Activities of the Rescue Robots at the World Trade Center from 11–21 September 2001

Trial by Fire

BY ROBIN R. MURPHY

On 11 September 2001, the Center for Robot-Assisted Search and Rescue (CRASAR) responded within six hours to the World Trade Center (WTC) disaster; this is the first known use of robots for urban search and rescue (USAR). The University of South Florida (USF) was one of the four robot teams, and the only academic institution represented. The USF team participated onsite in the search efforts from 12–21 September 2001, collecting and archiving data on the use of all robots, in addition to actively fielding robots. This article provides an overview of the use of robots for USAR, concentrating on what robots were actually used and why. It describes the roles that the robots played in the response and the impact of the physical environment on the platforms. The article summarizes the quantitative and qualitative performance of the robots in terms of their components (mobility, sensors, control, communications, and power) and within the larger human-robot system. The article offers lessons learned and concludes with a synopsis of the current state of rescue robotics and activities at CRASAR.

Robots were used for USAR activities in the aftermath of the WTC attack on 11 September 2001. The robots were on site from 11 September until 2 October 2001. This was the first known actual use of robots for USAR. The robots were used for

- searching for victims
- searching for paths through the rubble that would be quicker to excavate
- structural inspection
- detection of hazardous materials.

In each case, small robots were used because they could go deeper than traditional search equipment (robots routinely went 5–20 m into the interior of the rubble pile versus 2 m for a camera mounted on a pole), could enter a void space too small for a human or search dog, or could enter a place still on fire or posing great risk of structural collapse. Though no survivors were discovered during the response, robots performed all their tasks well. The robots did find many sets of remains and, more importantly, were accepted by the rescue community. All robots were teleoperated

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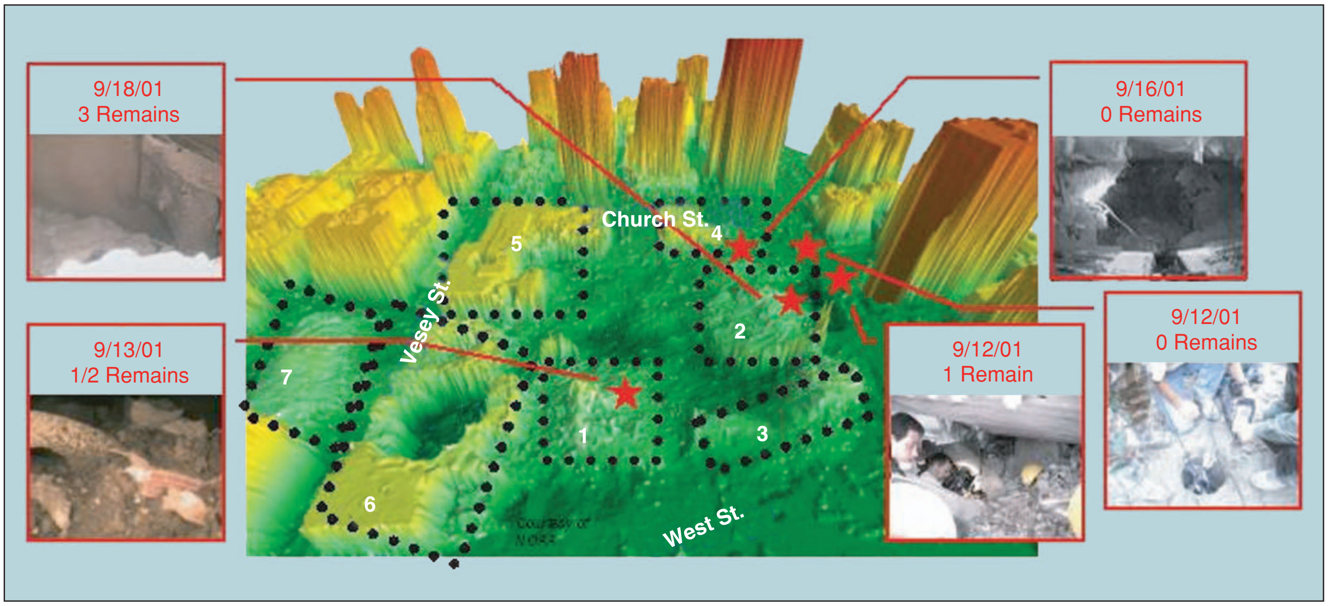

Figure 1. *A range map showing where the robots were deployed in the WTC rubble pile. The range map is courtesy of the National Oceanic and Atmospheric Administration (NOAA).*

owing to the unexpected complexity of the environment, the limitations of the sensors, and user acceptance issues.

Each robot deployment, or excursion into the disaster area for a workshift, was coordinated by the newly formed CRASAR under the direction of Lt.Col. John Blitch (retired). CRASAR worked as an independent team under the auspices of the Army Reserve National Guard, the New York Fire Department (FDNY), or the New York Police Department (NYPD), or served as an adjunct to Indiana Task Force 1, Pennsylvania Task Force 1, and Virginia Task Force 2, providing robots and operators plus training to task force members who might take the robots into areas off-limits to the CRASAR civilians. The Inuktun micro-Tracs and micro-variable-geometry tracked vehicle (VGTV) models and the Foster-Miller Solem and Talon models were the CRASAR robots used on the pile. The iRobot Packbot and Space and Naval Warfare Systems Command (SPAWAR) Urbot were used by CRASAR unofficially in nearby collaterally damaged buildings. Other robots and sensors from other organizations have been reported as being present, but were not fielded. For example, the U.S. Department of Justice brought in equipment from the Savannah River Technology Center, but only the sensors were used.

CRASAR coordinated four teams of scientists who worked during the rescue phase of the response (11–21 September), when there was still a possibility of survivors. Blitch and the first members of the teams from iRobot (led by Tom Frost) and Foster-Miller (led by Arnie Manigolds) arrived in the early evening of 11 September, while the USF team (led by Robin Murphy) arrived the morning of the next day. The U.S. Navy SPAWAR team from San Diego (led by Bart Everett) was unable to travel until the government permitted flights to resume, and so did not arrive until Friday, 14 September 2001. Figure 1 shows the locations where the robots were used on the rubble pile.

The scientists had varying degrees of relevant field expertise. Blitch had participated in the Oklahoma City bombing rescue efforts and subsequently completed a master's degree on robots for urban search and rescue under Murphy's coadvisement, continuing to publish and work in the area [1]–[3], [9]. In addition to numerous publications [5]–[8], [11]–[17], [19], [21] and research funding in rescue robotics, Murphy and two members of the USF team held actual certification in some forms of USAR. These were a side effect of conducting studies with Hillsborough County Fire Rescue since 1999. Members of the Foster-Miller and SPAWAR teams had military explosive-ordinance disposal experience.

The USF team also served as archivists—collecting, annotating, and backing up videotapes from the field, keeping up with the deployment details, and making field notes. Videotapes of the robot's-eye-view were made for each run, though the tapes from the two runs on 12 September were taped over. Videotaping of external surroundings was not permitted by the NYPD, so corresponding external views of the robots and where they entered the rubble pile are generally not available. The data collected from 11–21 September 2001 resulted in two master's theses, one concentrating on the performance of the robots in the field [10] and the other on human-robot issues [4].

A fifth team from U.S. Army Tank Automotive and Armaments Command-Army Research and Development Command—Explosive Ordinance Disposal technology division (led by David Platt) was brought in to assist Blitch and Foster-Miller with the recovery phase, 24 September to 2 October 2001. The teams frequently worked for the New York

The hot zone terrain was much different than an earthquake. This made robots necessary and also presented favorable conditions for their deployment.

Department of Design and Construction in structural assessment of the slurry wall and foundations of the WTC complex. The experience of the fifth team is reported in an article [20], though that article does not accurately represent the activities and use of robots prior to 24 September, when that team was not involved.

The Robots at the WTC

The majority of robots used at the WTC response were either developed as part of the Tactical Mobile Robots program sponsored by the U.S. Department of Defense (DoD) Defense Advanced Research Projects Agency (DARPA) or were being used by contractors within the program. The Tactical Mobile Robots program had been managed by Lt. Col. Blitch up until a few months before 11 September 2001. Tactical mobile robots are small enough to be carried in one or two backpacks (also known as man-packable) and were intended for hostage rescue and military search and rescue with a clear dual use for civilian USAR.

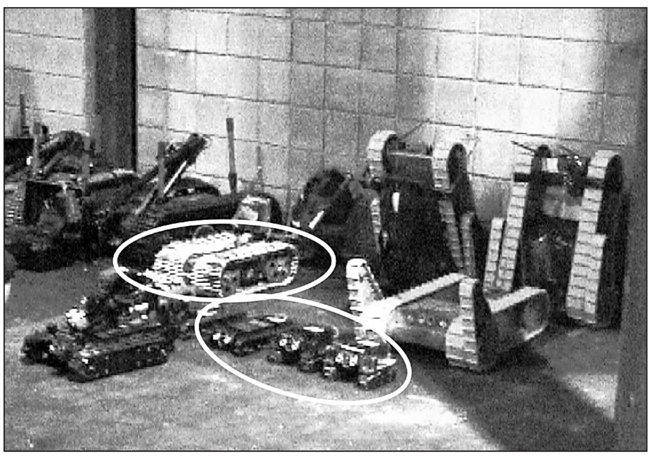

Figure 2. *Robots on static display at the Javits Convention Center where rescue teams were housed from 11–21 September 2001. Robots that were used on the rubble pile are circled.*

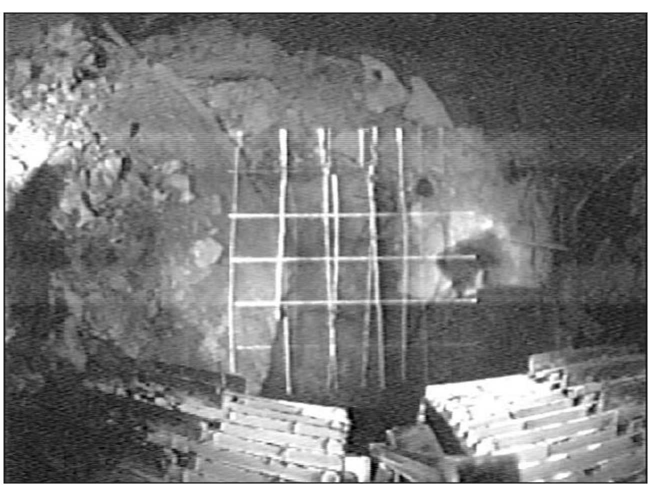

Figure 3. *A view from a Solem as it projected a range grid into a void in the area of WTC Building 4.*

Figure 2 shows the initial group of robots brought to the WTC. Only three models were actually used on the rubble pile from 11–21 September, for reasons described later. These models were the micro-Tracs, the Inuktun micro-VGTV, and the Solem, and are circled in the photograph. The robots either belonged to DARPA, the teams, or were sent by robot manufacturers.

Each of two Inuktun models could be carried in a backpack by one person. Both robots are tracked vehicles the size of a shoebox ($0.17 \times 0.32 \times 0.06$ m) and are teleoperated through a tether. The tether serves for both communications and power. An operator teleoperates the robot through a separate operator control unit (OCU) slightly larger and deeper than a laptop. Both robots have a color camera and two-way audio. The difference between the two vehicles is that the micro-VGTV is polymorphic, it can change its shape. Both models are designed for examination of heating, ventilation, and air-conditioning ducts and pipes. They do not have any inclinometers, odometers, or temperature probes, though newer models do. Neither are self-righting or invertible. The top speed for these robots is rated at 0.076 m/s, and the weight is 4.5 kg. The power supply is three 12-V batteries connected in series.

The Solem can be carried by two people. It is a tracked vehicle with wireless communication, a black and white camera on a tilt-up mast, and a laser range grid that can be projected onto the area in front of the camera for depth estimation (Figure 3). The robot weighs 15 kg and has a footprint of $0.51 \times 0.37 \times 0.2$ m. The operator teleoperates the robot through a separate OCU. The Solem does not have two-way audio. It is designed for military and civilian explosive ordinance disposal and has a top speed of 0.5 m/s. Four nickel hydride batteries serve as the onboard power supply. Although it is wireless, it was used with a safety rope, which imparted all the disadvantages of a tether.

The WTC Environment

The WTC environment was on the order of 80,000 m^2. The rubble pile formed the core of the hot zone, which is the area of devastation that poses significant safety risks to rescuers. Although the rubble pile was surrounded by buildings that were also collaterally damaged, these buildings were given low priority for search and rescue activities, in part because it was likely that occupants had exited from the building, and because the rescue focused on finding trapped first responders. As described in the following, the hot zone terrain was much different than an earthquake, especially in terms of the materials comprising the collapse and the types of voids. This

Figure 4. *View of the rubble near WTC Tower 2 and Building 4 showing pancaking and the lack of voids.*

made robots necessary and also presented favorable conditions for their deployment.

The WTC disaster was significantly different than an earthquake scenario, or even other terrorist attacks on buildings (Oklahoma City, Khobar Towers, etc.). The WTC was primarily constructed of steel, with concrete used only for flooring, while most commercial buildings and bridges are primarily constructed of concrete with steel reinforcement. The design of the WTC towers was unique. As a result, the collapse was a pancake type, where the buildings largely came straight down with few voids above the street level (Figure 4). The rubble was all steel, which is difficult to cut and remove, and the response teams were not trained to handle steel. The voids open to the surface were generally less than 1 m wide and still radiating heat from the jet-fuel fire in the basement. This meant that traditional methods, such as canine search, were not effective. None of the robots are designed to operate in temperatures higher than a person can tolerate.

The collapse type resulted in a situation where any chance of survivable voids was expected to be below grade in the basement areas. As a result, the bulk of the rubble above grade was not of interest and needed to be removed as quickly as possible in order to gain access to the basement. However, without being able to see the interior of the rubble, an efficient rubble-removal strategy that would speed up access to the basement could not be created. Therefore, the robots were needed to enter the extremely small voids and see if there was a way further down.

The voids themselves were generally more favorable to robotic exploration than a regular rubble pile, though far more demanding than the NIST Standard USAR Test Course developed for RoboCup [16]. Debris that typically cause problems, such as furniture, carpeting, and window coverings, were burned away or pulverized. Concrete chunks that pose hard-to-climb obstacles for most robots were not present because there was no structural concrete in the buildings. However, most voids were filled with paper, and the robots often sank deep into the paper and couldn't see or climb on top. The robot's camera was occluded an average of 18% during each run [10].

The majority of voids were the insides of the steel structural members, which had a hollow rectangular cross section (0.3×0.6 m) and were over 10 m long. These "box beams" acted like straws, penetrating the rubble. Figure 5(a) shows a contextual view of the WTC Tower 2 rubble pile with the box beams visible on the pile, Figure 5(b) a box beam that was explored by the robots, and Figure 5(c) a view from the robot as it investigated that void.

The Packbot and SPAWAR Urbot were used unofficially in collaterally damaged buildings for a few hours. The buildings were largely intact, which suggested that it would be favorable to larger robots. However, the insides were dark and covered with thick dust and mud from the sprinkler system, which made it difficult to get traction and for the human operator to recognize key attributes of the environment. The robots ran into expected challenges (closed doors) and unexpected situations (the mud on the stairs reduced the traction and the Packbot could not climb all the way up).

The WTC was also unusual in that it did not present major decontamination challenges for the robots. Unlike an

(a) (b) (c)

Figure 5. *WTC Tower 2: (a) view of the Tower 2 rubble pile, with long rectangular box beams littering the pile, (b) view of the box beam explored by the robots, and (c) robots-eye view of the interior of the box beam ledge with three sets of victim remains.*

Figure 6. *The CRASAR camp within the Javits Convention Center where team members rested, repaired or modified robots, or archived field data. Gary Mouru (Foster-Miller) is in the foreground, Brian Minten (USF) is in the middle, and Mark Micire (USF) is in the rear.*

earthquake or other mass casualty events, the remains of victims were severely burned. There was no blood or body fluids that would have to have been carefully washed off between runs and would have necessitated the use of medical protective gear for the robot operators.

Another aspect of the environment that affected robots and their deployment was the location of the cold and warm zones. A cold zone is where the rescue workers rest and rehabilitate their equipment, whereas a warm zone is the area immediately surrounding the hot zone. Rescue workers stage and decontaminate equipment in the warm zones, as well as remain on stand-by. The hot and warm zones were divided into sectors owing to the large size of the rubble pile. The warm zones at the WTC was subdivided into a base of operations (BoO) and a forward station.

The cold zone for federal response teams was at the Javits Convention Center, four miles away. Transportation between the Javits Center and the BoO was through commercial buses. If a robot did not fit in the luggage bays of the bus or on the seat inside the bus, it was not permitted to go to the warm and hot zones. Exceptions were not made until after 21 September. Figure 6 shows the CRASAR camp at the Javits Convention Center.

The warm zones were a three-block area surrounding the hot zone. Teams usually set up the BoO within an evacuated building. At the BoO, they stored equipment, watched CNN, rehydrated and ate, and took naps. Impromtu, or hasty, training on the robots was also held in the BoO. Hasty training for the federal teams was needed because, in the case of a particularly dangerous void, technical search specialists from the federal response team would have transported and operated the robots rather than expose the CRASAR civilians to a significant safety risk.

When a new area became available for technical search, operators would prepare the robots, pack them in their backpacks, and walk the three blocks to the forward station. At the forward station, the robots would remain powered up on "hot stand-by" until the area was deemed safe for human entry. Then, the robots would be called into the pile and escorted to the site. The robot operator would have to crawl over rubble and walk across beams or down straight ladders to get to the area of interest. Often, the robot and operator would have to evacuate from the rubble pile before reaching the void due to safety concerns.

Robot Roles and Missions

The robots were deployed eight times over the 11–21 September time period, but only used on four of those shifts. The purpose of each deployment was best described as technical search: trying to find deeper survivable voids within the rubble pile or less dense areas that could be more rapidly excavated, providing access to the basement where there might be survivors. In a more typical response, the technical search would have been more focused on finding survivors.

As noted earlier, the type of collapse and the density of the debris resulted in many extremely small voids. These voids could not be effectively examined by dog teams because the fire interfered with the scent and, later, rain washed off any residue. The voids were often very deep, precluding the use of search cameras on poles, which could only see about 2 m into the void. Many search cameras melted in the early hours of the WTC response when they were thrust into voids still on fire.

In future responses on a rubble pile, it is expected that a canine team or acoustic sensors would identify an area where there was some sign of a human. Voids within that area would first be examined by a search camera, then deeper voids would be investigated by the robots.

From the arrival of the first robots on the evening of 11 September through the morning of 13 September, the robots were deployed under the direction of the Army Reserve National Guard, the FDNY, or the NYPD. A CRASAR team would talk directly with a sector chief or other authority on the rubble pile and then be directed to a void. After 13 September, access to the rubble pile was formally controlled, and the robots were most often deployed as part of a federal task force team operating under the Federal Emergency Management Agency (FEMA), where CRASAR essentially acted as a server and processed requests for robots from client task force teams. In most cases, CRASAR operators accompanied FEMA Indiana Task Force 1. The micro-Trac was the most frequently used robot, deployed seven out of eight times. The micro-VGTV was second, and the Solem was used only once.

Choice of Robot for a Run

The choice of a robot for a run depended on four factors:

- transportation restrictions
- the robot's acceptance by the requesting authority
- the expected size of the void to be investigated

- any other contextual information.

Each factor is described below.

The transportation restrictions introduced earlier meant that only man-packable robots were permitted on the rubble pile during the rescue phase. This reduced the fieldable pool to the Inuktuns, the Solem, and the Packbot. These restrictions were relaxed in the recovery phase, and the pool became the Inuktuns and the Solem and Talon. (The Packbot was no longer available.)

An authority such as the leader of a FEMA task force would discuss their needs with CRASAR and determine which robots and operators they would take with them. The task force was responsible for the safety of the CRASAR members and also had the discretion of accepting training on the robots so that they could be deployed by one of their technical search specialists. Therefore, they tended to choose robots that were easier to operate. The Packbot was rejected by FEMA teams, despite its mobility advantages for larger voids, because it was still obviously in its early prototyping phase.

The void size was another important factor in what robots were requested. The choice of which Inuktun (micro-Trac or micro-VGTV) to use, or whether to use an Inuktun or Solem, was largely a function of the size of the void. Most of the voids were less than 1 m diameter, so the smaller Inuktun robots were always chosen. At the end of each shift, the task force teams would debrief the next shift about the area they would be working in. The teams would then request the robot(s) they thought most appropriate.

In addition to picking a robot, the task forces were concerned about the field expertise of the operators. Robot operators who could operate the Inuktuns and had direct USAR experience were preferred. Robot operators with no field experience did not go onto the pile, since that was the most dangerous location. An operator with field experience required less supervision than a civilian with no training and diverted less of a task force's manpower away from the search and rescue task.

Table 1. Date of deployments and voids searched, showing the location and the robot used.

Deployment	Void	Location	Date	Robot Used
1	1, 2	Cedar St.	9/12/01	micro-Tracs
2	3, 4, 5, 6	WTC 1	9/12–13/01	micro-Tracs
7	7	WTC 4	9/16–17/01	Solem
8	8	WTC 2	9/18–19/01	micro-Tracs, micro-VGTV

Context-dependent information, such as time constraints, were also important. In one deployment, the larger Solem robot was used because the window of opportunity to explore that newly opened void was only 20 min (at which point the cranes were to resume working in the area and all personnel would have to be evacuated for safety reasons). In that case, a crane operator had opened up a large network of three tunnels, one of which appeared to be related to the subway and food court areas. A rescuer could crawl on hands and knees in the tunnels, though the time to get permits for a safe entry was longer than 20 min. The Solem is more than three times faster than an Inuktun and was more likely to climb the more irregular rubble, therefore it was selected.

As of this writing, no FEMA teams have rescue robots, though CRASAR is working with several to set up memorandums of understanding to deploy with them.

Pattern of Use

The pattern of use for the robots was surprising, and quite different that what the USF team had experienced in previous training [6]. The robots were called out eight times, though used only on four deployments, and inspected a total of eight voids (Table 1). This may appear low. Indeed, it is likely that the robots were underutilized. This is due in part to the fact that the robots were a new technology that none of the task forces knew about. (Many task forces assumed the robots were the much larger, and inappropriate, explosive ordinance disposal robots used by bomb squads. CRASAR now conducts awareness training and plenary talks at emergency management conferences to educate the USAR community.) The primary reason for the low use is that there were few search opportunities at the WTC; the search and rescue teams themselves often spent an entire 12-hr shift without being able to get on the pile or to initiate a technical search due to safety considerations.

It is also surprising that the average time that a robot was in a void was a mere 6:44 min, with the longest time logged at 24:40 min. This is consistent with the nature of search and rescue, where voids are quickly searched but the followup extrication may take hours. In previous exercises [6], the robots were used to search rooms and buildings still standing—providing a much larger area. In the case of the WTC, the robots were used to explore confined space or smaller voids. The CRASAR team has participated in three training USAR exercises since the WTC with realistically damaged buildings. The robots tend to be deployed for either highly confined space voids (which may be shallow) or for quick excursions into partially structured areas. Therefore, it is expected that a 30 min or less run will be the norm for victim search. It should be noted that, because a technical search is so short and a search camera transmits images with a flip of a switch, rescuers would not accept a long boot or setup time for a

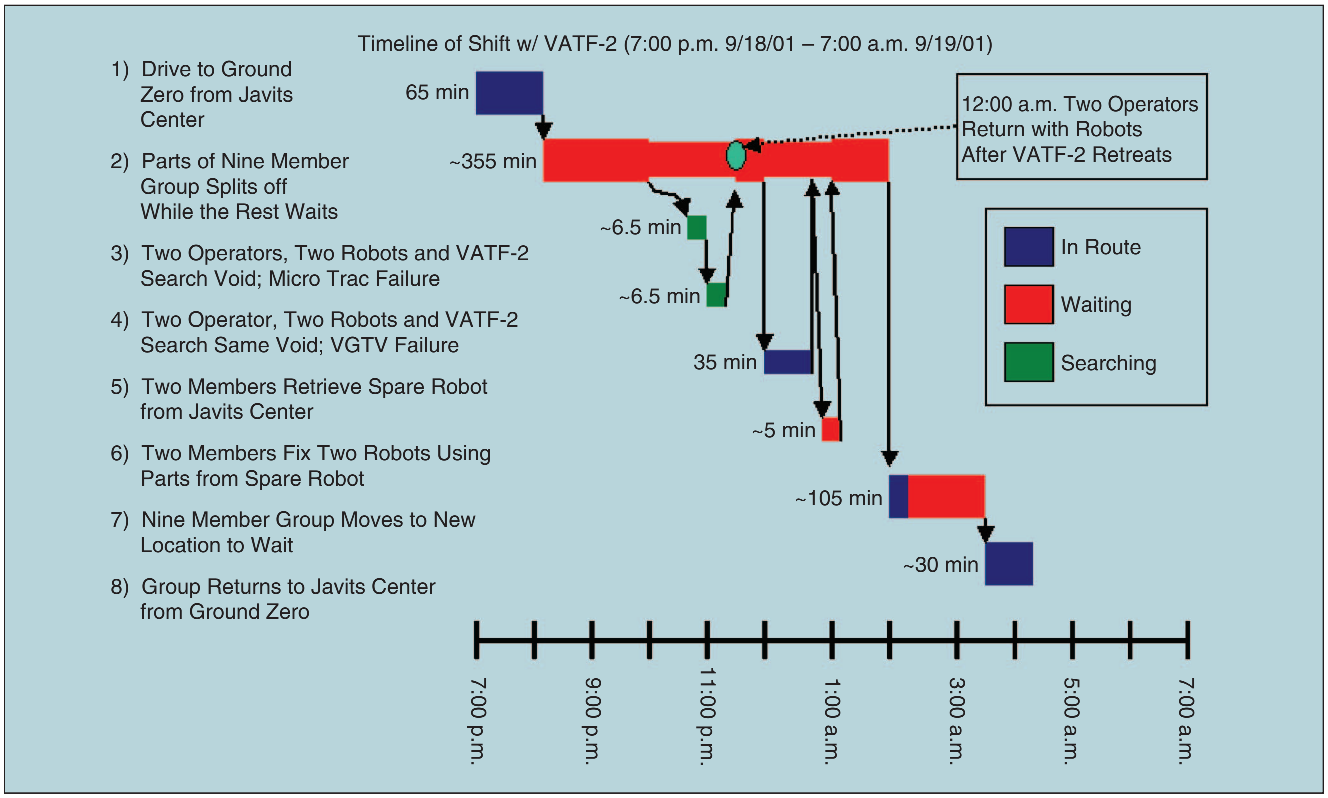

Figure 7. *Diagram showing the principal activities of deployment 8 on 18–19 September 2001.*

robot. Rescuers walked away from the robots on several occasions. The CRASAR teams realized that the robots had to be kept on "hot stand-by" so that the time from the technical search specialist saying "look here" and the robot in the void transmitting an image was cut to under 2 min.

Figure 7 shows a representative shift, which is discussed in more detail in [4]. In this shift, robots were requested by Virginia Task Force 2 to investigate the void on WTC Tower 2 [Figure 5(b)] during the evening shift. The team spent only 13 min out of the 12-hr shift searching the voids. The majority of time was spent waiting.

After 24 September, the robots were more commonly used for structural inspection and hazardous material detection, particularly to see if explosive gases were present. One of the robots was outfitted with a Multi-RAE, a gas detector commonly used by fire departments throughout the United States. The duration of the robot runs after 24 September (the recovery phase) were longer than the search for victims during the rescue phase. This was in part due to the nature of detailed structural inspection, as well as the reduced urgency.

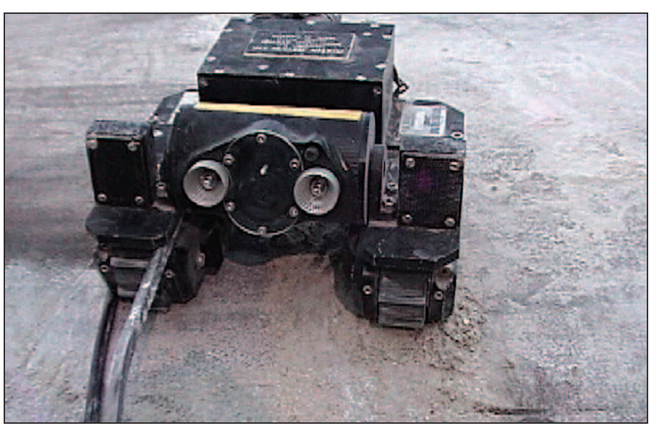

Figure 8. *Metal rod jammed between the tracks and housing on an micro-Tracs robot.*

Performance of Robots by Components

The robots performed well overall, with the primary measure being the acceptance by the rescue community. The robots did find multiple sets of human remains, but technical search is measured by the number of survivors found, so this statistic carries little weight within the rescue community. The performance of the robots may be better understood if described in terms of the components of the robots: mobility of the platform, sensors and sensing, control, and wireless communications. The fifth component, power, did not show any problems. All the robots were powered by batteries, which were sufficient to run the robots for a 12-hr shift.

Platforms and Mobility

The robot platforms generally performed well. The most common problems were with the tracks on the Inuktuns. A micro-Trac was damaged when a 0.25-in piece of metal, possibly from office furniture, became jammed in the 0.125-in gap between the tracks and the body (Figure 8). In one case, an Inuktun detracked one of its treads, had to be pulled out of the void, and the mission had to be suspended until a replacement track was brought to the site. The detracking is thought to have been due to the high heat in the void softening and permitting the rubber track to expand and come off.

The biggest fear, though unrealized, was a robot flipping over into a position where it could not be righted. None of the robots used on the rubble pile were invertible or self-righting. This put considerable pressure on the robot operators. The only time a robot (the Solem) flipped over, it was able to be righted by a judicious set of pulls on the safety rope. The micro-VGTV had an advantage in climbing rubble since, with its variable geometry, it could be configured to have a slightly raised bow, like a tank. However, the slightly heavier micro-Tracs was often better for smoother surfaces.

One unexpected outcome of the WTC was the high dependency of robots on tethers or safety ropes. This introduces the need for a second operator, where one operates the robot (the operator) and one handles the tether (the tether wrangler) (Figure 9). The size of most voids permitted only the Inuktun robots to be used. The small size of these robots is possible only by having the battery located with the OCU and all power and control transmitted through a tether. In the one run where a wireless robot was used, a safety rope was needed since there was always the possibility of a vertical decent or flipping the robot over.

Tethers and safety ropes had a significant disadvantage: they tangle. During the rescue phase, a robot tether got tangled and could not be retrieved without an intercession. In this case, the robot had gone from street level down into a boiler room. On the way back up, the tether became entangled with steel reinforcement bars (rebars). Since the robot had uncovered a promising void, rescue workers immediately shored up the void and entered. They retrieved the robot on their way into the void. The study of the videotapes by Micire [10] indicated that an operator had to pull on the tether an average of 7.75 times per drop, or approximately once a minute, in order to keep the tether from getting tangled.

However, tethers and safety ropes had additional advantages beyond keeping the robot small. In the case of the Solem, the safety rope made it possible to self-right the robot when it flipped upside down. Unfortunately, the Solem was lost when the safety rope broke during an attempt made to retrieve it. (The robot operators swapped to steel cables during the recovery phase.) In the case of the Inuktuns, the operator handling the tether could work with the robot operator and actually help the robot climb obstacles or work the robot deeper into the rubble. These gravity assists occurred an average of 9.25 times per drop [10]. Note that the gravity-assists, combined with proactive pulling to prevent tangling, meant that that tether operator interacted with the tether more than two times per minute.

Sensors and Sensing

The most commonly used sensors were the video cameras. The Inuktuns had color cameras while the Solem had a black and white camera. Each robot had some form of headlight, with adjustable headlight intensity on the Inuktuns. The color camera is preferable for searching for victims. Since the interior of a building collapse is covered in gray dust from concrete and sheet-rock, the presence of a colored region may indicate a survivor who has shaken off some dust or is bleeding. However, black and white cameras are considered better for structural assessment owing to their slightly higher resolution.

This is the first known use of robots for urban search and rescue (USAR).

CRASAR also had a number of Indigo Alpha forward looking infrared (FLIR) miniature cameras for thermal imaging from USF and on loan from the U.S. Army Night Vision Laboratory. These cameras are the size of a small cell phone and could be mounted on most robots. Thermal imaging is a popular sensor with fire rescue teams for at least two reasons. First, victims will produce a heat bloom, despite being nearly invisible to the naked eye, due to the coating of gray dust. Second, the thermal imagers can detect signs of excessive heat build-up, indicating a flash fire is incipient and that rescuers should evacuate. Unfortunately, the FLIR quickly proved not to be useful. The rubble pile interior was extremely hot, so any signs of survivors or structural cracks would have been masked.

One of the biggest difficulties encountered while using the video cameras was the lack of depth perception. The Solem had a range grid that could be projected onto the scene in front of the cameras, but that was hard to interpret. Another problem with the video was the lack of peripheral vision or feedback. The robots would often roll over something or get trapped against an obstacle just off to the side.

The use of a Sick laser ranger was not possible for the Solem or the Inuktun. The Solem does not have any on-board computer or mechanism for relaying that data, and the Inuktuns cannot support a payload that size. Besides, the efficacy of a single planar laser is unclear—the robots must go through

Figure 9. *Arnie Mangolds handling the tether for a robot inserted into a lean-to void across the street from WTC Tower 2.*

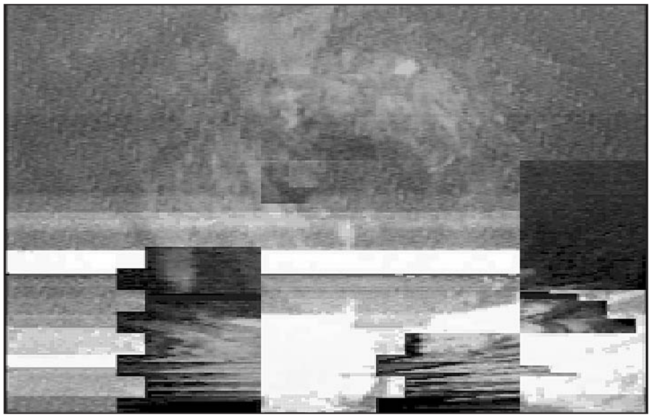

Figure 10. Frame from video of Solem as it experienced 1:40 min of communications loss duing a 7:00 min exploration of a void in WTC Building 4.

spaces that are heavily confined in all three dimensions. Estimating head clearances was a major problem at the WTC and unlikely to be resolved with a single laser and poor odometry.

Odometry was available on the Solem but not of use. The extreme terrain quickly invalidated the readings. The Inuktuns did not have odometry, and distance traveled was estimated by the length of the tether in the void. GPS signals would have been impossible to reliably acquire within the rubble due to the density and composition of the construction material. The Urbot operators employed a fairly useful strategy while operating in the collaterally damaged buildings—the odometry was reset periodically, and all distances were relative.

Control

All the robots at the WTC response were teleoperated. Neither the Inuktuns nor the Solem are equipped with an interface to permit computer control. Some forms of semiautonomous control or artificial intelligence for USAR had been demonstrated, but could not be used for a variety of reasons. USF, at one time, had a homemade computer interface for the Inuktuns, but it had broken and had not been replaced. The Packbot had an onboard computer and a computer as the OCU, but no software for autonomous control was available even if had been chosen for deployment. This was unfortunate since the iRobot Urban, the alpha version of the Packbot, had software developed for the Tactical Mobile Robot program. The software permitted the Urban to detect when it was flipped over and to right itself. Mapping software had also been written for the Urban but required the use of Sick lasers and accurate odometry. Perceptual cueing software agents, which detected skin color, heat, changes in color, and motion, had been developed for victim (or intruder) detection. The cueing software had been demonstrated on an Urban at the Montgomery County Fire Training Academy a year earlier. Unfortunately, the Packbot was not backwardly compatible with the Urban, and the software could not be readily transferred.

Wireless Communications

Only one wireless robot (the Solem) was used one time during the 11–21 September 2001 time period, and it was lost in the field due to wireless dropout. The Solem used a radio frequency that is normally good for 4.8-m line-of-sight transmissions. However, within the rubble, the Solem experienced 1:40 min of intermittent wireless dropout, and, at 7:00 min into the run, the connection was lost altogether as it returned to the entry point. The robot was estimated to be within 30–40 ft of the entry. An attempt was made to recover the robot by pulling its safety rope, but the rope broke. The robot was never recovered. Figure 10 has a representative image transmitted by the Solem that was not considered dropout. An important note about wireless communications is that the Solem, as well as the Packbot and Urbot, transmit video data using unencrypted, lossy compression algorithms. Lossy compression reduces bandwidth, but it strips out information critical to computer vision enhancements and artificial intelligence augmentation. A second concern about wireless communications is that unencrypted video might be intercepted by a news agency, violating a survivor's privacy.

Performance of Robots Within the System

Since the robots were teleoperated (and are likely to be so for the near future), it is instructive to view their performance within the larger human-robot system. The primary source of errors stem from poor user interfaces or from fundamental limitations of human perception.

In terms of quantifiable errors, the videotape analysis [10] reported that the robot operators made both mistakes (an intentional error or doing the wrong thing) and slips (an executional error in how to do the right thing) [18]. Approximately 10% of the duration of runs with the Inuktuns showed the same mistake. Experienced operators spent significant time adjusting the headlights, despite being aware that the video camera had auto gain optimization, essentially cancelling out any adjustment. The operators reported that they were trying to do something, anything, to get a better view of the highly deconstructed and unfamiliar environment.

The tapes revealed three types of slips: collisions, platform high-centered, and platform in the wrong configuration. There were an average of 0.25 collisions per drop, probably due to oversteering by the operator. For an average of 8.9% of the duration of a run, the robot was either high centered on a piece of rubble or in the wrong configuration. These slips appear to be the result of a lack of sensors and poor user interfaces.

A less quantifiable but very important error was missed remains. This is not quantifiable, since there is no ground truth. Figure 5(c) shows a view of three sets of remains: a torso to the left of the alley, a head near the center (with a wristwatch on the far right), and a hand in the alley. Only the torso on the left was identified at the WTC, despite repeated viewing by numerous task force members. The other remains were only noticed on a review of the videotapes back in

Tampa by Hillsborough County Fire Rescue, and later verified by others. This shows that unaided human perception, especially impaired by physical and cognitive fatigue, may not be sufficient for search and rescue.

The robots performed well overall, with the primary measure being the acceptance by the rescue community.

Lessons Learned and Observations

The WTC response provided many lessons for the robotics community. These lessons can be distilled into

- the overall scenario for use of mobile robots
- recommendations for a rescue robot system
- observations as to the practicality of fully autonomous rescue robots.

Platforms must be man-packable in order to be used, but there is no one right size. A color video camera and two-way audio should be on each platform, with the OCU capable of recording video data. Both the robot and the OCU should be water-resistant and readily decontaminated.

Scenarios

Based on the WTC, six field studies conducted by CRASAR with rescue workers since 11 September, and our experiences with the CRASAR international robotics response team, now recognized by the United Nations, the role of robots in search and rescue is becoming more clear. Small robots are proving especially effective for two situations: very small, deep voids, smaller than a human could crawl into or deeper than a boroscope can penetrate, or larger semistructured voids that humans cannot enter until it has been declared safe (a process that takes up to 8 hr). The variance in void sizes and the numerous activities now enabled by rescue robots (search, structural and hazards assessment, and medical facilitation) precludes a single ideal platform and payload. Instead, operators and robots mirror the interaction and deployment of human-canine teams.

It should be noted that the field experience indicates that robots will be used much like dogs. The robot operator will carry the robot to a void identified by rescue workers performing reconnaissance, insert the robot into the void, work with other rescue professionals to assess the data being provided by the robot, and then remove the robot and move to the next void. Scenarios where a swarm of hundreds of robot insects are set loose to autonomously search the rubble pile and report to a single operator appear to be both physically impractical and at odds with the larger rescue organization.

Recommendations for a Rescue Robot System

In terms of platforms and sensors, there is no single right size for a rescue robot. Both the Inuktun and the much larger Solem were used on the rubble pile, and the fully developed Packbot would have been used. The size of the void influences the size of the robot. Based on transportation issues, a rescue robot should be man-packable. Also, a rescue robot will always have to have at least a safety rope, so the design of the platform should specifically incorporate that feature. It is desirable for wireless robots to have a communications tether that can be attached to the safety line to eliminate communications drop-out.

The mobility characteristics for a platform cannot be specified since the different types of terrain corresponding to different void types is as yet unknown. There is no known characterization of rubble terrain that would indicate the necessary clearances needed for robots or even project energy consumption. Any platform design should take into consideration that the robot is likely to flip over at some point. It appears that invertibility is more desirable than self-righting, since the robot may not have enough room to execute a complex set of self-right motions.

Regardless of the size, each robot system should have the following components for technical search. It should have at least a color video camera and two-way audio (to enable rescuers to talk with a survivor). The OCU should be able to record and play back video data. If a victim or structural condition is found, it will be helpful for the members of the task force command structure and extrication crew to be able to view the tapes. It is desirable for the OCU to support computer vision algorithms to enhance the image (e.g., color histogramming) or to perform perceptual cueing. The robot should allow for at least one additional camera (FLIR or black and white) to be added as needed to meet specific mission needs. The desirability of having platforms that support the addition of payloads for hazardous material assessment, structural assessment, and victim management cannot be overemphasized.

The robot and OCU should be waterproof or, at the very least, water resistant. Building collapses often are muddy, with pools of standing water, because of water from broken sewer pipes and the release of the sprinkler system. A rescue robot also needs to be water resistant so that it can be decontaminated. Most biological decontamination agents are a weak (2–5%) solution of chlorine bleach, though rescuers are shifting to more equipment-friendly alcohol-based solutions. Finally, the robot and OCU need to be waterproof to be able to operate in the rain and snow.

Autonomous Control

Autonomous control appears unrealistic at this time and undesirable for the near term. It is unrealistic because of the challenges previously described. It is undesirable because rescue workers do not trust full autonomy, and user acceptance is critical for the field of rescue robotics. The term "autonomous control" may also create confusion.

Autonomous navigation may be more likely to be acheived with the advent of miniaturized range sensors, but autonomous detection of victims may be extremely difficult, owing to the inherent challenges of computer vision under unstructured lighting conditions.

The USAR terrain is very difficult for humans to teleoperate through. The viewpoint from the robot is very low to the ground with a narrow field of view, and the rubble is disorganized by definition. Automating navigation is expected to be very difficult. It is quite different than going down a hallway with a smooth floor or even going outside on a sidewalk or a park. In USAR, the density of obstacles is much higher, and the robot cannot often go around. Behaviors for climbing obstacles with polymorphic vehicles will become increasingly important.

Another challenge for fully autonomous navigation is how to operate in the truly three-dimensional nature of the space. There are hazards both above and below the robot, and the robot will most likely have to descend vertically at some point. The spaces for navigation are much more confined than in any other previously proposed domain for mobile robots, and the lighting is uncontrolled. It is expected that miniature range sensors will be needed to provide the data necessary for truly autonomous navigation.

As seen in Figure 5, victims may be unrecognizable to the human eye. Computer vision is nowhere near the level of human perception, so it is unlikely that unassisted machine perception will be able to produce no false negatives (miss a victim) while minimizing annoying false positives. Computer image enhancements and cueing of interesting regions for human detection appears promising.

Conclusions and Future Work

The first use of robots for USAR was successful, and the robots were well received by rescue professionals. The robots were called out onto the rubble pile for rescue operations eight times in the 11–21 September 2001 time period and actually used on four of those deployments for an examination of eight voids on WTC Tower 1, Tower 2, Building 4, and adjacent areas. The robots were tasked with victim and structural search, focusing on identifying shortcuts to the basement or possible survivable voids. Only one robot was lost in the field during that time, and that was due to a wireless communications failure. While the research issues for rescue robotics span computer science, all the engineering disciplines, as well the life sciences, the need for mechanically superior platforms cannot be underestimated.

Rescue robotics for USAR is still in its infancy. There are no robots made explicitly for USAR. The models of robots used at the WTC have a long delivery time owing in part to the competing demand by the U.S. military for operations in urban terrains. CRASAR is now based at the USF under the direction of Prof. Murphy and has cooperative agreements with the International Rescue System Institute in Japan. In addition to pursuing research, CRASAR maintains the only known trained and equipped rescue robotics response team in the world. As of this writing, no FEMA teams have rescue robots, though CRASAR is working with several to set up memorandums of understanding to deploy with them.

One possible road map for rescue robotics research was presented [19]. In order to maximize the short-term benefit, it was recommended that research should concentrate on helping the teleoperator perceive the environment and search for victims. Remains were missed at the WTC, and to miss survivors in another response would be tragic. Research into user interfaces and semiautonomous and cooperative control should enable an operator to more easily teleoperate the robot while under extreme physical and cognitive fatigue and to not miss victims or key structural defects. In the next five to eight years, advances in platforms and sensors should enable a more complete situational understanding of the environment. Serpentine robots and miniature sensors that can penetrate more deeply into the rubble are a must. Simultaneous localization and mapping of highly confined spaces will create accurate maps to help the incident command better manage the extrication of survivors. Many techniques have been created that would be useful if only the sensors were small enough to use with man-packable mobile robots. In the next eight to ten years, advances in the civil and biomedical engineering disciplines, combined with telemedicine, should lead to robots that can care for unconscious, trapped victims.

Since the WTC, CRASAR has focused its research efforts on human-robot interaction to create better, cooperative interfaces, medical missions, and shoring and extrication. CRASAR has collected ethnographic data at three collapsed buildings, performed training exercises since 11 September, and continued to develop deployment and training strategies, as well as identifing the requirements for platforms and sensors. CRASAR has contributed to the development of a lightweight medical triage sensor, which is being commercialized, and a fluid delivery system for victim management. A new project is concentrating on the use of robots to emplace airbags and structural supports within the rubble pile to speed up extrication of survivors.

The tapes from the WTC and subsequent training exercises are available for scientific use on mini-DV or VHS from CRASAR. Edited photos and videos can be downloaded from http://www.crasar.org. (Due to the presence of human remains on the videotapes, unedited data sets are not released to the public.)

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ERRATUM

There were three errors in the article published by Antonio Bicchi and Giovanni Tonietti published in the June 2004 (Vol. 11, No. 2, pp. 22–33) issue of *IEEE Robotics and Automation Magazine*.

First, the correct title of the article is "Fast and Soft Arm Tactics."

Also, on the formulas for the Gadd severity index (GSI) and head injury criterion (HIC) on page 23, the acceleration is measured in multiples of the acceleration of gravity (g) [not grams!], while time is measured in seconds.

Finally, within Figure 1, one should read "Compliant Covering," rather than "Complaint Covering," and

$$\text{“}M_{rob} = M_{rotor} + M_{link}\text{” instead of “}K_{rob} = K_{rotor} + K_{link}.\text{”}$$

The errors were introduced during production. We apologize to the authors and our readers.