Human-Robot Interactions during the Robot-Assisted Urban Search and Rescue Effort at the World Trade Center

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Abstract

1 Introduction

The September 11th attack on the World Trade Center towers resulted in a mass casualty incident requiring the resources of search and rescue teams from across North America, volunteers, large equipment companies, and specialized equipment. Robots were part of the specialized equipment. For the first known time, robots were used in an Urban Search and Rescue (USAR) effort. The robots were brought to Ground Zero by the Center for Robotic Assisted Search and Rescue (CRASAR) under an invitation from Fire Department New York (FDNY) Special Operations Chief Ray Downey. John Blitch, the director of CRASAR, invited groups from the University of South Florida, Foster-Miller, iRobot, Space and Naval Warfare Systems Center (SPAWAR), Joint Programs Office (JPO), and Army Explosive Ordnance Disposal (Army EOD) to join CRASAR and help with the rescue.

Robots are useful for rescue efforts by being able to perform tasks humans or dogs cannot do, or cannot do safely. For example, robots were used to search confined spaces at Ground Zero that dogs would not go in, much less a rescuer. In the case of the Mexico City earthquake, 135 rescuers died; 65 of those deaths due to rescuers searching confined spaces that flooded [1]. This is just one of the many incidents showing the dangers disaster incidents place on the professionals working in them. Also, there are not enough trained individuals to perform the multitude of tasks during a rescue. It takes, on average, 10 trained professionals 4 hours to remove a victim in a void space and 10 trained professionals 10 hours to remove an entombed victim [2]. These trained professionals also need to search the dangerous confined spaces and inspect any surrounding areas for victims. Robots are capable of assisting the rescuers with the many
tasks they face.

The purpose of this article is to present the case study of human robot interactions during the first use of robots in a disaster incident, the World Trade Center rescue effort. The information in this article comes from analysis of video taken by CRASAR members, written record while working at Ground Zero, and notes taken as part of HRI grant (GRANT# or REF).

The following section begins by describing the World Trade Center disaster incident in terms of the environment, chronology on CRASAR events during the incident, and robot equipment used on site. Section ?? describes the tasks performed by FEMA task forces, the task force organization and addition of robot technology into the organization, and on-site operations during the disaster incident. The next section follows the same pattern of task description, team organization and on-site operations for the rescue robot team. Section ?? discusses an informal evaluation of the robot performance at the World Trade Center in terms of human factors, information and distribution, and user interfaces. Section 6 concludes the article with a summary of the human robot interaction lessons learned during the World Trade Center disaster.

2 World Trade Center Disaster Incident

2.1 Disaster Environment

The disaster site resulting from the September 11th terrorist attack on the World Trade Center proved to be an exceptional environment. Figure 1 shows images taken at Ground Zero by CRASAR and their corresponding locations on the map. Paper, dust, and metal were the three main materials found in the rubble pile. The main rubble pile encompassed the 1 through 7 World Trade Center buildings. 4, 5, and 6 World Trade Center buildings were partially erect but highly unsafe. Surrounding buildings were still standing, but were damaged and unsafe. BUILDINGX was damaged by the collapse of WTCX resulting in a large gash threatening the building integrity. Figure 2 shows examples of damaged buildings surrounding the main rubble pile at the World Trade Center disaster site. For a documented description of the September 11th terrorist attack, refer to [12]. Refer to [4] as a source for the World Trade Center construction and social implications.

Figure 1: Ground Zero images and corresponding areas on Ground Zero map.
Figure 2: Damaged buildings surrounding the main rubble pile at Ground Zero.

The rubble terrain greatly challenged the mobility of the robot equipment as well as sensing and communication capabilities. Robot operators needed to carry the equipment onto the rubble pile in order to get near the void or area needing to be searched because the robots could not navigate the World Trade Center rubble terrain. The large amounts of steel caused periodic loss of communication with robots while searching as well. Extreme heat sources deep within the pile caused softening of robot tracks that led to immobilizing them.

The disaster environment and incident inflicted more cognitive fatigue than physical fatigue on the involved individuals. The emotional and unstable situation placed a great deal of mental stress on these individuals. However, the environment itself was less physically fatiguing, relative to other disaster incidents, in terms of weather and sensory input. The weather cooperated most of the days during the two weeks after the incident. Temperatures ranged from the 60s at night to mid-70s during the day (as recorded in FEMA ops-briefing documents). No live victims were seen after the first few hours post-collapse. Recoveries were few and far between. The predominant sounds coming from the rubble pile were of trucks, cranes, other vehicles, and occasional orders being shouted between rescuers. Minimal, if any, smell lingered around the rubble pile. Asbestos and general dust threatened the health of the rescuers, who were then required to wear certified air masks and eye protection. The rain and whatever structural integrity the rubble had threatened safety of the victims and rescuers. Varying rain created slip hazards and started flooding in below-grade areas. The rain did, however, help to decrease the amount of dust in the air and wash away the thick blanket covering Ground Zero. Although washing away the blanket of dust was helpful, the initial scent trail needed by the search dogs was also washed away. People were needed to form bucket lines to remove smaller debris in order to further search the pile. All equipment, including robots, was hand carried into the rubble pile. As the crane operators pulled pieces of debris from the pile, large craters were created for rescuers to work in. An example of such a crater is seen in Figure 3.

Figure 3: A large approx. 40ft. deep crater near WTC 2.
2.2 CRASAR Event Chronology from September 11th to 20th

After the second jet collided with the South Tower of the World Trade Center at 9:03am on September 11th, CRASAR Director John Blitch had already been corresponding with Chief Ray Downey and alerting Dr. Robin Murphy from USF. The USF group, Dr. Robin Murphy, Mark Micire, Brian Minten, and Jennifer Casper, was mobilized from Tampa by 2:30pm, September 11th. John Blitch and the Foster-Miller group, Arnie Mangolds, Jay Haglund, and Gary X, arrived in the New York area early evening on September 11th. By 11am the next morning, they were at Ground Zero on the first robot deployment. At 10am the same day, the USF team arrived in Newburg, NY where the other CRASAR teams were meeting. At 10pm on September 12th, John Blitch escorted the USF and part of the iRobot team to Ground Zero where they met Arnie Mangolds. The 2nd robot deployment began around 2am on September 13th. At 9:30am that morning, CRASAR retreated from Ground Zero to the Javits Center, where the base was set up with FEMA and the FEMA Task Forces, for debriefing. From this point on, the CRASAR team worked out of the Javits Center. The SPAWAR team arrived at Ground Zero a day or two after the attack. John Blitch gave the demobilization of USF, Foster-Miller, SPAWAR, and iRobot the morning of September 17th. Re-assignment to return to Ground Zero the following morning was given the evening of September 17th and was followed by USF, iRobot, and Foster-Miller. iRobot and Foster-Miller finally demobilized on the 19th. USF demobilized on the 21st. John Blitch stayed to continue working at Ground Zero until October 1st. He re-assigned Foster-Miller to return and mobilized a group from the Army EOD during this time.

Nine robot deployments took place between September 11th and the 20th. Table 1 enumerates each deployment, the date and shift, which task force was accompanied, the number of robot operators, the robot equipment used, and any major activity that took place during the deployment. Figure 4 shows a map of Ground Zero with the corresponding deployment number revealing the areas with voids searched by robots during four of the nine deployments and the area damaged buildings were searched during the 7th deployment.

Figure 4: Ground Zero map with marked locations of voids searched by robots.
2.3 Robot Equipment

17 robots were made available by CRASAR for rescue teams to use on site. Figure 5 shows the robot equipment lined up in the rear of the Javits Center (convention center in Manhattan where the FEMA task forces and CRASAR were based). Only the robots used during the rescue effort at the World Trade Center disaster site will be discussed.

Figure 5: Robot equipment stored at the Javits Center.

Seven robots were used to execute three types of tasks: confined space search, semi-structured search, and inspection. These seven robots are listed in Table 2 along with the tasks they were used to perform (further description of the robot tasks can be found in Section 4.1).

The three Inuktun robots are shoebox-sized, multi-tracked, tethered robots that have a common set of sensors: color camera providing the operator with the robot’s eye view of the environment and two way communication through a set of microphone and speakers on the robot and operator control unit. The MicroTracs and VGTV cameras and headlights are mounted on tilt units. The tether provides power, video and two-way communication. The three Inuktuns differ in mobility. The MicroTracs robot has basic maneuverability with the advantage of a higher clearance than the VGTV. The VGTV is a shapeshifting robot, capable of changing shape from a flat formation to a triangular formation. The advantage of this is the higher viewpoint and more maneuverability to traverse obstacles the MicroTracs cannot. The Vertical Crawler is unique in that it may be configured for normal ground traversal or pipe traversal. The Vertical Crawler can handle pipes of different diameters. The operator is also provided with force and angle feedback information. Figure 6 shows the three Inuktun robots.

Figure 6: Inuktun MicroTracs System, VGTV and VersaTrax Vertical Crawler.

The two Foster-Miller robots are suitcase-sized, tracked, wireless robots. Each has two-way communication capability through microphone and speakers and can house multiple color cameras for obtaining different viewpoints. Wireless communication is supported by a two-way RF link between the robot and operator control unit (OCU). The Solem carries a camera on the end of an arm to obtain higher viewpoints. The Solem provides the operator with relative distance information, vehicle heading, and arm angle through use of encoders, compass, and potentiometer. A grid system on the OCU display provides
relative environment object size information. The Talon robot is a little larger than the Solem and contains a removable arm and gripper. A wearable OCU is available for both and contains a hand held display for video, control, VR goggles, battery, etc. Both robots have a high degree of mobility allowing them to traverse stairs and multiple terrains; such as sand and snow. Figure 7 shows the two Foster-Miller robots.

Figure 7: Foster-Miller Solem and Talon.

The iRobot Packbot is a wireless, suitcase-sized, tracked vehicle. The Packbot sensor suite consists of a color camera and inclinometers. An Indigo Alpha miniature FLIR was attached during deployment. On board computing power consists of a Pentium III 700 MHz 100 MHZ bus, and 256 MB 100 MHz SDRAM. The 2.4 GHz radio Ethernet provides wireless communications. The tracked flippers provide the Packbot’s shape shifiting capability. The flippers are used to prop the robot up to obtain a higher vantage point, self-righting, and traverse difficult terrain. Figure 8 shows an image of the iRobot Packbot.

Figure 8: iRobot Packbot.

The SPAWAR Urbot is a wireless, large suitcase-sized, tracked vehicle. The Urbot contains multiple cameras to provide different viewpoints, two way verbal communication and compasses. Headlights in the front illuminate the area ahead of the robot. A front camera with 24x zoom capability allows the operator to zoom in on interesting elements of the environment. The Urbot is invertible in that once turned over, the robot compensates by flipping the video and appropriate controls so the inversion is seamless for the operator. Two on board 66 MHz PowerPC-based ipEngine processors are used for the navigation and sensory controls. A wireless Ethernet link between the robot and OCU is used for communication. Figure 9 shows an image of the SPAWAR Urbot.

Figure 9: SPAWAR Urbot.
3 FEMA Task Force

The purpose of this section is to present the USAR tasks for task forces, pre-existing FEMA USAR Response System, how robot systems may be and have been implemented, and the task force on-site operations. This information presents how professionals currently respond to disaster incidents and how robot systems may be easily added.

3.1 USAR Tasks

The primary task for Urban Search and Rescue teams is to recover victims for maximum recovery. This task is composed of several subtasks, found in [11], organized into four categories that define the organization of a team. The search subtask is locating live victims. The rescue subtasks are evaluation of compromised areas, structural stabilization, breaching and site exploration, and live victim extrication. The medical subtasks are provide potentially prolonged sophisticated pre-hospital and emergency medical care, minimize health risks, intervention of critical incident stress syndrome, limited treatment of hazardous materials exposure, and provide treatment for canines. And the technical subtasks are evaluation of hazardous or compromised areas, structural assessment, stabilization advice, hazardous materials monitoring, liaison with local capabilities, communications and logistics responsibilities, and the information management and documentation requirements of the task force.

3.2 Task Force Organization

A FEMA task force is a 56 member force with 2 task force leaders, 4 DoD Liaisons and Radio Operators, and 4 branches; search, rescue, medical, and technical. Figure 10 shows the task force organization, information hierarchy, and number of each position on a team. The task force leaders are responsible for managing and supervising all search and rescue activities of the task force during mission assignment and communication with the appropriate local authority or incident commander [11]. The task force leaders, DoD liaisons and radio operators provide an interface to the yet larger disaster management organization termed the Incident Command System (ICS). For further description of the ICS, see [2] or [3]. The ICS is most often composed of the local authority. As task forces are deployed to an incident, they are integrated into the ICS. This allows the local authorities to maintain control of a chaotic incident and use valuable outside resources to work in the site. The advantages of this response system are keeping the local authorities and experts in control of the situation but an emotional distance from the incident by utilizing outside resources. And it also keeps from diminishing local resources from responding to other incidents. This
may seem like an iron-clad plan, however it doesn’t work as efficiently if the local authority doesn’t set up the ICS for the task forces. In the case of the World Trade Center disaster incident, these trained individuals were tragically lost when the two towers collapsed after they had already started responding and setting up a base of operations. This resulted in an even more chaotic environment with the lack of authority structure and thousands of emotionally driven firemen, rescuers, family and nation.

Figure 10: Top: FEMA task force organization; the number under each title in every block represents the total positions on the team. Bottom: Adjusted FEMA task force organization for specialty team; additional robot search team in gray print.

3.2.1 Addition of Rescue Robot Team into Organization

The purpose of this section is to discuss how a rescue robot team fits into the pre-existing response organization. This is important, first of all, because a tight response organization already exists and is highly accepted. A time-strained disaster is not the time for experimental equipment and untrained individuals to show up and expect to be successful without any prior training, experience, or knowledge. Individuals who are part of the response organization are more likely to choose equipment and methods that are tried and true.

A rescue robot team’s tasks, discussed in Section 4.1, make the team eligible to belong in all four branches of a task force organization. There are two ways in which a robot team may be added: as a tool, or a specialty team like the canine search teams. As a tool, those who would use it in any of the four branches would have to be trained on it in the same manner used for other tools. Rescuers train on technical search tools during 30-minute session bi-annually in ideal conditions. Figure 11 shows a fireman training on an Inuktun robot during the Nov. 27th - 30th training with Rescue Training Associates (RTA) in Miami, FL. As a specialty team, only certain individuals would be certified to use the robots. These individuals may be civilians not with a fire department, thus requiring a contract with a task force similar to how canine search teams are employed. In the case of the World Trade Center incident, INTF-1, PATF-1, and VATF-2 invited a specialty robot team to assist them. Select CRASAR members and robots were assigned accordingly (see Table 1). The bottom of Figure 10 visually represents how robot search specialists would be added. The dashed lines represent additional branches that may need the robots.
3.3 On-Site Operations

Task forces follow a defined workflow designed for maximum effort from the teams with as little strain as possible on the team members. 56-member task forces divide into two groups in order to cover two 12-hour shifts, as seen during the World Trade Center rescue. The day shift, during the World Trade Center response, was scheduled from 7:00AM to 7:00PM and the night shift from 7:00PM to 7:00AM. Teams boarded buses approximately one hour before the start of the shift and were dropped off at their respective Bases of Operations (BoOs) near the main rubble pile at Ground Zero. Each team constructs a BoO to house equipment, food, medical center, and rehabilitation center for the rescuers upon initial arrival. The BoO is used throughout the 10 days, maximum consecutive days a force may work at a site before standing down [11]. At the end of the shift, the buses were loaded again to return teams to the Javits Center to rehabilitate. During the 12-hour shift, a team is deployed to the rubble pile to work an area, clear it off and search for victims. Specialty teams, such as the canine search team, stay in the BoO until called to the forward station near the pile. This essentially gets the team ready for immediate use. It is common for a specialty team to be returned to the BoO after being called out if the situation changes. The task force handles any victims or important finds immediately unless otherwise specified by the local authority. This information simultaneously travels up the task force's hierarchy to the task force leader who then communicates directly or indirectly with the local authority and any other necessary personnel.

4 Rescue Robot Team

The purpose of this section is to describe how the robots were used and fit into a pre-existing rescue organization, using the World Trade Center disaster incident as the case in study. The following subsections address the topics of the types of USAR tasks robots did and can perform, the members of the rescue robot team, and the team’s workflow as a strike force and as an independent.

4.1 Robot-Assisted USAR Tasks

There are five main robot-assisted USAR tasks: confined space search, semi-structured search, inspection, payloads, and monitoring. Robots were used to perform three of the five tasks during the
World Trade Center rescue effort. Table 3 presents the robot tasks and number of times the tasks were executed during the World Trade Center rescue effort. Confined space search is searching confined spaces. Confined space is defined as "a space that is large enough and so configured that an employee can bodily enter and perform assigned work, has limited or restricted means for entry or exit and is not designed for continuous employee occupancy" [6]. Semi-structured search is the act of searching potentially dangerous structures that are partially standing. Examples of this type of structure would be the damaged buildings surrounding the main rubble pile at Ground Zero. Inspection involves using the robots to structurally inspect the area rescuers are working. In the case of the World Trade Center, the robots were used to assist structural engineers in assessing the safety of sections of the main rubble pile. The payloads task refers to the robots carrying items into unsafe areas. For instance, an Inuktun robot is capable of carrying a medical tube down to a victim for purposes of providing water or fresh air. This would also be useful for checking the air quality. Monitoring air quality is a required continuous task that has been requested to be automated by robots in the future.

4.2 Rescue Robot Team Organization

There are two types of members or agents on a rescue robot team that work together: robots and humans. The rescue robot teams used during the World Trade Center incident consisted of 2 to 4 people with 1 to 3 robots. The Inuktun MicroTracs System and VGTV robots could each be transported and operated by one person; a 1:1 robot to operator ratio. The Foster-Miller Solem and Talon, iRobot Packbot, and SPAWAR Urobot required the use of two people to transport, but only one to operate; a 2:1 robot to operator ratio. The robot search teams deployed with INTF-1, PATF-1 and VATF-2 consisted of 3 people and 2 robots, 2 people and 2 robots, or 4 people and 3 robots (See Table 1). The optimal combination for a robot search team was 4 people with 3 robots deployed with INTF-1. The 4 individuals worked in pairs; one pair was in charge of 2 Inuktuns and the other pair was in charge of the Solem. The diversity in robots provided options for the rescue team leader to chose from, depending on what situation needed use of robots. In the case of the operator pair with 2 Inuktuns, the advantage was redundant robots and operators. The extra operator was needed to assist the primary operator in controlling the tether. In the case of the Solem operator pair, the redundant operators assisted each other while transporting the robot to a part of the rubble pile and the secondary operator was available to assist the primary operator.

The robot equipment varied in levels of intelligence and mobility. Section 2.3 describes the capabilities of the seven robots used during the World Trade Center disaster incident. The Inuktun robots are very primitive in terms of intelligence, but were used 8 of the 9 robot deployments (see Table 1). The iRobot
Packbot was capable of utilizing intelligence, although did not due to the lack of software on the particular Packbot brought. CRASAR members and rescuers, who used the robot equipment, had varying levels of USAR and robot training. The CRASAR director, John Blitch, had basic USAR training and experience in past disaster incidents. The USF team members had experience in the field through trench rescue certification, HAZMAT training, and structural building collapse training. None of the rescuers had experience using robots for USAR purposes. They were then trained during the 8th robot deployment (see Table 1) to use the equipment if the occasion arose.

4.3 On-Site Operations

Robots were implemented into the rescue workflow performing the tasks discussed in Section 4.1 either as a strike force or an independent force. A strike force here means an adjunct addition of an official FEMA task force. As an independent force, the team worked searching the pile independently while under FDNY authority. Six of the nine robot deployments between September 11th and the 20th (See Table 1) were with official FEMA task forces; specifically INTF-1, PATF-1, and VATF-2. During these deployments, the robots and operators were treated like specialty search teams. The operators and equipment were loaded onto the bus one hour before the shift started, stayed at the BoO until needed, and returned to the Javits Center with the task force by bus. One of the six strike force deployments, the 9th robot deployment in Table 1, was unique in having a specialty robot group near Ground Zero limits while two team members and two Inuktun robots were deployed with VATF-2. This group was needed to retrieve the spare Inuktun VGTV and help repair the primary VGTV using parts from the spare. The other three deployments were performed independently, under FDNY authority. During these deployments, the robots and operators naturally divided into smaller specialty search teams. The independent robot search teams were transported to and from the site by means of CRASAR.

Specific timelines from the 6th and 9th deployments provide examples of what a strike force deployment was like. Figure 12 shows the timeline for the 6th deployment. It was common for the robot search team to be called to the forward station (area closest to the rubble pile where the rescue team was working) from the BoO only to be returned to the BoO without being used. During this deployment, a fire flare threatened the safety of the rescue team and caused early termination of the shift. Figure 13 shows the timeline of the 9th deployment. Two robot operators were deployed with VATF-2 while other members of the CRASAR teams waited in case outside assistance was needed. During the deployment, one void was searched twice. The timeline shows the small amount of time the robots spent in the void versus the time in the field. Eight confined spaces were searched in 9 deployments taking place from September 11th -
20th. Robots were dropped into the same void multiple times while searching three of the confined spaces. The average time a robot spent in a void was 6 minutes, 44 seconds. Table 4 shows the breakdown of times in voids used to calculate the average.

Figure 12: Timeline of the 6th robot deployment in Table 1.

Figure 13: Timeline of the 9th robot deployment in Table 1.

5 Evaluation of Robot Performance

Previous sections have provided information of the World Trade Center disaster incident, how the FEMA USAR Response Systems works, how robots may be implemented into this system and have been during the World Trade Center response, what the robots were used for, and how CRASAR responded to the incident and operated. The purpose of this section is to present an evaluation of the robot performance. The evaluation is based on observed events during the World Trade Center response and direct discussion with the rescue professionals who were involved in the robot deployments. The evaluation is divided into three categories: human factors, information and distribution, and user interfaces.

5.1 Human Factors

Acceptance of robot technology is questionable. During the World Trade Center rescue effort, rescuers expected less than 1.5 minutes to set up the robot equipment. The current technical search equipment used, such as search cams and fiber optic cams, require less than 1.5 minutes of set up time. Rescuers questioned how to integrate robotic systems as they are familiar with search tools or canine search teams. Section 3.2.1 describes the differences and advantages/disadvantages in further detail.

The World Trade Center disaster incident inflicted more cognitive fatigue than physical fatigue on the rescuers and roboticists. As discussed in Section 2.1, the environment conditions were good relative to past disaster incidents thus relieve much physical fatigue. However, the emotional and mental stress of the situation inflicted a great deal of cognitive fatigue. Robots should not add to the cognitive fatigue. Unfortunately, the robots added to the operator's fatigue by requiring the operator to perform the in-
elligent tasks. The primitive control units and robots left the operator concentrating on navigation and victim searching. An operator cannot perform both tasks well due to deliberately dividing concentration, as discussed in [9].

**Multiple human-robot relationships require different interfaces.** Multiple relationships result from information being distributed to others besides just the operator, as discussed below in Section 5.2. Different individuals need different information. The interface changes depending upon what information needs to be provided.

### 5.2 Information and Distribution

The robot operator is not the only individual who needs feedback from the robot/s. Strong recommendations were made for **robot information to be distributed.** Key members within the task force hierarchy and ICS need certain types of information. Section 3.2 and Figure 10 describe the ICS and task force hierarchy in greater detail. The robot operator was not experienced enough to know what to look for in terms of victims, remains, or key objects. It would have been helpful to have experts viewing the video footage simultaneously during the World Trade Center disaster incident. Special Operations Chief of Hillsborough County, Ron Rogers, found a watch in the CRASAR video footage of the 8th void search during the 9th deployment after the USF team returned to Tampa. The following is a list of key members that the robot operator needs to share findings with:

- Robot Operator
- Robot Search Leader
- Search Team Leader
- Task Force Leader
- Sector Chief
- Incident Commander (IC)
- Structural Specialists
- Robot Specialists
- Backup Specialists
The list is ordered in increasing command. For instance, the Robot Search Leader is in charge of the robot operator and reports to the Search Team Leader. The last three members listed are unique in that outside specialists are either brought into the incident to assist temporarily or contacted remotely. The information being fed off of the robot needs to be properly analyzed and passed on to the appropriate individuals in a timely manner. Figure 14 visually demonstrates how the key members are placed within the hot, warm and cold zones of a disaster incident [3].

Figure 14: How the key members are placed within a disaster incident.

Little information was available for the operator regarding the state of the robot. In most cases, the only feedback to the operator was video of the robot’s eye view. Table 5 lists the types of errors observed during the September 11th - 20th deployments at Ground Zero, how the errors were detected, how the robot recovered, and the average detection and recovery time. All failure detection methods involved concentrating on the robot eye view while testing the robot. Failure detection is crucial to prevent time wasted trying to figure out what has failed. The xth error in Table 5 occurred during the 2nd deployment. The operator ended up spending x time figuring out what was preventing robot movement and recovering from the error before the robot returned to searching the void (see Figure 15 for images of the lodged metal rod from the robot’s eye view and an external view). During this time, the operator was consumed with helping the robot and not searching for victims. Considering the average time a robot spent searching a void is 0:6:44 (see Table 4), the amount of time wasted recovering the robot is significant. Also x time was spent recovering the MicroTracs after the headlamps burnt out during the 9th deployment, only to have the replacement robot throw a track. The primary recovery method involved yanking the robot out of the void. The secondary method involved tugging or shifting the tether or rope to assist the robot. More graceful detection and recovery methods are needed if just for the sake of saving time.

Figure 15: Images of metal rod from the robot view and external view.

Little information was also available for the operator regarding the state of the world. None of the equipment at the World Trade Center had the ability to inform the operator of the location of the robot in the world. This information is acceptable in either metric or topographic form. The point is to provide the location of the robot in a way that rescuers will know what areas have been searched and if a
victim is found, how to get to that victim. If the robot knows where it is, then it may provide a relative location of where a found victim is. During the 2nd and 9th robot deployments, the operator didn’t know how far the robot had traveled in what direction or orientation. The weight of the robot at the end of the tether gave an idea of the travel direction. The tether was measured in arm lengths when the robot was pulled out. Object recognition is another crucial ability for the robot to have. The most important is live victim recognition. The operator is not always fully concentrated on searching for victims [9], thus assisting the operator by automating perception may be useful [10]. Identifying bodies or remains are helpful in guiding the search and for future recovery. DNA testing was implemented during the World Trade Center rescue effort to help identify those lost. The robots would be of use in providing closure for families by identifying bodies and remains for recovery. It is equally as important to identify key objects. During the World Trade Center rescue, the black boxes were a priority. Another example of a key object is any item that is shiny or looks out of place shape-wise. The watch, as seen through the robot’s eye view in Figure 16, was recognized by Special Operations Chief Ron Rogers one week after the USF team returned to Florida. Personal items, such as the watch in Figure 16, help direct the search. Rescue professionals keep an eye out for these finds when searching for victims. Environment conditions are crucial in letting the operator know if the environment is hazardous. The operator had no idea of the temperature in the void during the 9th deployment which caused the robot track to soften, leaving the robot immobilized.

Figure 16: Watch found in the 8th void searched in the 9th deployment.

Information regarding the state of what has been seen involves human-robot collaborative identification and mapping. Human-robot collaborative identification and mapping may be defined as determining what viewpoints have already been seen for object recognition and mapping. An example of when this information would have been useful was during the 2nd robot deployment at the World Trade Center, a piece of metal was mistaken for a boot by many individuals until the video was rewound far enough to obtain a different viewpoint. Figure 17 shows images of the metal object from two different vantage points.

Figure 17: Images of the piece of metal mistaken for a boot taken from two different vantage points.

Information needs to be delivered to the appropriate individuals within one of three different time frames: immediately, within the shift, or on demand. Table 6 shows who might need what information
when. For instance, the operator will receive robot, world and previously seen information immediately.
The search team leader only needs the world and previously seen information within the shift. Technology
may be able to assist in quickly distributing information, but bandwidth will be limited. Object identifi-
cation will improve with more sets of eyes viewing the robot video. Personnel in the B0O may be able to
help, or outside specialists whom the video/information is being distributed to.

5.3 User Interfaces

**USAR user interfaces need improvement.** Section 2.3 describes the robot equipment used during
the World Trade Center rescue. In Figure 18, the Packbot control unit is on the left and a screen shot of
the user interface on the right. Figure 19 shows the control unit used for the Talon and Solem. A screen
shot of the user interface using the relative sizing grid is on the right. Figure 20 presents the Urbot control
unit and screen shot of the user interface including on screen menu options. And lastly, Figure 21 shows
the control units for the MicroTracs, VGTV, and Vertical Crawler and a screen shot of the user interface.

Figure 18: iRobot Packbot user interface.

Figure 19: Foster-Miller Talon and Solem user interface.

Figure 20: SPAWAR Urbot user interface.

Figure 21: Inuktun MicroTracs System, VGTV and Vertical Crawler user interfaces.

Over all, the **user interfaces were sensor impoverished.** The MicroTracs and VGTV provided
the operator with basic controls: headlight function, forward, back, left and right traversal, camera tilt,
camera focus, and, in the case of the VGTV, platform height control. The only feedback to the operator
was the robot’s eye view on a hand held display and two-way communication through speakers and a
microphone on both ends. The Solem, Talon and Urbot are similar in terms of feedback from the robot.
The control units are different in basic design and added functionality depending upon the robot. For instance, the control unit for the Solem includes basic traversal and ability to move the arm with the camera on the end of it.

The **visual channel appeared to be inappropriately used**, or under-used depending upon the viewpoint. The color video was the only means by which the operator had to determine the status of the robot and its location in the environment, and search for victims. Figure 22 is an example of a disorienting interface. In this case, the robot had flipped over quickly while searching a void during the 8th robot deployment. The robot's orientation, or what had happened, was not known as it happened so quickly and the only feedback from the robot was video. The Urbot is programmed to compensate for this special case by automatically adjusting the user's display. The **audio channel appeared inappropriately used**. It was used, however, for diagnostic purposes. For example, when the MicroTracs lodged itself on a metal rod during the 2nd robot deployment, the operator listened to the strain of the motors to help determine that the robot was trying to move but was blocked.

Figure 22: Disorienting user interface example when Solem flipped upside down in a void during the 8th robot deployment.

The color video is necessary, but the **usefulness or uselessness of the FLIR** was never determined as it wasn't used extensively during the void searches. The FLIR was too large to attach to the Inuktuns. The Packbot used the FLIR briefly during the 7th deployment while searching the damaged building. It appeared to be of little use navigating. Past research has shown the FLIR to be useful searching for live victims [9]. It has also been suggested by rescue professionals that the FLIR may be useful in locating remains after a period of time.

Although it may be agreed upon that the user interfaces discussed in the previous paragraphs are too simple of a design, a **complex user interface** designed for the roboticist and not the general user may be detrimental to the application of USAR robots. Figure 18 shows the Packbot's user interface. Clearly it is more complex than the other user interfaces. This brings to surface the issue of what a USAR user interface should look like and contain.

As more sensors are added to a USAR robot, the issue of **sensor adaptability relating to user interfaces** arises. For example, range information is useful while navigating the robot. Multiple sensors provide range information, such as ultrasonic sensors and lasers. The user interface should be able to adapt,
perhaps use a similar display, to the range sensor being used without making it painfully obvious to the operator. Otherwise, the operator is forced to mentally compensate for the user interfaces insufficiencies while working in an already stressful environment. The FLIR was added to the Packbot for the 7th robot deployment, but the robot operator had to deliberately switch between the color camera and the FLIR. The operator had to deliberately switch between color and IR.

The **user interface appearance** is also an issue. Appearance will often affect how quickly an individual may learn the interface. A more complex design may be intimidating, thus straining the individual’s ability to learn. The technical search equipment used for USAR, such as search cams, has simplistic and touchable interfaces. Robot interfaces must look inviting to use in order to further encourage rescue professionals.

## 6 Summary

Many lessons on human robot interactions were learned during the World Trade Center disaster incident. Support for the lessons are found in previous four sections. The lessons are summarized here using the human robot interaction definition. Human robot interaction is the space in which the agent system works that includes the task, agents and skill, environment and conditions, social informatics, and communication. The five HRI elements are divided into the ecological niche and social niche.

The ecological niche for Urban Search and Rescue human robot interactions (USAR HRIs) is comprised of three parts: tasks, agents and skills, and conditions or environment. The **main robot tasks performed** were searching confined spaces and semi-structures for victims and inspecting structures for safety. The robots were also capable of payloads and monitoring although they were not required to do so during this incident response. The only **two types of agents involved were robots with varying intelligence and humans with varying levels of USAR and robot training**. Section 2.1 provides a description of the environment in which the USAR agents worked.

The social niche for USAR HRIs contains two major categories: social informatics and communication. Social informatics contains two major lessons. First, **information from the robot/s needs to be distributed**. Second, **human factors affect robot usage**. Three minor lessons provide support for this major lesson. The acceptance of robot technology is questionable. More cognitive fatigue than physical fatigue was inflicted on rescuers in this incident. Also, multiple human robot relationships, resulting from the need for distributed information, requires wider acceptance by rescuers and different interfaces providing appropriate information.
Three major lessons and eleven total minor lessons are categorized under communication. First, **USAR user interfaces need improvement**. The user interfaces were sensor impoverished. Both the audio and visual channels appeared to be inappropriately used as well. The complex user interfaces available were undesirable. The true advantage of adding a FLIR to the user interface is unclear at this time. User interfaces need to adapt to different sensor types. Also, user interface appearance is a factor when learning the technology. Second, **more types of information is needed from USAR robots**. Specifically needed are, information of the state of the robot, state of the world, and state of what has been seen. Third, **types of information from robot/s need to be distributed at appropriate times**. These times are loosely defined as immediately, within the shift, and on demand.

World Trade Center disaster incident provided an unfortunate case study for the use of robots in Urban Search and Rescue. The invaluable lessons learned during the incident contribute to the field of Urban Search and Rescue robotic systems research by defining Urban Search and Rescue human robot interactions (USAR HRIs). The USAR HRI definition in turn is used to guide USAR robotic systems research by providing a knowledge base for continued USAR robotic systems research.

**Acknowledgments**

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**References**


[8] FEMA equipment list.


[10] anything supporting perception automation?


<table>
<thead>
<tr>
<th>Deployment#</th>
<th>Date/Shift</th>
<th>Task Force</th>
<th># Robot Operators</th>
<th>Robot Equipment</th>
<th>Activity and Void# (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9/12/01 Day Shift</td>
<td>FDNY</td>
<td>2 for MicroTracs</td>
<td>MicroTracs</td>
<td>Used robot to <em>search two voids</em> 1. Sewer pipe void. 2. Void led to a boiler room.</td>
</tr>
<tr>
<td>2</td>
<td>9/13/01 Night Shift</td>
<td>FDNY</td>
<td>3 for MicroTracs</td>
<td>2 MicroTracs</td>
<td>Used robot to <em>search four voids</em> 3. Void led to an area where rescuers were actively working. Robot was dropped into the void twice. 4. Void, vertical core support from towers, contained unrecognizable remains of approximately 2 victims. 5. Void, vertical core support from towers, was similar and close to the previous void, but was bare except for the small amount of water at the end. 6. Void contained large amounts of metal debris; robot was dropped in the void twice due to lodging itself on a metal stick and needing to be removed during the first drop.</td>
</tr>
<tr>
<td>3</td>
<td>9/14/01 Day/Night Shift</td>
<td>Army</td>
<td>1 for MicroTracs</td>
<td>MicroTracs</td>
<td>Deployed with army group.</td>
</tr>
<tr>
<td>4</td>
<td>9/14/01 Night Shift</td>
<td>INTF-1</td>
<td>1 for MicroTracs 2 for Solem</td>
<td>VGTV, Solem</td>
<td>Deployed with Indiana Task Force 1 for 12-hour night shift.</td>
</tr>
<tr>
<td>5</td>
<td>9/15/01 Day/Night Shift</td>
<td>PATF-1</td>
<td>1 for MicroTracs 1 for VGTV</td>
<td>MicroTracs, VGTV</td>
<td>Deployed with Pennsylvania Task Force 1. Called in rubble pile 4 times but had to evacuate before dropping robot.</td>
</tr>
<tr>
<td>6</td>
<td>9/15/01 Night Shift</td>
<td>INTF-1</td>
<td>1 for MicroTracs 1 for VGTV 2 for Solem</td>
<td>MicroTracs, VGTV, Solem</td>
<td>Deployed with INTF-1 for 12-hour night shift. Called to forward station twice.</td>
</tr>
<tr>
<td>7</td>
<td>9/15/01 Night Shift</td>
<td>FDNY</td>
<td>‘8 total</td>
<td>Urbot, Talon, Packbot</td>
<td>Independently deployed to inspect surrounding damaged buildings.</td>
</tr>
<tr>
<td>8</td>
<td>9/16/01 Night Shift</td>
<td>INTF-1</td>
<td>1 for MicroTracs 1 for VGTV 2 for Solem</td>
<td>MicroTracs, VGTV, Solem</td>
<td>Deployed with INTF-1. Trained INTF-1 members to use the MicroTracs, VGTV and Solem robots while at the BoO. <em>Searched one void</em> using the Solem. 7. Lost communications with the Solem in an unsafe void and ended up losing it without recovery.</td>
</tr>
<tr>
<td>9</td>
<td>9/18/01 Night Shift</td>
<td>VATF-2</td>
<td>1 for MicroTracs 1 for VGTV</td>
<td>MicroTracs, VGTV</td>
<td>Deployed with Virginia Task Force 2. <em>Searched one void</em> containing semi-recognizable remains of approximately three victims. 8. The MicroTracs blew its lights during the first drop. It was pulled out and replaced by the VGTV, which threw its track. Both failures are believed to be due to the extreme heat in the void.</td>
</tr>
</tbody>
</table>

Table 1: Description of 9 robot deployments.
<table>
<thead>
<tr>
<th>Robot</th>
<th>Confined space search task (Week 1 - 2)</th>
<th>Semi-structured search task (Deployment 7, Day 5)</th>
<th>Inspection task (Week 2 - 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inuktun MicroTracs System</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Inuktun VGTV</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Inuktun VersaTrax Vertical Crawler</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Foster-Miller Solem</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Foster-Miller Talon</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>iRobot</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SPAWAR Urbot</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 2: Robots used during the World Trade Center rescue for what tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th># Times Executed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confined Space Search</td>
<td>8 voids searched</td>
</tr>
<tr>
<td>Semi-structured Search</td>
<td>1 structure</td>
</tr>
<tr>
<td>Inspection</td>
<td>GET FROM FM VIDEO</td>
</tr>
<tr>
<td>Payloads</td>
<td>n/a</td>
</tr>
<tr>
<td>Monitoring</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 3: Robot tasks and number of times executed during the World Trade Center rescue.
<table>
<thead>
<tr>
<th>Void#</th>
<th>Deployment#</th>
<th>Time (h:m:s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0:5:39</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>3a</td>
<td>2</td>
<td>0:2:49</td>
</tr>
<tr>
<td>3b</td>
<td>2</td>
<td>0:2:52</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0:24:40</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0:3:58</td>
</tr>
<tr>
<td>6a</td>
<td>2</td>
<td>0:4:10</td>
</tr>
<tr>
<td>6b</td>
<td>2</td>
<td>0:2:49</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0:6:55</td>
</tr>
<tr>
<td>8a</td>
<td>9</td>
<td>0:6:36</td>
</tr>
<tr>
<td>8b</td>
<td>9</td>
<td>0:6:55</td>
</tr>
<tr>
<td>Avg. Time in Voids</td>
<td></td>
<td>0:6:44</td>
</tr>
</tbody>
</table>

Table 4: Average times spent in 8 voids searched in 9 deployments.

<table>
<thead>
<tr>
<th>Failure</th>
<th>Detection Method</th>
<th>Recovery Method</th>
<th>Detection and Recovery Time</th>
</tr>
</thead>
</table>

Table 5: Table of observed failures.

<table>
<thead>
<tr>
<th>Key Members</th>
<th>Robot Info.</th>
<th>World Info.</th>
<th>Seen Info.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
<td>Immed.</td>
<td>Immed.</td>
<td>Immed.</td>
</tr>
<tr>
<td>Technical Rescue Leader</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td></td>
</tr>
<tr>
<td>Search Team Leader</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td></td>
</tr>
<tr>
<td>Task Force Leader</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td></td>
</tr>
<tr>
<td>Sector Chief/IC</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td></td>
</tr>
<tr>
<td>Structural Engin.</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td></td>
</tr>
<tr>
<td>Robot Specialists</td>
<td>Within Shift</td>
<td>Within Shift</td>
<td>Within Shift</td>
</tr>
<tr>
<td>Backup Specialists</td>
<td>On Demand</td>
<td>On Demand</td>
<td>On Demand</td>
</tr>
</tbody>
</table>

Table 6: Time period key members need to receive information types.