Firefighter-Robot Interaction during a Hazardous Materials Incident Exercise

Ángela Brando **Carolina Chang**

Departamento de Computación y TI
Universidad Simón Bolívar
Caracas, Venezuela
{97-29313,cchang}@ldc.usb.ve

Abstract

This paper describes the interactions between certified firefighters and a mobile robot during a hazardous materials (HazMat) incident exercise. The experiment was carried out inside a simple office environment using a Pioneer 2-DX robot equipped with sonars, a pan-tilt-zoom CCD camera, and wireless Ethernet. Two firefighters were tested separately as commanders of the HazMat incident. They were helped by an operator that controlled the robot's actions according to their instructions. No details about the incident were given to the firefighters. Each commander had to determine what happened, and make sure that the area had been evicted. Through the robot, the commanders collected data about three toxic liquids and a live victim that were found inside an office. We report the results of the experiment, and the firefighters' reactions to their first exposure to this robotic technology.

1 Introduction

Urban Search and Rescue (USAR) is becoming an important domain for robotic applications [1], [2], [3], [4]. The interest in this research field has grown partly due to initiatives such as the AAAI USAR Competition and RoboCupRescue.

A milestone was the participation of several USAR Robot in the recovery of victims of the World Trade Center, after the terrorist attack of September 11th, 2001. The Center for Robot Assisted Search and Rescue (CRASAR) deployed teams from Foster Miller, iRobot, the Space and Naval Warfare Systems Center, and the University of South Florida. CRASAR teams have participated also in the search of victims of the Turkey and India earthquakes.

Outstanding research has been carried out at the Perceptual Robotics Laboratory [5], [6], [7]. In 2001, the lab conducted a field test in Tampa, Florida, with the help of the Hillsborough County Fire Department. Casper & Murphy study the human-robot interactions that took place during four search and rescue tasks. Their field tests have inspired the work that we report in this paper. Other applications of robotics to hazardous material incidents are reported in [8].

USAR robots are expensive since they must be able to operate in very unstructured and hazardous environments. To do so, they should be equipped with sophisticated sensors, locomotion mechanisms, and communications. There are no USAR robots in our country, but we are very interested in this technology since Caracas, Venezuela's capital, lies on an earthquake zone. Some studies predict that a major earthquake would take place in Caracas in this decade.

While we continue the quest for funding, we have decided to start this project using our indoors Pioneer 2-DX robot from Activmedia. One goal of this work is to promote the development of the USAR robotics research field in our country, and to set some awareness in our Fire Departments about the opportunities that robotic technologies may bring to them. We are developing a robotics application prototype for victim search and rescue. We find very important to get some insight from trained rescuers about the true potential of USAR robotics. We are completely aware that our robot has too many limitations as to be useful in a real USAR incident, yet we think that it can help us learn many lessons about this research field.

2 The Robotics Platform

Pioneer 2-DX is a 9Kg, 44x38x22cm differential-drive robot (see figure 1). It has a frontal ring of eight ultrasound sensors, a pan-tilt-zoom Sony CCD camera, an internal PC104 computer, frame grabber, and linux operating system. It has wireless Ethernet communications in a range of 50m by means of an access point. The robot can operate autonomously on batteries for about 4 hours.

We are developing an application for remote and semi-autonomous robot operation. We use the Saphira environment and the VisLib library. In the

Figure 1: *The Pioneer2-DX Robot*

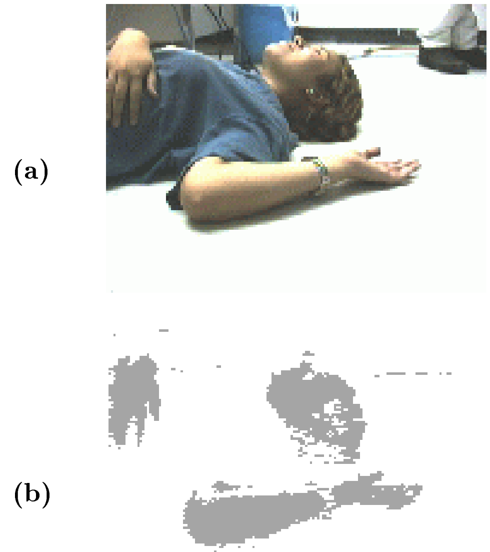

Figure 2: *Skin detection using Support Vector Machines.* **(a)** *The image captured by the robot's CCD camera.* **(b)** *Pixels of the image classified as skin-color by the SVM. Note that part of the hair and some pixels of the background are misclassified.*

semi-autonomous mode the robot explores a building looking for victims. When it finds an object that might be a person lying on the floor, the robot notifies the finding via e-mail and cell-phone text messages. An incident commander receives the information and decides whether to ignore the object and continue the autonomous search, or to operate the robot remotely in order to collect more data about the victim and the environment. For the time being we use a very simple module for victim detection, based on the recognition of skin color using support vector machines (figure 2). This module needs to be improved in order to become useful, since it fails under many conditions, such as dim lightning, debris-covered skin, skin-like color objects, and so on. We think that the process of recognition of human beings in collapsed structures requires other sensors more appropriate for this task, such as thermal cameras.

In this paper we focus on the remote operation of the robot. Our interface allows us to control the robot's velocity and direction of movement, the camera's movements and zoom, and the image brightness and contrast. A "protection zone" of variable length can be set in order to protect the robot from collisions due to unsafe movement commands. When the protection zone is active, the robot ignores commands that would place it close to obstacles. Graphical information is provided about the readings of the ultrasound sensors. This feature may aid navigation in the dark. Finally, a horizontal line can be placed on top of the camera image to help the rescuer detect whether a victim is breathing or not (this feature was suggested to Casper&Murphy by Special Operations Chief R. Rogers during their 2001 field test [7]). We want to test if certified firefighters that have never interacted with a robot would find it easy and useful to explore an environment remotely through this interface.

3 The Experiment

The experiment was carried out in the building where our lab and offices are located since it was the easiest place to set up our equipment and we did not need any special permission to work in there. The experiments were done on weekends in order to not disturb other people. We asked for the help of the University's Voluntary Fire Department, which is formed mostly by undergraduate students who are certified firefighters. Prof. Carolina Chang, one of the authors of this paper, is also a certified firefighter of our University. Hence, it was relatively simple to set up the simulated incident and to find other firefighters willing to collaborate. We ran the experiment with the help of two firefighters: Franklyn Jiménez and Carmelo Álvarez who were tested individually as incident commanders. Ángela Brando acted as the operator of the robot in both runs.

The experiment was set as follows: We receive an alarm of a HazMat incident in the building. We are told that all people have already evicted. The incident commander has to use the robot to explore the environment, in order to determine the exact location of the incident, get information about the type of hazardous materials spilled and the risks involved, and make sure that the building has been completely evicted.

For the sake of simplicity, we assume that the office where we have our computers and robot is the incident *Cold Zone*, *i.e.*, a safe zone where the command is established. The *Hot Zone*, or area affected by the incident are the aisles, restrooms and open offices, as shown in figure 3. A small aisle connects the hot zone

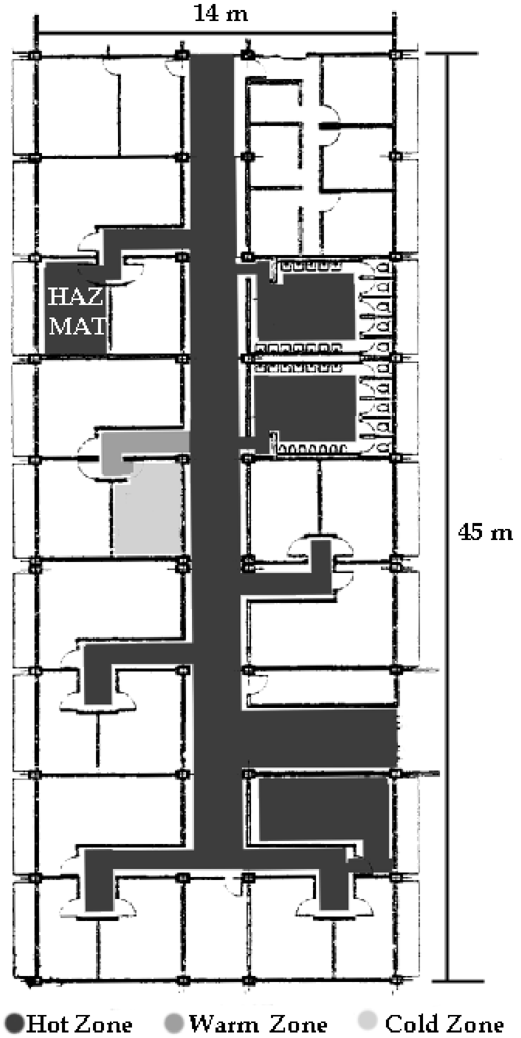

Figure 3: *Map of the area of the building covered by this experiment. White areas are closed faculty offices not explored by the robot. The robot departs from the cold zone. The incident takes place inside the office labeled "HAZ MAT" on the map.*

(a) **(b)**

Figure 4: *The Hazardous Materials.* **(a)** *Two containers lie on top of a desk. Right, there is an opened container of a liquid pesticide. Left, there is a red, closed container, labeled 3123.* **(b)** *There is a small spill of the 2929 liquid material on the floor. See text for details.*

and the cold zone. This is the *Warm Zone*, an area where equipment is checked and decontaminated. In a real incident the cold zone would be established outside and away from the hot zone, neither isolated nor surrounded by any hazard.

Three containers were placed inside one of the opened offices, as shown in figure 4. One container had the hand-written label "Plaguicida/Pesticide" and a "Inhalation Hazard" placard. The other two containers had 4-digit numbers that correspond to the United Nations (UN) ID Numbers of materials. The UN numbers that we used were 3123 and 2929. The names of the materials, the safety recommendations, and the emergency response guidance associated to the UN numbers are listed in the U.S. Department of Transportation (DOT) Emergency Response Guidebook [9]. The 3123 material is a toxic or poisonous liquid, which in contact with water may emit flammable gases. The 2929 material is also a poisonous liquid, flammable, organic and inhalation hazard. Needless to say, we only used the ID numbers in our experiment, not the real hazardous materials. The containers of the pesticide and the 3123 material were placed on a desk, while the container of the 2929 material was laying on the floor. The container of the pesticide had no lid, the container of the 3123 material had a cover, and there was a spill on the floor of about 200ml of the 2929 material. Near to the spill was a person lying on the floor, who acted as an unconscious victim that had increased breathing frequency (*i.e., tachypnea*). The door of the office was left partially open.

All lights of the hot zone were turned off in order to add some complexity to the experiment. Therefore, the aisles became very dark. However, the offices and restrooms had natural light entering through the windows since the experiments were carried out in the afternoon. We placed a flashlight on top of the robot to give it a small aid, and to help people see the robot in the dark.

Before starting the experiment we devoted some minutes to show the computer interface to the firefighters, and to explain the current limitations of our system. We asked them to try to foresee the future development of the USAR robotics field, and to give us feed-back about the feasibility of this technology. Whenever possible the firefighters should verbose and explain what they were doing during the experiment. We asked them to ignore and excuse possible disturbances caused by our team members that were videotaping the exercise. We taped the firefighter and operator actions in the cold zone, and the robot's actions in the hot zone. We also taped some segments of the view from the robot's own camera. Ángela, the robot operator, was to follow the commands given by the firefighter to control the robot's actions. Ángela knows very well the building since she works there.

However, she was not allowed to help the firefighter find his way in the hot zone. Moreover, the first time the experiment was done, Ángela had absolutely no knowledge about how to proceed during a HazMat incident. To study her interaction with the firefighter and the robot was part of the exercise.

No details about the HazMat incident were given to the incident commander. He had to explore the building in order to learn what happened, but no human beings were allowed into the hot zone until enough data had been collected. The only tools available to the firefighter were the remotely operated robot and the DOT Emergency Response Guidebook. First we ran the experiment with firefighter F. Jiménez, and asked him to not disclose any information about the exercise. Several days later we ran a similar experiment with firefighter C. Álvarez.

4 Results

The two runs of the experiments produced very interesting results. In both cases the commander was capable of completing the exercise, which should mean that he had some level of success in his interactions with the operator and the robot.

Firefighter F. Jiménez (see figure 5(a)) commanded the first run of the experiment. His strategy was to explore the hot zone starting from the nearest room, *i.e.*, the gentlemen's restroom located in front of the warm zone (see the building's map, figure 3). When the robot was leaving the restroom the commander decided to turn to the left and search those areas at the bottom of the map. When possible, the commander tried to maintain a wall-following guided search, but he kept the strategy of entering the closest rooms or inner aisles, regardless whether the entrance was located to the right or to the left side of the robot. It was possible to do so because the commander asked frequently to pan the camera to both sides. The aisle was very dark, but the operator made adjustments to the image brightness and contrast that improved the image quality. No people or hazardous materials were found in this part of the building. The commander decided to return to a reference point that he had identified earlier near to the restroom. He proceeded to explore the ladies' restroom, as shown in figure 5(b). Once outside the restroom he made sure that the rest of the aisle was clear. Lastly, the robot entered the HazMat room. As we said before, the office door was not wide open. From the outside the robot's camera could capture images of the victim's legs (figure 5(c)). The robot had to force its entry to the room, but this procedure was never tried by the operator before. It took the team several minutes to plan and execute the robot's movements. They were concerned about the robot's safety, but it was not hard to get the robot to push the door and enter the room. Once inside the

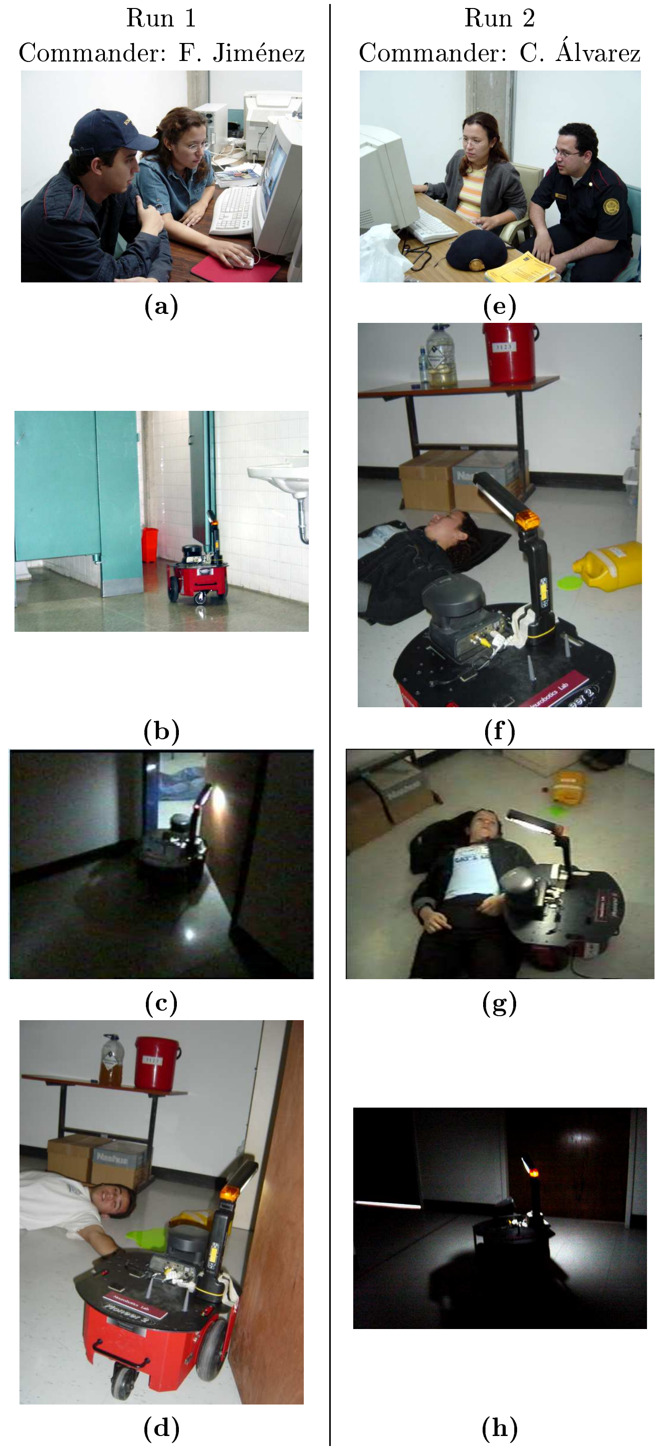

Figure 5: *The two runs of the experiment. Panels* **(a)**, **(b)**, **(c)**, *and* **(d)** *show some images of the first run, which was commanded by F. Jiménez. Panels* **(e)**, **(f)**, **(g)**, *and* **(h)** *are images of the exercise commanded by C. Álvarez. See text for details.*

room, the robot was used to evaluate the victim's condition and identify the hazardous materials, as shown in figure 5(d). During the whole experiment the commander took the time to explore the environment very carefully, using frequently all the camera's pan-tilt-zoom capabilities. He explained that he had to make sure that there were no signs of structural collapse, such as objects hanging or falling from the ceiling, or cracks in the walls and door frames.

Firefighter C. Álvarez was the incident commander (figure 5(e)) of the second run of the experiment. His strategy was quite different from the one described above. At the end of the warm zone, he ordered the robot to turn left. He maintained a left-wall-following search during the whole exploration. Hence, the HazMat room was the first room found by the robot. It was much easier to enter the room this time since the robot operator had more experience at pushing the door remotely. The firefighter could identify the hazardous materials and assess the victim's condition, as seen in figure 5(f). Moreover, the robot was used to hit the victim gently in order to determine her level of consciousness (figure 5(g)). After collecting data about the HazMat room, the robot had to explore the rest of the hot zone to make sure that there were no more victims or hazards. Figure 5(h) shows the robot exploring an inner aisle. Notice that the flashlight provides some source of light to the robot in the dark. C. Álvarez ordered fewer camera movements, and tried to inspect the hot zone much faster than F. Jiménez. The experiment was affected by an error in the wireless Ethernet communication with the robot, that lasted 10 minutes approximately. Ángela had to reboot the system to restore the connection.

The two firefighter were able to assess the victim's respiratory frequency. Both found very useful the feature that draws a line on top of the camera image, as shown in figure 6. They said that the guideline helped them to detect the chest or abdomen movements associated with the process of breathing. These movements can be so slight that would go unnoticed without the guideline. The line also helped the firefighter to count the number of respirations per minute, which revealed that the victim had increased respiratory frequency, allegedly due to the inhalation of the hazardous materials.

They also tried to determine the level of consciousness of the victim. To this end, they watched for any movements of the victim's body, especially, on the face. On the first run the victim made several movements of the head and limbs, but the commander concluded that the victim was not fully conscious. On the second run the victim made no voluntary movements. The commander decided to push gently the victim's body with the robot while trying to observe any reaction on her face. No movements were detected. The commander concluded that the level of awareness was *"pain"* or *"unconsciousness"* according to the AVPU scale (*i.e., Awareness-Verbal-Pain-Unconsciousness*).

(a)

(b)

Figure 6: *Screenshots of the victim's condition assessment. The red line drawn on top of the image helps the commander detect chest movements. There is a difference between panels (a) and (b). The chest* (a) *expands when the victim breaths in, and* (b) *contracts when she breaths out.*

The two firefighters were capable of reading all the labels of the containers, determining whether the containers were open or closed, and looking for liquid spills and other hazards. They read the DOT Emergency Guidebook and learned the recommendations for handling those materials. The guidebook recommends the use of chemical protective clothing and self-contained breathing apparatus. The area should be isolated for at least 100m. The guidebook also indicated that contact with the 2929 material may cause irritation or burns in eyes and skin. Therefore, the firefighters tried to find traces of the 2929-liquid or any wounds on the victim skin. There were none.

The experiment had a duration of 1h 49min in the first run, and 1h 26min in the second run. The robotics exploration resulted way too slow. The firefighters argued that a human-being would have completed the same task in less than 15 minutes. The runs were this long in part because of the limitations of our robot, but also because we interrupted the commander's work frequently to ask questions about the procedure. Also, the commanders chose to move the robot slowly, even though the robot can navigate faster. We think that fast robot swarms, more versatile sensors, and training of the commanders and operators can improve performance significantly.

At the end of the exercise we asked the firefighters to draw a map of the building. The map of F.

Jiménez was accurate. C.Álvarez' map missed an aisle. The robot operator did not recall exploring that area. The firefighter argued that he did not see the entrance when the robot navigated nearby. We decided to watch the tapes to find out what really happened. As it turns out, he missed that entrance because he turned his sight away from the computer screen for several seconds. He did so because we asked him a question about the procedure. He turned to the video camera that was recording him, and answered. We realized that it was a mistake to distract the commander during the experiment. If this were a real incident, he could have failed to find victims or hazards.

Interactions between the commanders and the operator were effective even though they had never worked together before. During the experiment Ángela became disoriented several times about the heading direction or location of the robot. This is an interesting result since she knows the building very well. She said that this happened because she was too concentrated on controlling the robot. On the other hand, the firefighters never became disoriented. They helped the operator in such cases. We conclude that at least two people are needed to interact with the robot, as suggested in [7], and done in our experiment. We also believe that the operator should have some training on emergency response in order to know how to proceed during an incident, and to have a highly effective interaction with the commander. Ideally, firefighter, operator, and robot should become a well-trained work team.

5 Conclusions

We received many suggestions from the firefighters that participated in this experiment. As we expected, they suggested the addition of sophisticated accessories that we cannot currently afford, such as a robot arm, a thermal camera, a laser sensor, wide-angle camera lenses, tracks, bidirectional audio, lights, chemical sensors, disposable outer-shells or special decontamination methods, smaller robot size, and so on.

Other ideas are more within our reach, such as adding joysticks to the interface to simplify the robot operation. It was suggested to couple an external portable radio to the robot. If the victim is fully conscious, she could take the radio and communicate with the firefighters. If the victim is conscious but cannot move, at least she would listen to the recommendations given to her.

The two firefighters were very enthusiastic about the experimental results and their interaction with the robot, and think that USAR robots will become a great tool for Fire Departments in the future. "It was just like being at the scene, yet I knew I was safe", said firefighter F. Jiménez at the end of the experiment. This statement summarizes very well one of the long-term goals of our research.

Acknowledgments

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