Human–Robot Interactions During the Robot-Assisted Urban Search and Rescue Response at the World Trade Center

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***Abstract*—The World Trade Center (WTC) rescue response provided an unfortunate opportunity to study the human–robot interactions (HRI) during a real unstaged rescue for the first time. A post-hoc analysis was performed on the data collected during the response, which resulted in 17 findings on the impact of the environment and conditions on the HRI: the skills displayed and needed by robots and humans, the details of the Urban Search and Rescue (USAR) task, the social informatics in the USAR domain, and what information is communicated at what time. The results of this work impact the field of robotics by providing a case study for HRI in USAR drawn from an unstaged USAR effort. Eleven recommendations are made based on the findings that impact the robotics, computer science, engineering, psychology, and rescue fields. These recommendations call for group organization and user confidence studies, more research into perceptual and assistive interfaces, and formal models of the state of the robot, state of the world, and information as to what has been observed.**

***Index Terms*—Human-robot interaction, urban search and rescue, World Trade Center (WTC).**

I. Introduction

THE September 11, 2001 attack on the World Trade Center (WTC) Towers [1] resulted in a mass casualty incident requiring the resources of search and rescue teams from across North America, volunteers, and large equipment companies. Specialized equipment, such as robot equipment, was also required to enter miniature voids and areas too hot or unsafe for humans. For the first known time, robots were actually used for technical search tasks in an Urban Search and Rescue (USAR) [2]. The robots were brought to Ground Zero by the Center for Robotic Assisted Search and Rescue (CRASAR) under a standing invitation from Fire Department New York (FDNY) Special Operations Chief Ray Downey, and later tasked by the New York City Office of Emergency Services. John Blitch, the director of CRASAR, led groups from the University of South Florida (USF), Foster–Miller, iRobot, Space and Naval Warfare Systems Center (SPAWAR) and the Picatinny, NJ, Arsenal Army Explosive Ordnance Disposal (Army EOD) to join CRASAR and assist with the rescue.

CRASAR arrived at Ground Zero on September 11 and demobilized on October 2. The two-part response consisted of the *rescue phase* (September 11–21) and the *inspection phase* (September 22–October 2). This article evaluates data collected and findings from the rescue phase of September 11–21. The focus of the rescue phase was the use of robots to search for victims and examine voids that could not be examined by humans or dogs. CRASAR teams deployed eight times to the rubble pile during the rescue phase, five of which were with Federal Emergency Management Agency (FEMA) task forces. Video recordings of the robots' camera output were made during the rescue phase. The focus of the inspection phase was to examine areas beneath the rubble pile under the direction of structural engineers from New York City Department of Design and Construction (DDC). Video recordings were not consistently made during the inspection phase and so an analysis could not be conducted. The remains of 10+ victims were found; 5+ during the rescue phase and 5+ during the inspection phase (the nature of the remains makes it impossible to adequately count).

The motivation for rescue robots is multifold. First, miniature robots can go into places that living things cannot due to size, extreme heat, toxicity of the environment, etc. Second, rescue safety and effectiveness is a serious issue. In the case of the Mexico City earthquake in 1985, 135 rescuers died; 65 of those deaths were due to rescuers searching confined spaces that flooded [3], [4]. We note that robots are expendable. Rescuers in the United States must adhere to the Occupational Safety and Health Administration (OSHA) standards, leading to over one hour of preparation for human entry. Third, a robot can be deployed in minutes. Finally, there are not enough trained individuals to perform the multitude of tasks during a rescue: search, extract, examine, inspect, and medically treat. It takes an average of ten trained professionals four hours to remove a victim simply enclosed in a void space and ten trained professionals ten hours to remove an entombed victim [5]. In addition, robots can aid in medical support by providing comfort through two-way audio, delivering medication and biosensors, and even helping place shoring devices and monitor shoring during extrication.

However, current mobile robot technology is not advanced enough for fully autonomous rescue robots and regardless, such robots will have to work with people. Therefore human–robot

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interaction is a key component of a successful rescue system. Following the DARPA/NSF Study on HRI [6], human–robot interaction is defined as the niche in which the agent system works. This niche space is the conjunction of two spaces: the *ecological niche*, used in behavior-based robotics [7], and the *social niche*, a concept emerging in the multiagent community. Note HRI is more focused on agency than on human factors and ergonomics typically associated with human–computer interaction (HCI).

The ecological niche consists of the environment and conditions, agents, and task. *Environment and conditions* are defined as the situation and atmosphere the agents are working in and largely define the domain. The conditions and environment will vary widely between domains. They cannot be changed in order to make the domain easier for the robot to work in; otherwise the result is an entirely different domain. *Agents* are the physically situated entitites that perform the domain task. The agents' cognitive and physical abilities define an agent's skill. Skill sets can be adjusted through hardware and software improvements on robots or training and education for humans. The *task* is the assignment the robot needs to fulfill. The task for a particular field, such as USAR, cannot be changed for the purpose of making the field easier for the robot to work in.

The social niche consists of the social informatics and communication between agents. *Social informatics* is defined as the agents' roles, how they organize, collaborate, interact with each other, and transition between roles. *Communication* is defined by the types of information shared or transmitted, how they are represented, time dependencies, and actual interfaces. The robots' physical interactions with the environment and how that is presented to people are categorized as communication interactions.

The article is organized as follows. Section II examines the body of related work on USAR as a robotic domain, hardware and software development, humans as part of the USAR team, and simulated USAR domains. Section III continues with a discussion of the robot-assisted response in terms of environment and conditions, agents and skills, tasks, workflow and operations, and data analysis. The post-hoc data analysis performed on the data collected during the rescue phase of the response (September 11–21) is described in Section IV. Section V presents the findings that resulted from the post-hoc data analysis. Section V-F discusses the consistency of the findings with findings resulting from staged USAR responses. Section VI contains recommendations for USAR HRI based on issues revealed by the findings in Section V. Section VII concludes by providing a summary for USAR HRI research through prioritized HRI research issues. In particular, the results indicate that robots are better at perception in this extreme environment than humans; therefore image processing and perceptualization is essential for future success and acceptance by fire rescue professions.

II. Related Work

The idea of USAR as a humanitarian research domain for robotics researchers was reinforced by the 1995 Oklahoma City bombing and the Kobe, Japan, earthquake [4], [8]–[11]. The literature shows that very little actual field work has been conducted in rescue robots and in most cases the human–robot interaction has been neglected.

As detailed in [12], USAR robotics work has concentrated on *platform development* [13]–[24] and *software development* [13], [25]–[29]. The robot platforms for USAR vary widely in terms of size, type of mobility (wheels, tracks, or combination), and ruggedness. In [13] and [14], the idea of marsupial and shape-shifting robots for USAR is explored. In [16], [23], and [24], biologically inspired snake robot platforms for USAR are explored. Fire rescue and outdoor robot developments are investigated in [15], [17]–[22]; however, these hardware developments have not been thoroughly tested during staged and unstaged USAR responses.

Software development for USAR has involved creating software for robot control, multirobot collaboration, multisensor control, and aiding humans using robot equipment. In [13], the idea of automated behaviors for shape-shifting robots is presented. Collaborative USAR robots are explored in [25]. A multiple sensor control system on a USAR robot is investigated in [26]. Software developed to aid the human operator through an intelligent expert system and mixed-initiative system is described in [27]–[29]. These preliminary software developments have not been thoroughly tested in USAR situations nor did they significantly contribute to the WTC robot-assisted rescue response in terms of human–robot interaction.

Efforts have been made to identify the research issues associated with the human as a part of the robot team for [12] and [27]–[30]. Previous field tests, such as that described in [12] and [30], have attempted to characterize human–robot interactions for USAR during staged field tests but only report findings from a simulated response, not a real response. A staged USAR response cannot fully simulate all aspects of an unpredicted response; such as unforeseen weather and environmental conditions, emotions, and time pressured situations. Thus findings from an unstaged USAR response are not always useful in providing findings from a situation that was not prepared for. Section V-F further discusses this topic.

It is difficult for researchers to thoroughly test equipment and software intended for USAR without an environment that closely simulates real disaster environments. The National Institute of Standards and Technology (NIST) developed a USAR testbed for the RoboCup/AAAI Robot Urban Search and Rescue competition. The competition has been in effect since 2000 [31]–[36]. The goals of the competition are to promote research in the USAR domain for the development of intelligent fieldable robotic systems and allow testing of current robot systems [37], [38]. However, as noted in [39] and [40] the testbed does not closely simulate a USAR site.

Minimal human–robot interaction research, software development, and hardware development has been performed for USAR due to the lack of USAR testbeds and difficulties of working within the USAR field (logistics of finding a USAR training site, obtaining permission, logistics of taking equipment to the field, etc.) The developments for USAR, such as those in [13]–[22] and [25]–[29], have not been thoroughly tested in USAR situations, and do appear to take advantage

Fig. 1. Views of the rubble pile consuming WTC 1, WTC 2, WTC 3, and WTC 7.

Fig. 2. Damaged buildings surrounding the main rubble pile at Ground Zero.

of findings from staged USAR studies such as those in [12], [30], [37], and [38]. The staged USAR studies provide findings from prepared events that cannot simulate all of unpredictable aspects of a USAR response, as discussed in Section V-F. Thus, unstaged events like the WTC robot-assisted response provide valuable findings to contribute to future USAR robotic research.

III. World Trade Center Disaster Rescue Response

This section provides an overview of the disaster environment, the CRASAR team, robot-assisted response, and response analysis, setting the foundation for the findings in Section findings. In particular, it highlights an issue in human–robot ratios: the number of people needed to transport the robot may be different than the number of people needed to operate the robot. This section essentially provides an ontology of the USAR domain.

A. Ecological Niche

The environment and conditions, agents, and robot-assisted tasks define the ecological niche for USAR. The three subniche categories are described in the following sections.

1) Environment and Conditions: The WTC complex included seven buildings (denoted as WTC 1–7). The main rubble pile consisted of WTC 1, WTC 2, WTC 3 and WTC 7, all of which collapsed on September 11. Fig. 1 shows images of the rubble pile (for video of rubble in WTC 2 area, see attachment 1 and attachment 2 or pitsweep.mpg and day2sweep.mpg at http://www.csee.usf.edu/robotics/crasar/movies/). WTC 4, WTC 5, and WTC 6 were partially erect but highly unsafe. Surrounding buildings were still standing, but were damaged and unsafe. Fig. 2 shows images of damaged buildings surrounding the main rubble pile. Unlike previous earthquakes and disasters where furniture and other recognizable items littered the site [41]–[43], paper, dust, and metal were the three main materials found in the rubble pile.

The rubble created challenging terrain for the robots. Robot operators had to carry the equipment onto the rubble pile in order to get near voids or areas needing to be searched because the robots could not traverse the rubble alone. Fig. 3 shows a below grade area approximately 2.5 stories deep. The robot operators had to haul the equipment down a ladder, walk across the bottom, and up the other side to search the assigned void. Extreme heat sources deep within the pile were threatening and caused softening of robot tracks that led to immobilization

Fig. 3. A large (approximately 12.19 m deep) crater near WTC 2. The white square marks the entrance to a void searched, approximately 0.3 × 0.5 m cross section.

TABLE I
ROBOTS BY SIZE CLASS AND VOID TYPE. THE MAJORITY OF VOIDS EXPLORED BY ROBOTS AT WTC WERE $d \leq 0.5\ m$, WHERE d IS THE AVERAGE CROSS SECTION DIAMETER

Class	*Model*	*Void Type Suitability*		
		$d \leq 0.5m$	$0.5m \leq d \leq 2.0m$	semi-structured
Man-packable	MicroTracs	X	X	X
	MicroVGTV	X	X	X
	Packbot		X	X
	Solem		X	X
	Urban		X	X
Man-portable	ATRV			X
	Mini-Distruptor	X	X	
	Pipe Crawler	X		
	Talon			X
	Urbot			X

during the eighth deployment. The density of the terrain also interfered with wireless network control of the Solem robot which was abandoned during the seventh deployment after communication loss left the robot unoperable.

2) Agents: The CRASAR teams consisted of two types of *physically situated* agents: humans and robots. Each agent had a different set of skills. The human agents were responsible for operating and transporting the robots during the eight deployments and drops.

While ten different models of robots were at the response, only three models were actually used on the rubble pile during the rescue phase (MicroTracs, MicroVGTV, and Solem). See Table I for a model listing by size class and void type. The decision of what robots to use was made by the FEMA task force leader or the FDNY section chief. The rescuers weighed potential benefit versus safety and whether they could be trained to use the robots if the situation was too dangerous for CRASAR members. Once in the Hot Zone, the technical search leader decided if a particular robot was appropriate for a void. For example, the leader would decide whether it was acceptable to deploy a robot at all, given that none of the robots were intrinsically safe. In most cases, the teams went out with either two micro robots (the size of shoe boxes) or one micro robot and one mini robot (the size of a carry-on suitcase). Due to the small size of the voids, the micro robots were often the only robot that could fit and so were deployed despite any added risks.

Six *man-portable* models (Foster–Miller Talon, Inuktun Pipe Crawler, Inuktun Mini-Disruptor, iRobot ATRV, SPAWAR Urbot) were too large to be carried in one or two backpacks and so could not be physically transported into the rubble. Of the five remaining models of *man-packable* robots, the iRobot Urban was not used because they were too fragile; they were prototypes for the DARPA Tactical Mobile Robots program and not intended for actual field work. The iRobot Packbot was the hardened version of the Urban, but the FEMA teams declined to permit it on the rubble pile for two reasons. First, although the robot platform was hardened, the operator control interface was not. It had been constructed from consumer game joysticks and a laptop and was not suitable for field work. Second, the user interface was an internal developer's interface, not the final interface being developed by a separate DARPA contractor. The user interface was deemed by the rescuers as too hard to use. This left the Inuktun microtracks and Inuktun MicroVGTV models, each of which could be carried in a single backpack, and the Foster–Miller Solem, which could be carried by two people. The Inuktun micromodels were used in seven of the eight drops in the rubble pile because they were the smallest robots; many of the voids had a cross section of less than 0.5 m. The robots are discussed in more detail below.

Each of the fielded robots was battery-powered and could operate for at least seven hours continuously with one charge, and the Packbot could have operated for four hours. Onboard software for autonomy would not have changed the energy profile; the Inuktuns and Solem do not have true onboard computation, and while the Packbot does, the CPU cycles do not significantly alter the power consumption.

The two Inuktun robots are shoebox sized, multitracked, tethered robots that have a maximum speed of 30 ft/min and a common set of sensors: 53° field-of-view color CCD camera on a tilt unit (viewable remotely on a Sony TRV camera) and two-way audio through a set of microphones and speakers on the robot and operator control unit. The MicroVGTV is a shape-shifting robot, capable of changing shape from a flat formation to a triangular formation, standing 10.5 in high in the highest formation. The operator control unit consists of a Sony TRV camcorder for displaying the video from the robot and a joystick control unit for operating the robot. Fig. 4 shows the Inuktun MicroTracs Systems and MicroVGTV robots, and the control unit.

The two Foster–Miller robots are suitcase-sized, tracked, wireless robots. The common sensor suite consists of encoder feedback, three-axis compass, arm position feedback, and color CCD cameras. The Solem's camera is on the end of a 10-in-long arm on top of its body. The Talon has two cameras and a two-stage arm with a gripper attached topside. The operator control unit includes a joystick control contained in a 20-lb carrying case. Fig. 5 shows the two Foster–Miller robots.

The iRobot Packbot is a wireless, suitcase-sized, tracked vehicle with a maximum speed of 3.7 m/s. The sensor suite consists of an 84° field-of-view low light camera and 118-degree field of view color CCD camera. It is waterproof up to 3 m. The flippers provide self-righting capability and the ability to

Fig. 4. (Top) Inuktun MicroTracs System, (center) MicroVGTV, and (bottom) control unit. Courtesy of Inuktun Services Ltd.

increase the height of the camera on top. The on board computer is a Mobile PIII 700 MHz core running Linux. The operator control unit consists of a laptop running iRobot proprietary software for the interface and combination keypad and joystick for robot control. Fig. 6 shows an image of the iRobot Packbot.

The SPAWAR Urbot is a wireless, large suitcase-sized, invertable, tracked vehicle. The sensor suite consists of a Sony EVI-330/T camera system, two low-silhouette drive cameras on the top and bottom, attitude sensor to detect inversion, electronic compasses, and two-way audio through speakers and microphone. Two 66 MHz PowerPC-based ipEngines provides onboard computing power. The operator control unit consists of

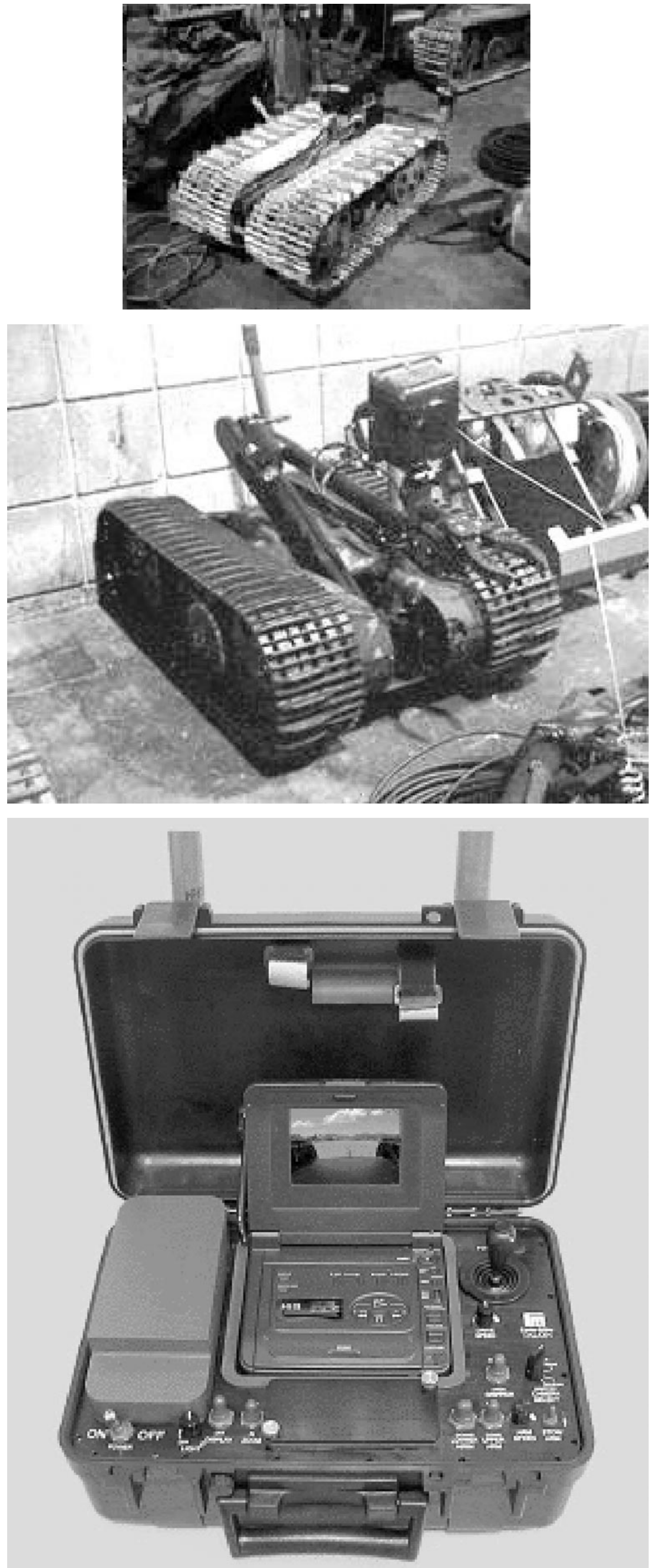


Fig. 5. (Top) Foster–Miller Solem, (center) Talon, and (bottom) control unit. Bottom image courtesy of Foster–Miller.

a 5–in handheld display and push-button control unit for drive commands. Fig. 7 shows an image of the Urbot.

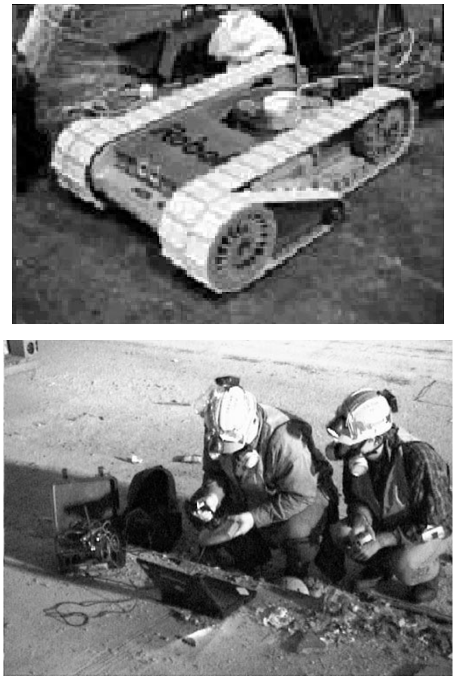


Fig. 6. (Top) The iRobot Packbot and (bottom) operator control unit.

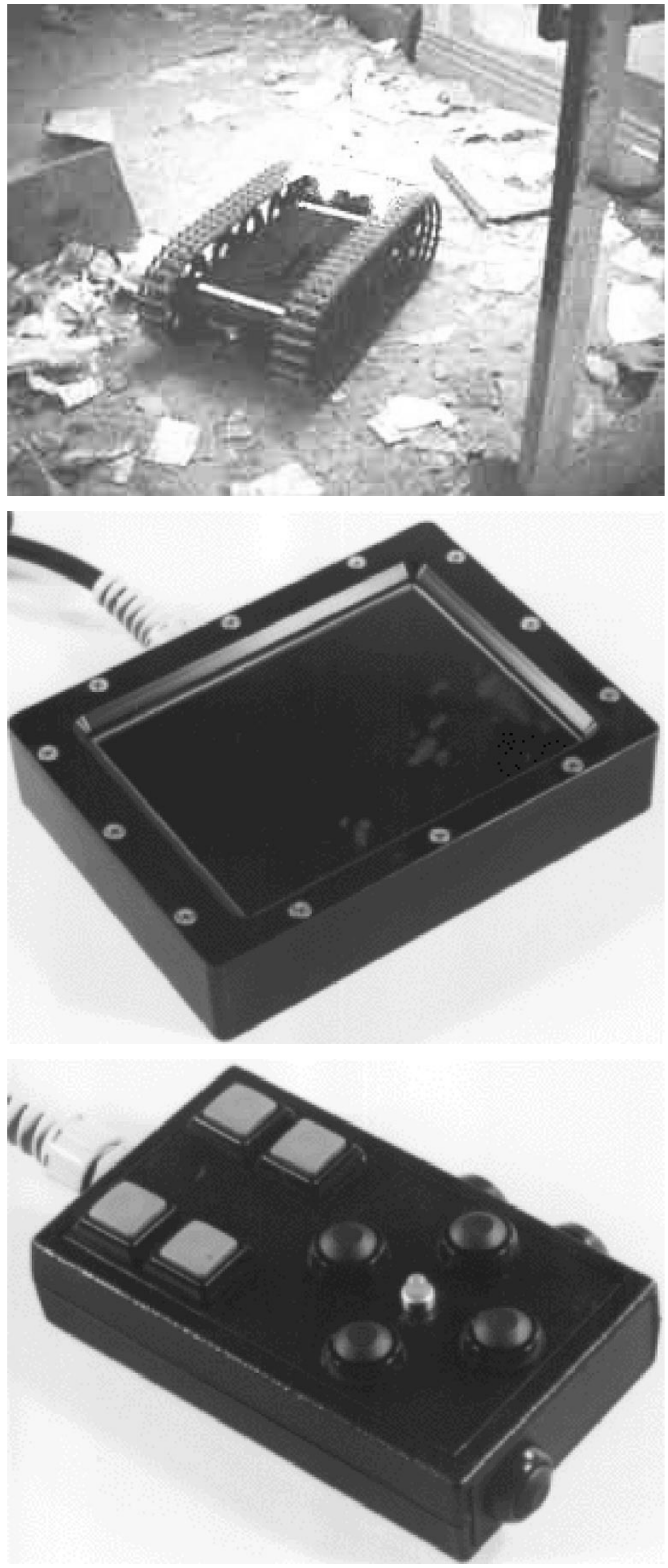


Fig. 7. (Top) SPAWAR Urbot, (center) display unit, and (bottom) control unit. Unit images courtesy of SPAWAR.

The operator control units (OCU) for the robots vary in interface and control capability. The Inuktun and Foster–Miller OCUs are the most similar. They provide video to the operator through a small screen in the Foster–Miller control unit or on the Sony TRV camcorder for the Inuktuns. Basic robot navigation is controlled through a joystick in the control units. Other robot specific functionality, such as camera tilt, robot shape changing, or arm positioning, is controlled by switches or knobs on the control units. The iRobot OCU requires a laptop to display the proprietary interface. Robot operation, such as flipper rotation and traversal, is provided through a joystick attached to the laptop and keyboard control. The SPAWAR OCU provides basic robot traversal through the push-button handheld unit. The robot eye view is displayed on the 5-in handheld display unit.

Each of the robots required a human operator. The CRASAR personnel came from industry (∼9), military (∼4), and academia (4). FEMA teams preferred to take a CRASAR team out on deployments with them in order to have individuals who were familiar with the field and already experts at operating the robots, thus not adding to the demands already on the FEMA team members.

Due to the intermittent demand for the robots, only four of the 11 members actually operated a robot on the rubble pile. The four operators were John Blitch, Arnie Mangolds, Gary Morin, and Mark Micire. The first three had military field robotic experience (disarming unexploded ordnance) while the later had USAR technical rescue certification.

3) Robot-Assisted Tasks: USAR tasks are divided into four branches, according to the FEMA task force organization [5]: search, rescue, medical and technical. Robots were able to assist with *confined space search and inspection*, and *semi-structure search* during the rescue phase and *monitoring* during the recovery phase. The robots were on standby to *transport medical payloads*. Fig. 8 shows the task force organization including the five robot-assisted tasks. *Confined space search and inspection* involves searching a confined area for victims while studying the area's structural aspects [44]. For video of an Inuktun searching a confined space, see attachment 3 or

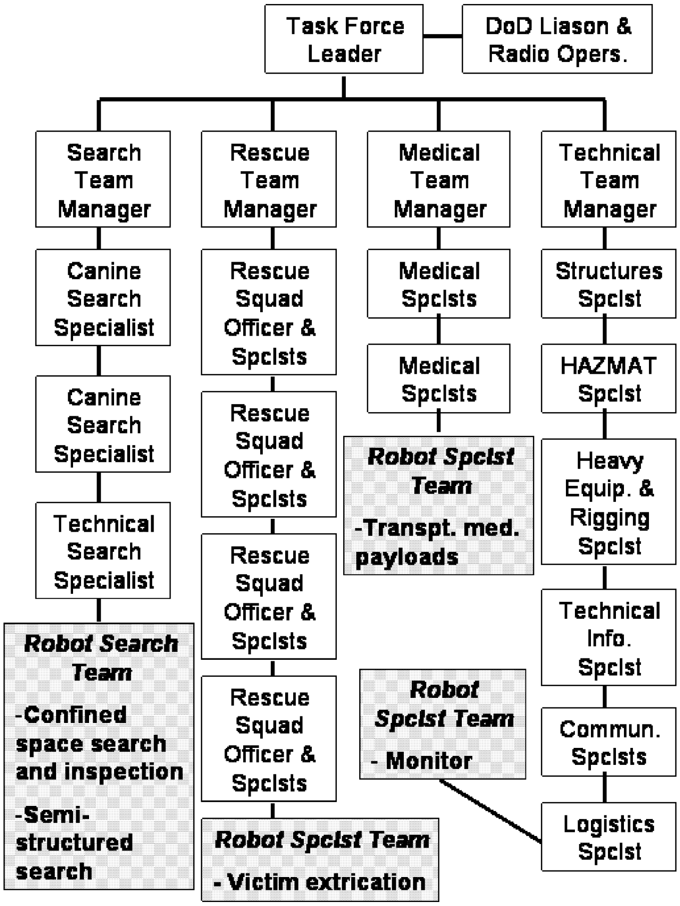


Fig. 8. Task force organization including robot teams and the five robot-assisted tasks, taken from [5].

sewerinsert.mpg at http://www.csee.usf.edu/robotics/crasar/ movies/. *Semi-structure search* is the act of searching potentially dangerous structures that are partially standing, but have not been declared safe for human entry. Examples of this type of structure would be the damaged buildings surrounding the main rubble pile at the site. For video of robots searching semi-structures, see attachment4 or packbotentry.mpg at http://www.csee.usf.edu/ robotics/crasar/movies/. Victim extrication involves extracting live victims or recovering deceased. *Transporting medical payloads* refers to the robots carrying items into unsafe areas. An Inuktun robot was ready to carry a medical tube down to a victim for purposes of providing water or fresh air though this was not used. *Monitoring* involves checking the air quality in a designated area.

B. Social Niche

Social informatics and communications define the social niche for USAR. Social informatics consist of human–robot ratios (Section III-B1), and workflow/operations (Section III-B2). The following three sections outline the two subniche categories.

1) Human–Robot Ratios: It is important to make the actual relationship between the human and the robot clear. The number of people needed to transport and operate a piece of equipment is an issue for at least three reasons. The people needed to haul an awkward robot to an unstable sight are counted by rescuers as operators. The sector chief limits on the number of people allowed in the hot zone. And more people increase logistical issues. The human-to-robot ratio has two components, the *transportation ratio* and the *operation ratio*. The transportation ratio represents the number of humans needed to transport the robot to the designated site. The operation ratio represents the number of humans required to run the robot. Each ratio is important as the two are not always the same.

TABLE II
TRANSPORTATION AND OPERATION HUMAN-TO-ROBOT RATIOS FOR THE MAN-PACKABLE ROBOT MODELS USED ON THE RUBBLE PILE

	Human-to-robot Ratio (h:r)	
Robot/s	Transportion	Operation
MicroTracs	1:1	2:1
MicroVGTV	1:1	2:1

Five of the robot systems described in Section III-A2 were considered man-packable and could be manually hauled safely. The Inuktun MicroTracs System and MicroVGTV robots could each be transported by one person; a 1:1 human-to-robot transportation ratio. The Foster–Miller Solem required two people for transportation; 2:1 human-to-robot transportation. While the Inuktuns and Foster–Miller robots in theory could be operatored by one person, in practice it took two people. One person controlled the OCU, but a second had to keep the tether or safety rope from tangling. Note this required the two humans to work cooperatively to effectively control the robot. See Table II for a list of robots and ratios.

The Inuktun robots had a better transportation ratio than the other four robot systems as they only required one person for hauling rather than two. The Inuktun robots have a 1:1 transportation ratio compared to the 2:1 transportation ratio for the Solem. The 1:1 transportation ratio is more advantageous in that two people who are already needed to operate one Inuktun can carry two robots. This allows for redundant equipment to be available in the case of a failure like the one seen during the eighth drop where the failed MicroTracs was quickly swapped out for the MicroVGTV.

2) Workflow and On-Site Operations: In order to understand the social niche, it is helpful to understand the workflow pattern. A workflow emerged for the CRASAR members after two to three days into the response. During the five deployments with FEMA task forces, the robot teams boarded the bus with the task force approximately one hour before the start of the shift (7:00 am or 7:00 pm). The bus stopped near the task force base of operations (BoO) where the group would gather their equipment and walk the few remaining blocks. During the shift, the robot team would wait at the BoO until called to the forward station near the pile. The team would then either be used or eventually returned to the BoO (this cycle can happen many times or none at all, depending upon the situation as seen in Fig. 9). At the end of a shift, the bus was again boarded and the group was returned to the Javits Center to rehabilitate. Upon return, the equipment and people were decontaminated. During the three deployments without task forces, the robot teams followed the same workflow but traveled to and from the site by personnel vehicles or back-up transportation through FEMA. CRASAR held group meetings once in the morning and once

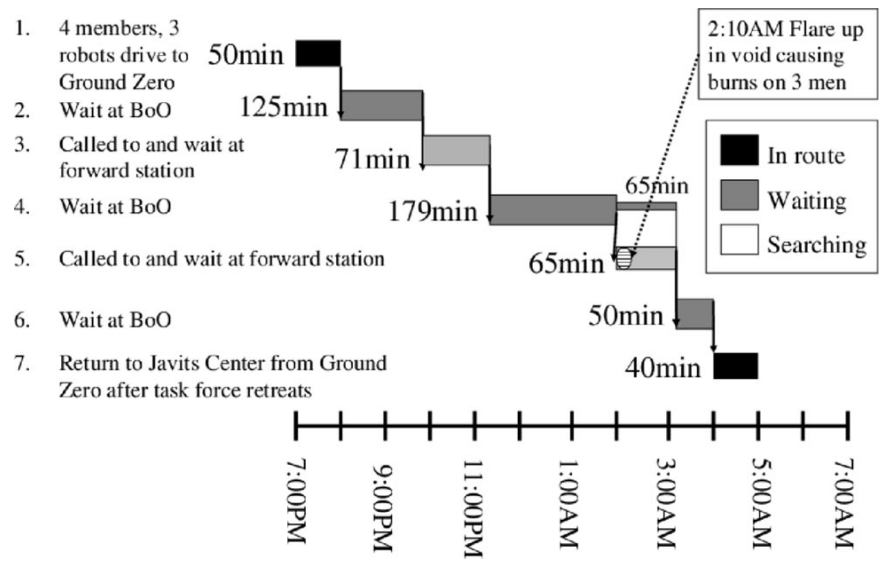


Fig. 9. Timeline of the sixth robot deployment with INTF-1.

TABLE III
TIMES OF THE EIGHT DROPS AND AVERAGE DROP TIME

Dplymnt #	Drop #	Time (h:m:s)
1	1	0:5:39
1	2	n/a
2	3a	0:2:49
2	3b	0:2:52
2	4	0:24:40
2	5	0:3:58
2	6a	0:4:10
2	6b	0:2:49
7	7	0:6:55
8	8a	0:6:36
8	8b	0:6:55
Avg. Drop Time		0:6:44

in the evening. The purpose of the meetings was for debriefing and discussion with personnel. CRASAR representatives also attended the FEMA operations briefing meetings.

Eight robot deployments took place on the rubble pile between September 11 and September 20. For this work, a *deployment* is defined as *when a team is sent to the warm zone (designated and restricted area around the hot zone) [3] for a defined period of time (called a shift) to work in the hot zone (immediate area encompassing the disaster) [3] or stand by until needed*. Eight drops took place during four of the eight deployments. A *drop* is defined for this work as *placing robots into an individual void or space*. For details of the deployments and drops, see [30].

The average time a robot spent in a void during a drop was 6 minutes 44 seconds. Table III lists the time a robot spent in a void for each drop. During the third, sixth, and eighth drops, two attempts at exploring the same void were made due to an error during the first attempt. These drops have two times, one for each attempt, because a robot was placed and removed twice. The attempt times are noted in Table III as an a or b next to the drop number.

Robots were inserted into the rescue workflow performing the tasks discussed in Section III-A3 either as an *adjunct team* or an *independent team*. An adjunct team was a temporary addition to an official FEMA task force and occupied the same organizational and social niche as a civilian dog team. Five of the eight robot deployments between September 11 and September 20 were with official FEMA task forces (INTF-1, PATF-1, and VATF-2). One of the five deployments as an adjunct team 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. The specialty robot group was needed to retrieve the spare Inuktun MicroVGTV and help repair the primary MicroVGTV using parts from the spare. The team worked on the pile without direct supervision though still under FDNY and NYPD authority. The remaining three of the eight deployments were performed independently, under FDNY authority.

The timelines of the sixth and eighth deployments provide details of the deployments with task forces. The detailed timelines for these two deployments were the only two in which times were recorded. Fig. 9 shows the timeline for the sixth 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 base of operations (BoO) only to be returned to the BoO without being used. In this case, the team was called out twice without actually using the robot. During this deployment, a fire flare threatened the safety of the rescue team and caused early termination of the shift. Interruptions like this occurred countless times throughout the response.

Fig. 10 shows the timeline of the eighth deployment. Two robot operators were deployed with VATF-2 while other members of the CRASAR teams waited in case outside assistance was needed. One void was searched twice due to a failure on the first attempt. The second robot was swapped in immediately. The timeline shows that the robots spent approximately 12 minutes in the void during the two hours spent with VATF-2. For video of the robot eye view in the support conduit void on WTC2, see attachment 5 or tunnelentry.mpg at http://www.csee.usf.edu/robotics/crasar/movies/.

3) Communications: The human and robot agents communicated by passing information and commands. Communication

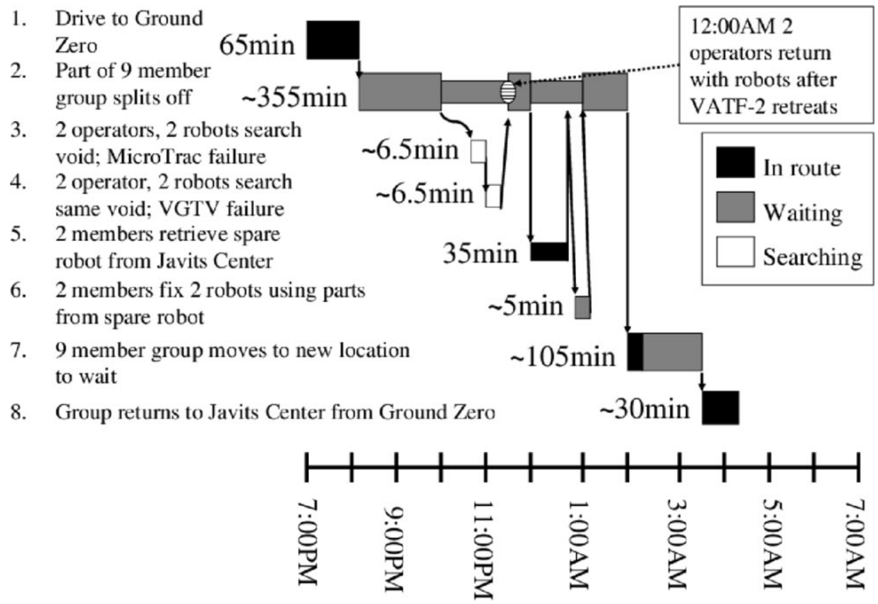


Fig. 10. Timeline of the eighth robot deployment with VATF-2 in which robots were used.

was limited to robot control commands from the operator and robot eye view (along with robot status information on some systems) from the robot. The human operators used the OCU to control the robot's movements. Information was passed back to the operators through robot interfaces. The robot systems varied in communications.

The Inuktun robots had limited communication capability. The operator was given basic control capability: traversal, power, camera tilt, focus, illumination, and height change for the MicroVGTV. The only feedback provided to the operator was the robot eye view on a Sony TRV camera.

The Foster–Miller robots were also limited in communications. The OCU provided the operator with the following controls: power, laser, illumination, camera tilt, arm height, traversal, and speed range. The robot eye view and video overlay containing robot status information was given to the operator through a LCD display. Range to target on the Solem, through an overlaid grid on the display, was the only information about the remote environment provided besides the camera view.

IV. Post-Hoc Data Analysis

The following data was collected during the WTC response from September 11 to 21: approximately 5.5 h of video, two sets of field notes belonging to Jennifer Casper and Robin Murphy, notes taken from informal interviews with fire professionals (Justin Reuter and Mark Rapp from INTF-1, Chase Sargent from VATF-2, approximately 5 members of FLTF-2) and CRASAR members, FEMA operations briefing reports provided twice daily around 5:30AM and 5:30PM, CRASAR meeting notes taken twice daily at around 5:00AM and 5:00PM, and post-response meeting notes. The data from the first two drops (see Table III) is not reported because the video was taped over. Data was not consistently collected and accurately cataloged after September 21.

The video data and sets of notes were examined over a period of six months after USF returned from the response on September 23. The video was thoroughly cataloged by identifying and documenting interesting events relative to human–robot interaction. These events were a) how the robot was intended to be used versus how it was actually used, b) what tasks the rescue professionals chose the robots to do, c) how the rescue professionals used the robots, d) the number of people required to effectively operate the robots, and e) information needed from the robot. Mark Micire and Gary Morin controlled robots on the rubble pile for the recorded runs and were consulted heavily in order to extract further HRI information during the data analysis. Hillsborough County Fire Rescue Special Operations Chief Ron Rogers and Paramedic Stewart Beale the ground truth for the recognition tasks.

Ideally the CRASAR workflow during the response at the WTC would have been captured as an ethnographic study. Due to the chaotic nature of the response and the security sensitive situation, the workflow was only recorded as frequently as possible from one viewpoint or sometimes two nonsimultaneous viewpoints: robot eye view during deployments, and external views of the site and deployment areas. The work in [12] indicates that four recorded viewpoints would be ideal: view of the operators' face and hands, the robot interface on the OCU, robot eye view, and external view of the robot.

The data is incomplete due to data collection being hindered by the chaotic response and high security. The robot eye views from the first and seconds drops are missing. Timeline information was only complete for two of the eight deployments on the rubble pile. Informal interviews were not consistently recorded for each deployment.

V. Findings

Seventeen findings resulted from the post-hoc analysis of the data collected during the robot-assisted response at the WTC. The findings are organized according to five niche subcategories (environment and conditions, agents and skills, task, social informatics, and communication) that create the ecological and social niches of the human–robot interaction definition (see Section I). Support and impact of each finding follows the finding statement.

A. Environment and Conditions

The environment and conditions are defined as the situation and atmosphere in which the agents are working. Three findings related to environment and conditions are presented.

1) The WTC disaster represented a tame environment relative to other disasters. This disaster gives a false sense of what disaster conditions are like and may lead people to improperly prepare for future disasters; not all disasters occur in pleasant weather with few weather problems, and few insects. Temperatures ranged from 60°F at night to the mid-70s during the day (as recorded in FEMA operation briefings reports). CRASAR personnel were comfortable working in mild temperatures wearing reinforced steel boots, work pants, short or long sleeved shirts, gloves, helmets, and respirators. Additional work jackets were worn during night operations due to cooler temperatures. The only extreme weather encountered between September 11 and 21 was two days of rain. The rain was a blessing because it cleaned some dust out of the air and off of the rubble pile. On the other hand, the rain created slip hazards and contributed to minor flooding in the rubble pile below grade spaces. The predominant sounds around the rubble pile came from trucks working in the area, cranes, vehicles, tools, and orders being shouted between rescue professionals. Minimal, if any, smell lingered around the rubble pile. The extreme core temperature of the rubble pile caused by burning jet fuel and the nature of the collapse appeared to pulverize great amounts of material. Asbestos and general dust threatened the health of the individuals working in the rubble pile area without respirators. Unclean air is a typical hazard resulting from structural collapses. Encounters with biomaterial were minimal over all (body fluids, remains, etc). The WTC disaster was favorable for people to work in, in terms of environment conditions.

2) Lack of sleep was a major source of CRASAR personnel's cognitive fatigue. A decrease in CRASAR personnel performance caused by cognitive fatigue was visible through the mistakes they made. Of the initial 52 hours the USF team experienced, less than three hours included sleep. The Foster–Miller team leader initially had gone approximately 56 hours without sleep. This is not atypical during the initial stages of a response as initial preparations, even for task forces, require the efforts of everyone on the force. The initial block of time without sleep for task forces is approximately 48 hours. This is due to the initial arrival responsibilities of unpacking equipment, setting up the temporary living area, and setting up the base of operations near the hot zone. Task forces are organized and designed with enough professionals to cover two 12-hour shifts for a 24-hour continuous response capability. This organization enables one shift to work while the other sleeps once the camp is set up. Both FEMA and CRASAR personnel took about three days to fall into the two 12-hour shift schedule.

Cognitive fatigue affects individuals' abilities to perform at peak level. One CRASAR member packed everything but the robot before going to the field during the fifth deployment. Another member walked by the same robot sitting in the Javits Center twice without making the mental connection that it should have been deployed.

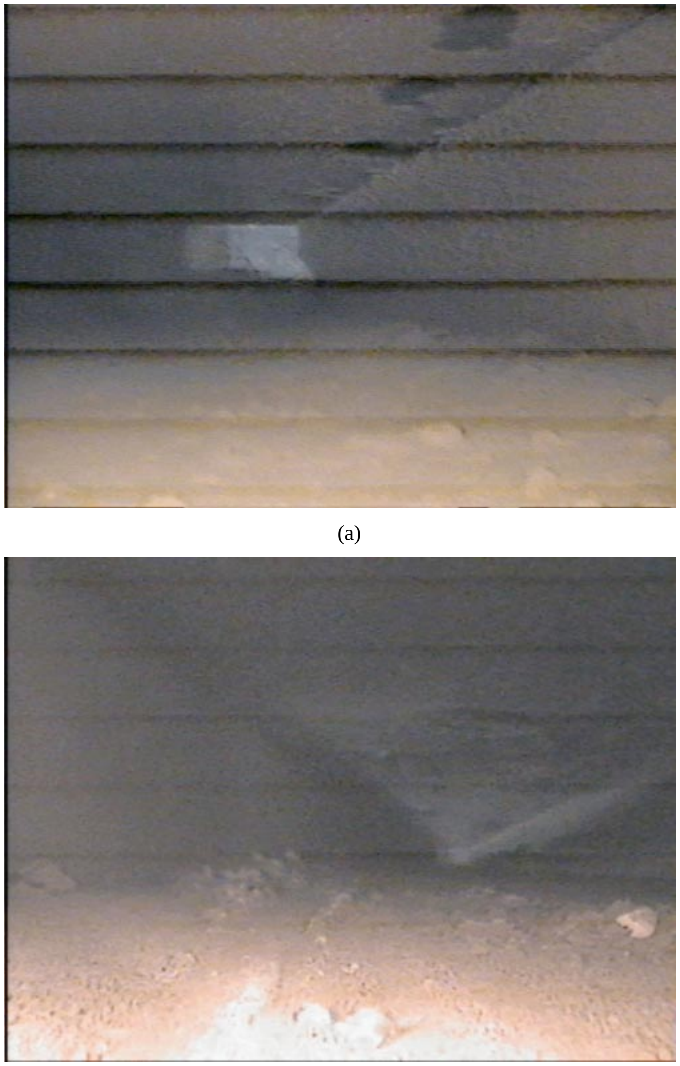
Fig. 11. Secondary robot operator responsible for managing the tether or rope was left in a vulnerable position.

3) Logistics is a key overlooked attribute of the ecological niche. Transporting robots and providing for the safety and support of humans in the field is critical. One lesson learned is that robots have to be carried the final three blocks from the BoO to the forward station and more than 75 feet over rubble. Pelican cases were too big and awkward to carry forcing members to donate backpacks. Rescuers preferred the MicroTracs and MicroVGTV robots not only for size but also the 1:1 human-to-robot transportation ratio over the 2:1 human-to-robot transportation ratio for the Solem. An advantage of having two people with two Inuktun robots is redundancy. During the eighth drop, the primary operator was able to immediately switch out the MicroTracs robot with blown halogen bulbs for the fully functioning MicroVGTV. The deployment would have been ended if not for a redundant robot. The secondary operator responsible for managing the tether or rope was always left in a vulnerable place. Next, the secondary operator had to stand next to the void opening in order to manage the tether or rope and was left vulnerable to the hazards of the void. This would have been deadly during the 6th deployment if the robot was dropped in and the secondary operator was standing at the entrance of the void when a flash over (fire unexpectantly appears) occurred. Fig. 11 shows the dangerous position the secondary operator was placed in while the primary operated the robot from a further distance away.

B. Agents

Agents are defined as the types of representatives involved in performing the field tasks. The agents' cognitive and physical abilities define their skills. Five findings relating to agents and skills resulted from the post-hoc data analysis.

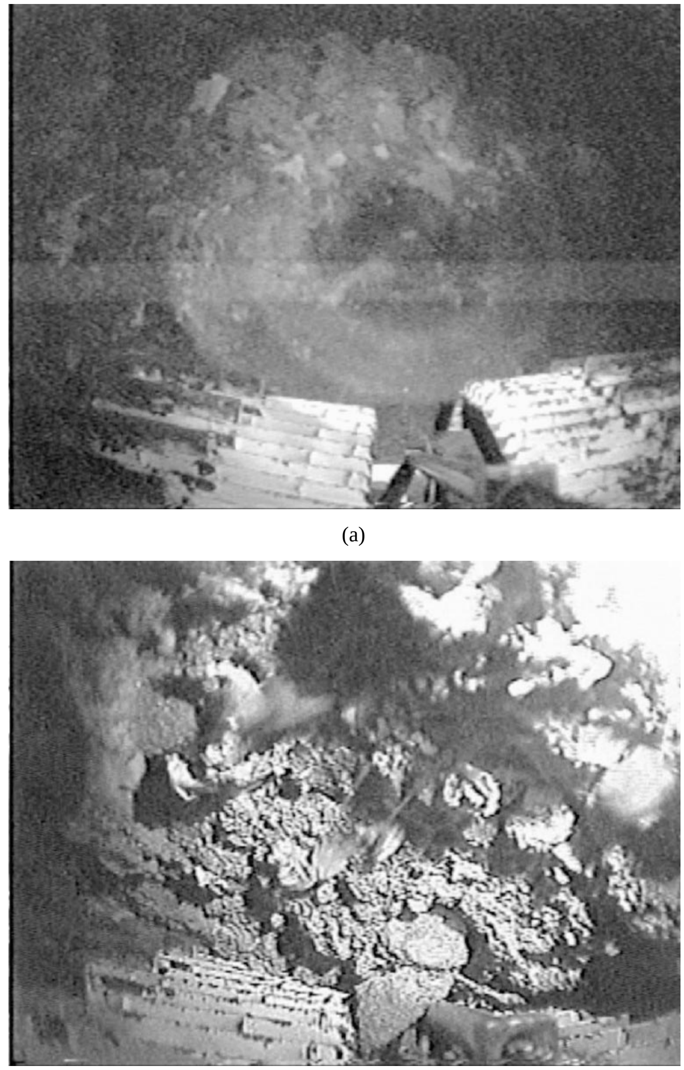
1) *A gap in skills and task description existed between the two groups of humans (USAR and CRASAR professionals) involved in the WTC response*. The obvious gap affected how much rescuers trusted and accepted the robots and CRASAR personnel. By law, an incident commander is not



(a)

(b)

Fig. 12. (a) Inuktun MicroTracs System and (b) VGTV robot views during the eighth drop.



(a)

(b)

Fig. 13. Disorienting robot view when Solem [right side up in (a)] flipped upside down (b) in a void during the 7th drop.

required to accept volunteer help, especially if the volunteer does not have direct USAR training. If equipment and/or people are unknown, they are not employed to the field as the risk is too high for rescuers. Three FEMA teams, especially INTF-1, thoroughly probed CRASAR members to determine that they were indeed knowledgeable of and experienced in the USAR field, and thus could be trusted. A USAR professional is required to have approximately 140 hours of training to even qualify for a position with a task force. The 140 hours is broken down into 40 hours of Rescue Systems I and about 100 hours of additional specialized training [3]. Once on a task force, each member is required to participate in a monthly eight hour refresher training session (96 training hours/year per person). On the other hand, CRASAR personnel have backgrounds in industry, military, academia. All CRASAR members had B.S., M.S., or Ph.D. degrees. Four of the 17 members had USAR certifications (Jennifer Casper, Mark Micire, and Robin Murphy) and three had worked in military EOD operations (John Blitch, Arnie Mangolds, and Gary Molin). The four CRASAR members from USF had an average of 62 training hours per person over the past 2.5 years plus more than 50 hours in the field at USAR sites.

2) *The robots used during the eight drops were sensor impoverished. Minimum sensor information was available to the operator impairing effectiveness*. On average, the robot got stuck 2.1 times per minute during a drop. The MicroVGTV and MicroTracs provided the operator with video from the color camera and two-way audio, and the Solem only provided video. Fig. 12 shows the MicroTracs and MicroVGTV robot views. Fig. 13 shows the two views taken from the Solem before and after it flipped upside down. The operator had to use video from a single color camera to determine the status and location of the robot, search for victims, and inspect the environment. Existing proprioceptive sensors were not included in the robot systems. Inertial measurement unit (IMU) sensors and global position system (GPS) units provide location information but were also not included. A forward looking infrared (FLIR) camera was available but not portable to the MicroVGTV, MicroTracs, or Solem. Existing

Fig. 14. Solem robot with air meter strapped to it.

range and temperature sensors provide environment condition information.

3) *Sensors used on the robots during the eight drops could not be substituted for other sensors and new sensors could not be added*. The lack of sensor adaptability decreased the utility of the robots during the WTC response and limited the tasks the operators could perform. The FLIR camera was available but could not be attached to the MicroTracs, MicroVGTV, or Solem because the robots lacked a physical interface to incorporate sensors. Rescuers wanted to attach air meters to remotely check air quality which was eventually accomplished on the Solem in a nonelegant manner (see Fig. 14 of the Solem with an air meter strapped to it). Existing air meters, such as the MultiRae Plus meter, have the capability to pass information through a serial port, but the air meter used on the Solem was read when the robot was returned. In terms of software interface issues, the Packbot interface allowed the operator to only access one camera at a time. Fig. 15 shows the Packbot interface with the one camera view. The operator had to click and choose either the color camera or FLIR for display.
4) *All robots available during the WTC response lacked image processing skills*. Lack of image processing reduced the robots' skill set and added to the operators' cognitive responsibilities. This is unusual as robots perform image processing for other applications (i.e., military and autonomous driving). The RWI Urban, an older model related to the Packbot, had image processing skills that were not portable to any other robots at the WTC. The image processing skills included skin color detection, heat detection using the FLIR, motion detection, and color difference [29]. During the eight drops, the operator performed the image processing while navigating, detecting error, and recovering the robot. Task force positions are purposely overspecialized to prevent members from incurring too many tasks, like they did in this case. The robot operators were also at a disadvantage because they were not trained for or experienced in recognizing victims, key objects and structural weaknesses like task force specialists are.

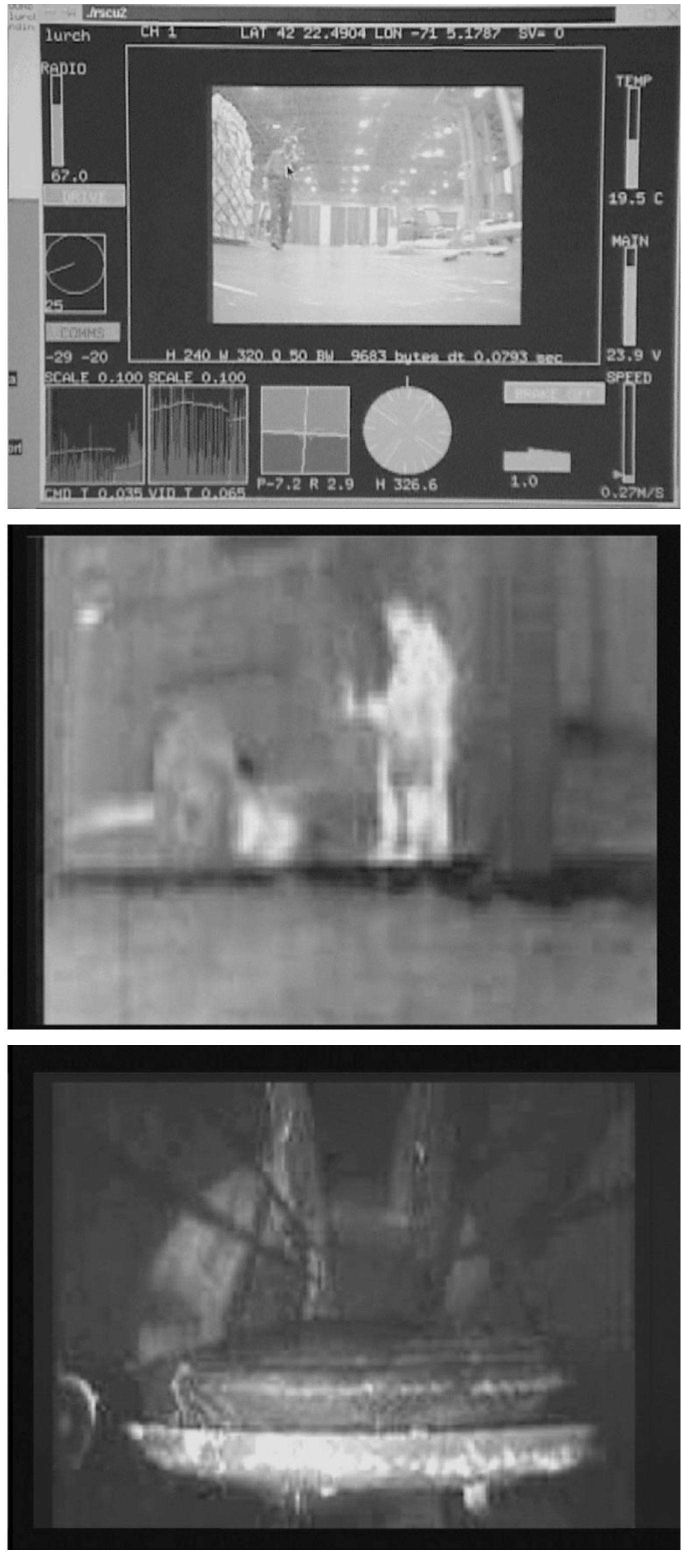


Fig. 15. Packbot control unit, user interface, and robot view using the FLIR. The interface only allowed one camera view at a time and required the operator to manually choose the view.

Remains that were overlooked by operators and rescue professionals during the response were still being recognized months later. More than six people, including the robot operators, viewed the video from the eighth drop within six hours of the drop finding only one torso. A wrist watch, a

Fig. 16. Material resembling a human hand remain recorded during the eighth drop recognized five months after returning from the WTC response.

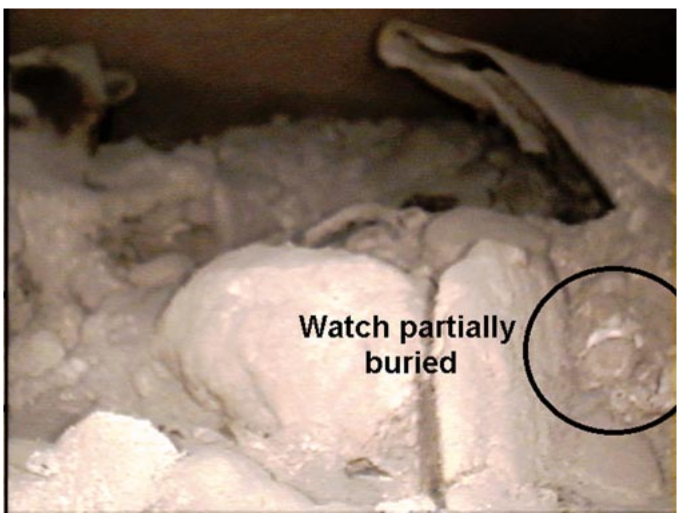


Fig. 17. HCFR Specials Operations Chief Ron Rogers found a key object, a wrist watch, in the video of the eighth drop one week after the USF group returned to Florida.

key object, was spotted in the video from the eighth drop on October 3, 2001 by rescue expert Special Operations Chief Rogers. Fig. 17 is a view of the wrist watch during the eighth drop (see attachment 5 or tunnelentry.mpg at http://www.csee.usf.edu/robotics/crasar/movies/ for robot eye view). Similarly, Micire located material that resembles part of a human hand while analyzing the video of the eighth drop five months after returning from the response (see Fig. 16) by using simple histogram equalization. Performance is subject to degradation when the operator is not fully concentrating on searching for victims or weaknesses while navigating the robot [12]

5) *None of the robots available during the WTC response were designed or rated for USAR*. Equipment used in a field it is not designed or hardened for threatens the safety of the people using it and adds to the perception that roboticists are amateurs. All USAR equipment, down to rope, used by task forces is rated for rescue by the National Fire Protection Agency (NFPA). The Inuktuns' exposed halogen headlights could have sparked the hazardous confined atmospheres if cracked. The rating system used for this work is the NASA Technical Readiness Levels [45]. The Solem was rated technical readiness level (TRL) 9 for military applications. TRL9 signifies the complete system has been proven through actual operations. The Solem was rated TRL6 or TRL7 for USAR operations only because it had been used in a relevant environment (outdoor rugged terrain) and could be considered a prototype for USAR. The MicroTracs and MicroVGTV robots were rated TRL9 for HVAC duct. They were rated TRL6 or TRL7 for USAR operations because they had been used in a relevant environment (confined spaces). Thus, the MicroTracs and MicroVGTV could be considered USAR prototypes. None of the robot platforms available were commercially hardened.

C. Task

The task is defined as the assignment the robot needs to fulfill. Only one major finding related to the task resulted from the post-hoc data analysis.

The same robots were used, or available, for three of the five tasks spanning the four task branches. Current task force organization does not accommodate sharing of equipment or teams, and the social structure may have to change in order to take advantage of new technology. Fig. 8 represents where the five tasks fit into the task force organization. The organization consists of four branches: search, rescue, medical, and technical. Each branch covers the four sets of tasks. The confined space search resides in the search branch of the task force organization. The inspection task is often executed while searching confined spaces and also belongs to the search branch. The MicroTracs, MicroVGTV and Solem performed these two tasks simultaneously 8 times between September 11 and September 21. Semi-structure search also belongs to the search branch. The Packbot, Urbot, and Talon were used to search unsafe buildings near the rubble pile once between September 11 and September 21 (see Table I). The victim or remains extrication task resides in the rescue branch. The rescuers inquired about the robots' abilities to extract remains from the void. The idea was abandoned even though a temporary creative solution could have been implemented. The transportation of medical payloads task falls under the medical branch. Preparations were made to provide material, water or air, through medical tubing into a void, but were unnecessary during the WTC response. The monitoring task belongs to the technical branch. The Solem was used to monitor air quality more than eight times between September 22 and October 1. Solem's tasks spanned the search and technical branches. The MicroTracs and MicroVGTV executed the two tasks under the search branch.

D. Social Informatics

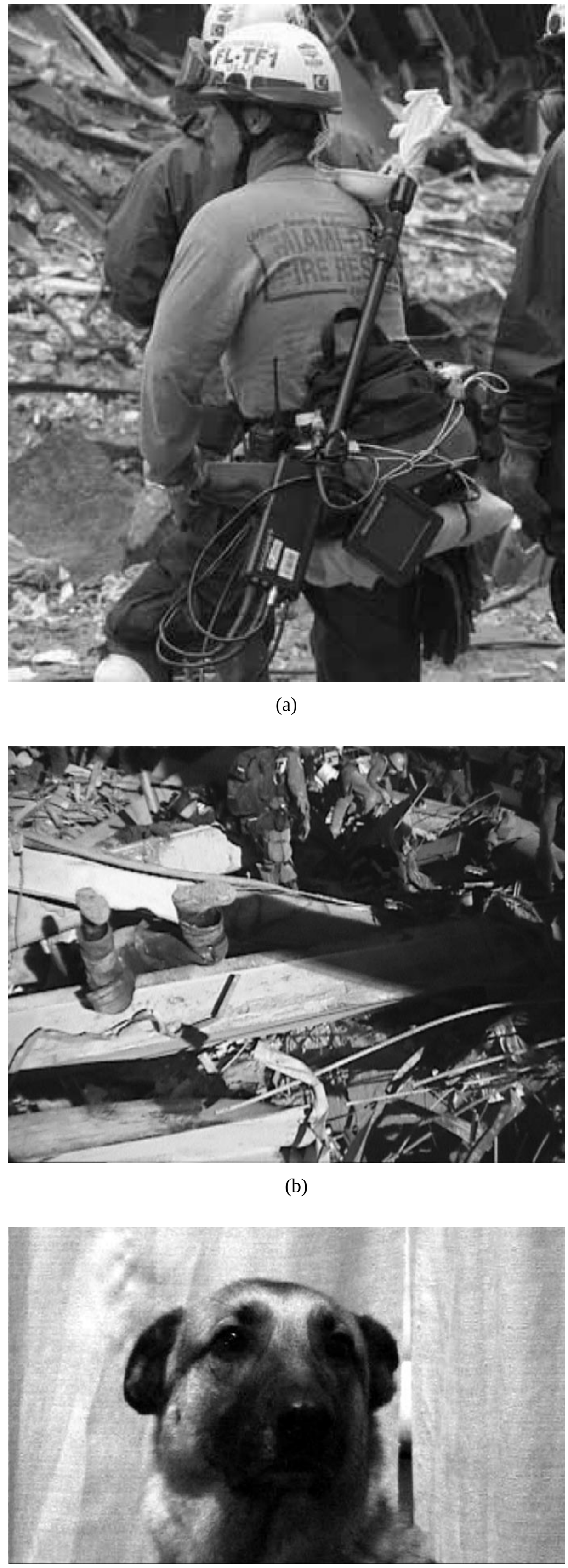
Social informatics is defined as the agents' roles, how they organize, collaborate, and transition between roles. Three social informatic findings resulted from the post-hoc data analysis.

1) *Acceptance of robot technology appears to be based on the similarity to current technical search equipment*. The rescue professionals chose which robots to use and train on before

going out to the rubble pile. The MicroTracs, MicroVGTV, and Solem were preferred over the other robots for their simplistic interfaces and control units, size, and number of people required to operate. They were the most similar to current technical search equipment in complexity and information. The MicroTracs and MicroVGTV have the same functionality as the search cams; they provide remote video. The major difference is that the search camera is a camera on the end of a telescoping pole and the two robots are like "cameras on wheels." The "camera on wheels" phrase, though no robots had wheels, immediately led to rescuer interest because it provided a clear comparison to current technical search equipment. It also inferred the advantage of the robot over the search camera; the robot can travel farther into a void (with a 100-foot tether) by being mobile and rugged. The rescue professionals expected short setup times with a minimum number of operators; their search cameras can be powered up in less than 30 seconds using one or two operators. The MicroTracs, MicroVGTV and Solem could be set up within 1.5 minutes by experienced operators.

2) *The ideal form of group interaction is an open issue*. There are two ways a rescue team were observed to interact with the robots: the rescuer uses it as a technical search tool or the robots are treated as a separate unit much like a dog team. During the seventh deployment, robots were treated like a technical search tool and the tool was not considered significantly different from a search camera. CRASAR personnel trained an INTF-1 technical search specialist for 23 minutes on how to run a MicroTracs and a Solem. The technical search specialist was given awareness training and was capable of taking the equipment out if necessary. During the fourth, fifth, sixth, and eighth deployments, the robots and operators were treated like dog teams. The robot specialist teams were outsiders welcomed into the group. The teams would wait at the base of operations until called to the forward station and eventually onto the rubble pile. In this mode, the searching capabilities were prioritized in some cases: human, search tool, dog, and then robot (see Fig. 18). During the third deployment, the rescue professionals followed this priority for searching a void. A rescuer would look in void with a flashlight. Then a search camera would be used. A dog would be called in next to sniff the area. The robots were never used, though they may have saved time had they been used first. However, the human, search tool, and dog are trusted and familiar versus the perceived complexity of the robot systems.

3) *The robot design, including the user interface, must account for infrequent and minimum training time dedicated to equipment*. The complexity of the robot system designs affects how quickly rescuers can be trained on the equipment to the awareness, operations, technician, and expert levels [5]. Task force members train a minimum of 30 minutes biannually on technical search equipment. This is enough training to provide everyone on the task force with technical search equipment awareness. Technical search specialists are required to operate the equipment at least once every few weeks, not including time spent maintaining the equipment. Technical search specialists are supposed to be com-



(a) (b) (c)

Fig. 18. A searching order was employed by some rescuers: (a) human, (b) search camera, (c) dog, and then robot (see Figs. 4–7). Search cam picture courtesy of Search Systems Inc. for search camera picture. Robot picture courtesy of Inuktun Services, Ltd.

fortable with the equipment before using it in a real disaster. If the technical search specialist is not comfortable with the new equipment, they will default to older equipment when called to a real disaster. A disaster is not the time to test new equipment when lives may be at stake. The robot systems designed for USAR must take this into consideration if the systems are to be used. The INTF-1 technical search specialist was given only 23 minutes of awareness training on MicroTracs and Solem while waiting in the BoO during the seventh deployment. Technical search equipment training is unlike equipment training in other fields. NASA and military specialist personnel are given time for extensive training (on the order of years) to be considered expert operators. Rescue professionals do not have this luxury.

E. Communication

Communication in the social niche refers to the types of information shared or transmitted between agents, how they are represented, time dependencies, and actual interfaces to facilitate understanding. Five communication findings resulted from the post-hoc data analysis.

1) *Robot information is a one to many mapping, not one to one. Robots currently provide information to only the operator*. Robots currently provide information to only the operator. Robots specialist teams were expected to distribute information to the technical search leader, task force leader, and incident commander. They are useless without information distribution. During the response, this was done manually by CRASAR members verbally informing the search leader of findings. Often it was 12 hours before information on victims made it to the right authority. INTF-1 task force leader, Justin Reuter, requested the development of an Incident Commander laptop that could display maps of who was working where and provide updated event information.
2) *Robot information is a one to many mapping with temporal and abstraction hierarchies*. The response illustrated that information is not simply distributed by broadcasting: not all members within the task force need the same information at the same time. For instance, a structural specialist requires structural information from the robot, while the search team leader expects victim and void information. For instance, the search team leader does not care how often robot problems occur only the operator cares. Information will have to be packaged to meet the needs of the users.
3) Three types of robot information were lacking during the WTC response.
   a) *The lack of state of the robot (proprioception) information required the operator to diagnose problems using only the video* Lack of state of the robot information wasted approximately 54% of the time spent in voids diagnosing problems through video during the sixth and eighth drops. The only failure detection method available during the eight drops was to concentrate on the robot eye view and guess. During the eighth drop, the heat from the void softened a track, leaving the robot immobile. The operator only knew the robot was not driving correctly and eventually pulled the robot out of the void. Approximately 54.5% (3:46 minutes of the 6:55 minute drop) of the total time in the void was spent trying to determine the failure and recover the robot. During the sixth drop, the robot lodged itself on a metal rod. The operator had difficulty maneuvering the robot but did not know about the metal rod until the robot was recovered. See Fig. 19 for the robot eye view and external view of the metal rod. Approximately 54% (2:15 minute of the 4:10 minute drop) of the total time in the void was spent maneuvering the robot, diagnosing the problem, and recovering the robot.
   b) *Lack of state of the world (mapping and environment) information left operators and rescuers questioning the details of where the robots searched and the conditions during the drops*. The need for localization and maps was not a surprise. Robots lacked the ability to inform the operator of their location, how far they traveled, the length and extent of voids, etc. Operators could only approximate the distance traveled by measuring the tether/rope in arm lengths when the robot was retrieved. The lack of information about the environment caused the operator to continue operating a robot in an environment it was not capable of handling during the eighth deployment. The temperature in the void was estimated to be above 350°F. The operator stated that standing at the void opening felt like standing in front of an open oven. As a result of the high void temperatures, the MicroVGTV lost its track and had to be recovered.
   c) *Information on what has been seen would be helpful in obtaining different views to identify objects and map the environment*. This would have eliminated the time and emotional impact on the six rescue professionals who debated whether the piece of metal in the eighth drop was a fireman's boot (see Fig. 20). It was not until the video was fully rewound, days later, that it was realized that the robot had captured an overhead view on its way down into the void. The different view of the object showed that it was indeed a piece of metal, not a boot.
4) *Multiple information channels were available but not well used*. The consensus of the robot operators was that the visual channel appeared to be overused. The operator was forced to use only the visual channel for all responsibilities (navigating, error detecting, image processing). Two-way audio was available on the Inuktun MicroTracs System and MicroVGTV robots, but was not used as the headset and personal protective gear could not be worn at the same time. Also, lack of response organization prevented complete cooperation to shut down all noise sources and allow rescue teams to use the robots and their listening devices in searching for victims.
5) *Communication dropouts may have impacts on user acceptance*. The communication dropout altered the rescuers' confidence. The Solem was lost

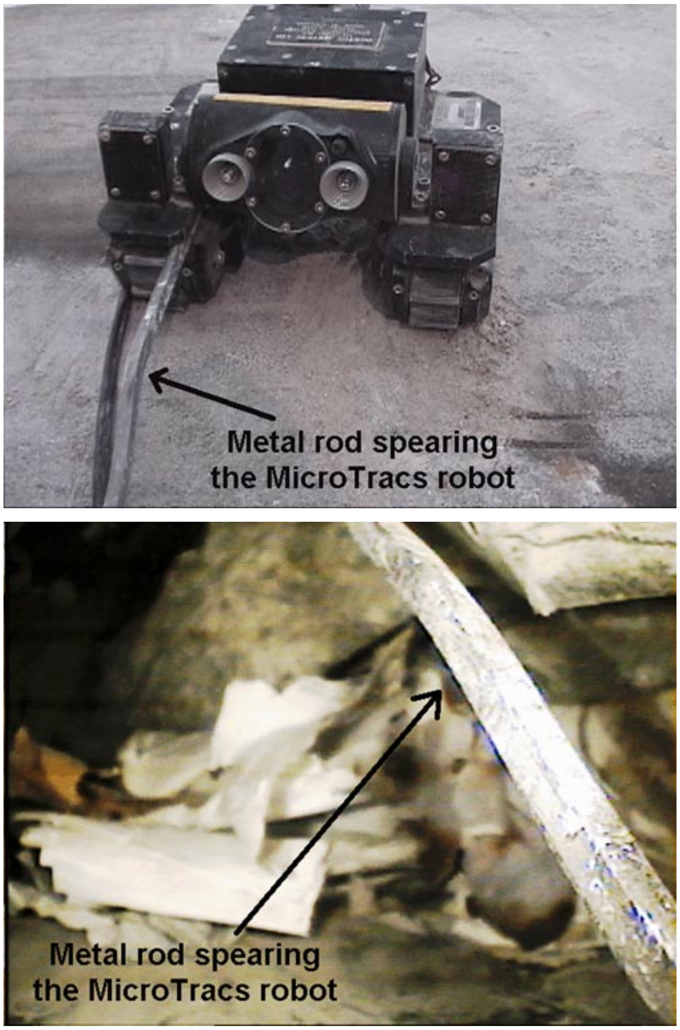


Fig. 19. Images of metal rod from the robot view and external view.

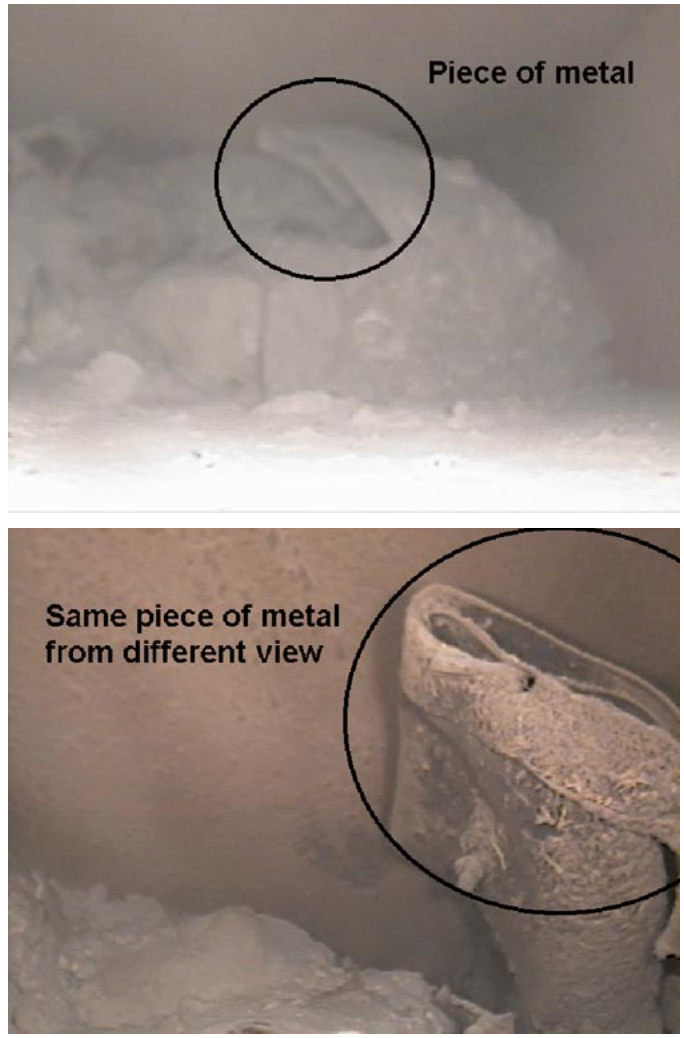


Fig. 20. Images of the piece of metal mistaken for a boot taken from two different vantage points.

during the seventh deployment due to communication dropout. Twenty-one complete communication dropouts (equating to 1:40 minutes) occurred during the seventh deployment drop which lasted 6:55 minutes (for video see attachment 6 or solemeye.mpg at http://www.csee.usf.edu/robotics/crasar/movies/). The dropout incident affected the confidence rescuers had in the robots. The rescuers questioned how to get the robot back, if the robot would be operable, what the operators were going to do, and whether they should put someone in the unsafe void to retrieve the robot.

F. WTC Findings versus Previous Studies

Four of the findings mirror findings from previous field tests reported in [12] and [30]. The common themes are *logistics is a key overlooked attribute of the ecological niche, the same robots were used for three of the five tasks spanning the four task branches, acceptance of robot technology appears to be based on rescuers' experience with current search equipment, and three states of robot information were lacking and are needed*. The remaining 13 findings emerged during the WTC response because it was an unstaged event. The conditions could not be adequately simulated during a staged response. For example, the findings related to cognitive fatigue could not be easily simulated for training, nor the impact of logistics on the need for man-packable equipment. In [39], [40], it is noted that current rescue robot competitions do not capture these aspects of a real event.

VI. Discussion and Recommendations

This article concentrates only on the human–robot interaction aspects of the robot-assisted rescue at the WTC. The reader is directed to [46] for a discussion of how the robots failed and the platform and sensor specific technical challenges. Recommendations based on the findings are presented and discussed below.

In our opinion, the first critical step in rescue robots is to concentrate on the human–robot interaction. Three facets merit equal attention: *the robotic, software, and human agent roles, human–computer interaction, and human factors*. The first goal should not be to make platforms with higher mobility. Although the platforms were far from perfect, they were acceptable. Inside the first goal should be to improve recognition of victims and structures. In WTC Tower 2, robot specialists and trained FEMA professionals did not recognize remains the robot rolled past;

this could have been tragic if the victims had been unconscious survivors.

The nature of the domain suggests that human cognition is not adequate; the physiological and psychological fatigue is nearly overwhelming. Instead, the appropriate *assistive roles* for the robot and operator workstation must be identified through followup ethnographic studies. The sensor suite and user interfaces themselves must be redesigned to provide *intelligent assistance*. For example, every robot needed more proprioceptive sensors to determine things such as whether the robot was upside down, entering an area on fire, etc. Even when a robot had almost all of the needed sensors, the information was not effectively presented to the operator and the interface did not adapt. While it is impossible for a single study of historical data to determine which exteroceptive sensors would have improved performance, it is our opinion that a sensor providing three-dimensional range information is the single most important missing sensor. At this time no ranger capable of operating in these lighting and environmental conditions is small enough to fit on a man-packable robot.

The user interfaces themselves were very limited and relied too heavily on the visual channel; it is our expectation that perceptual interfaces which use tones or touch to alert and inform the operator will lessen some of the visual loading. However, it should be noted that natural language interfaces and heads-up displays appear to be impractical for USAR. The rescuers work in a very noisy environment and often must wear respirators or other safety equipment; this interferes with natural language interfaces. Likewise, the need for high resolution "robot eye views," seeing well enough to walk through dangerous rubble, and physical limitations of the rescue gear, precludes most heads-up displays.

The impact of human factors, which limits the use of heads-up displays and natural language, cannot be underestimated. No robot used in the field could be assembled and operated with technical extrication gloves. The operators often had to violate safety practices to accomplish simple tasks. Robot manufacturers appear unfamiliar with HCI and ergonomics.

A. Recommendations

Eleven recommendations are made based on the findings presented in Section V. The recommendations give rise to research issues that need to be addressed in order to advance human–robot interactions for USAR. They are not ordered in terms of priority, rather by findings.

1) *Human–computer interfaces and robot systems need to support people working without sleep and in an environment worse than the WTC disaster*. Challenging environments and initial lack of sleep during the response are inevitable. Robot systems need to be designed with this in mind in order to develop truly useful robot systems for USAR.
2) *Robots must be man-packable and preferably have a 1:1 human-to-robot ratio for transportation and operation*. A 1:1 transportation ratio allows two people to carry redundant equipment in the case of an error. A 1:1 operation ratio is the goal for developing robot systems that require one operator who can operate the robot from a relatively safe distance and remove the second operator placed in a dangerous position for managing the tether or rope.
3) *Fieldable robot groups need to adopt existing task organization for future deployments in order to minimize cognitive fatigue*. It is unnecessary for group organization to contribute to cognitive fatigue. The current two shift scheduling used by task forces creates consistent sleep opportunities for everyone on the task force.
4) *Create a specification for "minimal competency" of a USAR rated robot*. Never allow a robot without proprioceptive sensors (sensors that provide "measurements of movements relative to an internal frame of reference" [7]) and image processing to be rated TRL9 for USAR. The lack of proprioceptive sensors and image processing decreases the utility of robots for USAR and the operators' performance by increasing the jobs executed using minimal sensor information. USAR robots must also have modular sensors and payloads. This increases the robots' utility for USAR operations. Sensors and payloads can be shared among multiple platforms. Feedback from robot platform analysis may create more levels of competency.
5) *Create standards for training professionals*. Train USAR professionals for four certification levels on robots rated TRL9 for USAR. The standard levels of training are awareness, operations, technician, and specialist [5]. Specialist training should only be available on TRL9 USAR robots. Provide robot awareness training on available TRL6 or TRL7 USAR robot systems until TRL9 USAR robots are produced. Train robot professionals to serve as robot specialist teams for USAR task forces. Provide awareness, operations, and technician level training for professionals who desire different levels of participation but still require basic USAR field knowledge.
6) *Investigate the ramifications of using the same robot platform for multiple tasks*. The current task force organization defines specific positions for people. People are not shared among the branches. Equipment is not shared either. A robot specialist team shared amongst the branches breaks current organization. This could affect the task force organization. No one platform belongs to any one branch, but belongs to all branches. The potential for families of robot platforms and modular sensors/payloads is realized. A single robot specialist team can have modular robot components that are chosen based on which branch needs the robot resource.
7) *Perform studies on ideal USAR specific user interfaces and robotic systems*. The task forces' social dynamics place constraints on USAR robot system designs. Time spent training is limited. If the rescuers trained on the robot systems are not comfortable with them, the robot systems will not be used when a disaster occurs; most rescuers use tried and true methods during disasters. The robot systems will then never get integrated if they are too complex to be trained on.
8) *Determine how robots that can perform multiple USAR tasks may be integrated into the task force organization*. It is unclear at this point as to how robots will be integrated

into the task force organization. The current methods employed by dog teams and technical search tools may not be ideal. A new integration method specifically for robots may be better than the existing methods.

9) *More research is needed in perceptual user interfaces*. The visual and audio channels are the most obvious ways of transferring information to the operator. Both channels need to be used properly. Also, there may be better ways of commanding the robots than through a keyboard or switch.
10) *Concentrate on researching how to extract and represent state of the robot and state of what has been seen to compliment existing work in state of the world*. Mapping and localization are challenging fields of research. However, robot state should not be overlooked.
11) *Investigate the user confidence in remote robots with intermittent communications*. The users' confidence affects how aggressively equipment is used. Communication dropouts may cause enough problems that wireless robots are not desired.

VII. Conclusions

This article has analyzed the ~11 hours of video tape and accompanying field notes from the WTC robot-assisted response. The analysis considered both the traditional ecological niche of the human and robot agents as well as the social niche. While the data collected was sparse due to the need to focus on the rescue, it contributes a case study of what was done and what worked, as well as an ontology of the USAR domain, providing a foundation for the HRI community.

The most pressing needs are: reducing both the transport and operator human–robot ratios, intelligent and assistive interfaces, and dedicated user studies to further identify issues in the social niche. Man-packable robots with 1:1 transport and operation ratios should be possible if more attention is paid to transportation constraints and tether management. Future fieldable robot groups deployed with the man-packable robots need to minimize the risk of cognitive fatigue and maximize response performance through team organization, similar to the existing FEMA task force organization. In order to facilitate acceptance of robots into a task force organization, training standards must be developed for professionals, both USAR and robotic. Robots that can perform multiple USAR tasks may not be easily integrated into the existing task force organization, thus research needs to be conducted on how to integrate them. User confidence of the USAR professionals in remote robots that have intermittent communications will also affect the acceptance of robots into a response and deserves attention as a research issue.

In order to support general human–robot interaction efforts, research is needed to define the domain ontology, "minimal competency" skills of a USAR rated robot, which will then drive more human–robot interaction work. The domain ontology is required to specify the possibility of using the same robot platform for multiple tasks, which introduces fundamental issues in the way a task force employing USAR robots is organized. This provides an opportunity to analyze how new technology affects group dynamics. Extensive studies on ideal USAR specific user interfaces and robotic systems are clearly needed, as is more research in perceptual user interfaces.

In the long term, human–computer interaction and robot systems need to support people working in environments more cognitively challenging than the WTC. This is a fundamental research topic which involves extensive development and testing of platforms, software, and sensors. Our current work is focusing on image processing and intelligent assistance to cooperatively aid with recognition and identification.

Finally, it should be emphasized that researchers who wish to help with an actual rescue must have acquired USAR training certification and established relations with USAR teams prior to the event. CRASAR is working to establish researcher training opportunities.

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