due to tele-operation control.

Yanco et al. studied awareness issues in USAR contests [6]. In this environment they were able to identify issues with the operator control unit, such as having to fuse information from multiple windows and lacking information about the area directly around the robot. [3] contains guidelines for presentation of information to the operator. While the contests are good tests of individual robot capabilities, there is no notion of a concept of operations.

VIII. CONCLUSIONS

We have described a multi-day field exercise culminating in an opportunity for responders to respond to a mock incident. In doing this, they selected robots appropriate for the venue and a concept of operations evolved. We observed the mock incident responses and noted how the robots, robot operators, and responders interacted. From this we were able to identify a number of issues that should be considered for human-robot interaction design. Some of the issues identified apply to individual robot OCUs. Other issues are concerned with the fusion of information to provide an overall assessment to the commanders.

These designs will need to be tested in the laboratory for effectiveness and usability but testing them in field exercises is essential to identify design requirements at a higher level. It is also interesting to compare these evolving concepts of operation to task analyses to determine if and how the strategies used by responders change as new technology is placed in use [7].

As a final note observations here led to discussion with some of the responders concerning metrics for evaluating the effectiveness of human-robot teams. Responders are concerned with how much of the disaster area is covered in how much time. Robots can contribute to this by coverage a good portion of this without putting the responders at risk. A proposed metric to use for judging the effectiveness of teams of humans and robots would be the amount of coverage/ time accomplished with only a robot. This addresses both the effectiveness and efficiency of the team along with the objective of minimizing the time responders are at risk.

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