Derived Performance Metrics and Measurements Compared to Field Experience for the PackBot

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ABSTRACT

Preparing an Unmanned Ground Vehicle for missions in abusive, dangerous environments requires suitable tests to define the system capabilities. Well-designed performance metrics can provide the government and industry designers with an understanding of how the system should be used in the field and how the system can be improved. This paper describes the metrics and measurements used for testing the PackBot system and compares those metrics and measurements against insights gained in field experience.

I. INTRODUCTION

The PackBot System, shown in Figure 1, is a ruggedized, man-transportable Unmanned Ground Vehicle system that provides a remote presence in dangerous locations. Reconnaissance and manipulation of a remote environment can be performed while the operator remains safe. The PackBot was designed primarily for Mobile Operations in Urban Terrain (MOUT). Designs for situational awareness capabilities and obstacles negotiation capabilities are driven by anticipated urban combat scenarios. The MOUT requirements have resulted in a system that also has many applications in other dangerous combat operations and Urban Search and Rescue (USAR) operations.

To prepare the PackBot for the hazardous duties that it will encounter in the real world, the PackBot has been tested at iRobot's facility and at the Small Robotic Vehicle Test Bed at the South West Research Institute, SwRI, at San Antonio, Texas. The PackBot system was also exercised at the Army simulated MOUT city at Fort Drum, New York. The predecessor to the PackBot system was tested at a testing ground in Rockville, Maryland. These tests helped to understand and measure the performance of the PackBot before the system was used in the real world. The real world scenario where the PackBot was employed was operations at the World Trade Center (WTC) disaster site. These experiences at the WTC disaster site held many lessons for future Unmanned Ground Vehicle use in the real world. This paper will look at the derived performance metrics and compare these to field experience.

Figure 1. PackBot System

II. PACKBOT HISTORY

The PackBot was developed by iRobot Corporation under DARPA's Tactical Mobile Robotics (TMR) program. iRobot began developing mobile robots for the TMR program in 1997 by creating a proof-of-concept robotic platform designed for MOUT called the Urban Robot. The Urban Robot was designed to be a small man-portable surveillance robot that could negotiate urban terrain. Under subsequent DARPA contracts, the Urban Robot platform became continually more rugged and sophisticated. The later versions incorporated sonar and infrared rangefinders with a more powerful CPU for onboard sensor processing. Under the PackBot contract, iRobot was assigned to develop a more robust and complete robotic system capable of surviving the abuses of real operations. Developing the PackBot became one of the primary focuses of the TMR program and iRobot Corporation was selected as the system integrator.

III. MOBILITY

The PackBot is a tracked robot vehicle designed for use in both urban and wilderness environments. PackBot is equipped with two main treads, used for locomotion, and two articulated flippers with treads that are used to climb over obstacles The PackBot can be fitted with extra treads for additional mobility, see Figure 2. Since the robots developed under DARPA's TMR program were primarily designed for urban environments, this commonality between USAR and MOUT is a large contribution to ease of mission transferability.

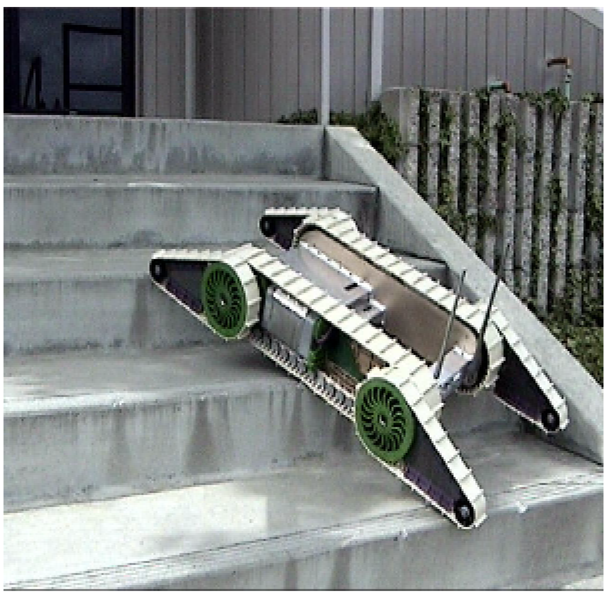

Figure 2. PackBot with additional flippers.

Urban environments typically include open spaces such as city streets and building interiors. Common obstacles that robots encounter in urban environments include: curbs, stairs, small rubble piles, pipes, railroad tracks, furniture, and wires. The ability to surmount these obstacles is essential to the success of these platforms.

The PackBot system was capable of traversing all of terrain encountered at the MOUT city at Fort Drum. With very little training, operators were able to drive the PackBot up stairs and through doorways. However, the MOUT city did not have piles of rubble that would be encountered from buildings that have been damaged in explosions or earthquakes.

The SwRI tests consisted of outdoor obstacles. Many of the obstacles, such as pipes and rubble piles, are also informative for predicting performance in urban environments. The obstacle course at the SwRI site consisted of various natural and man-made obstructions selected as a representative subset of robot-scale impediments to cross country movement. The following list is a description of the obstacles used for testing the PackBot and a brief description of the PackBot's performance with each obstacle:

- Railroad ties. No difficulty traversing
- Pipes of ten different diameters ranging from 1.25 inch to 9 inch. The robot had no difficulty traversing these pipes. The robot traversed the largest pipe by lifting itself onto the pipe using its flippers and doing a "backflip".
- Drainage Culvert. 24-inch wide culvert with two 45-degree bends. No difficulty traversing.
- Bamboo Forest. The bamboo forest consists of a matrix of 2 inch PVC pipes on 6 inch centers. The maze width is one pipe-width larger than the width of the robot. Under tele-operation, the PackBot failed to get through the maze on the first try in under the 20 minutes time limit. On the second try the robot was able to pass through the maze in 17 minutes using lessons learned from the first attempt and using the pose capabilities of the PackBot.
- Rock channel. The obstacle has rocks the size of a typical man-packable robotic vehicle. The obstacle was traversed without any problems. The articulators, power, and low center of gravity of the PackBot contributed to the successful negotiation.
- Large, medium, and small rock beds. These beds are populated with rocks that are football sized, softball size, and hockey-puck sized, respectively. The robot was able to traverse all three beds successfully. However, it went out of bounds (off the bed) in one out of the six runs.
- Dirt furrows. The furrows were dry, loose dirt formed into ridges in a 7 ft wide by 30 ft long obstacle. The robot had no difficulty moving through this obstacle.
- Vegetation obstacle. The course was divided into four sections with crops ranging in size from lawn grass to heavy crops, greater than 18 inches high. The light and medium crops were traversed with no difficulty. The heavy crops made the direction of the PackBot difficult to determine and the PackBot moved outside the course in several of the runs. The articulated head/neck unit being developed for

the TMR program will make navigation in thick brush easier.

- Flat Sand Pit. The pit was filled with dry sand and the robot transitioned the pit without difficulty
- Sand Furrows. Dry sand was formed into sand dunes. The robot had no difficulty with this obstacle.
- Mud pit. A pit 4 in by 7 ft by 16 ft was filled with a mud slurry. Figure 3 shows the PackBot after traversing the mud pit. The PackBot could go straight through the mudpit. If the PackBot turned 6-8 times in the center of the pit, the PackBot would become mired. The SwRI report stated "the robot has very good mobility in mud, despite its failure to complete the entire test."

Figure 3. PackBot after Traversing the Mud Pit.

- Inclined ramp. The ramp is adjustable from 0 to 60 degrees. With no payload, the PackBot climbed the ramp, was able to hold position, and was able to skid steer in both directions. With 22.5 pounds of payload, the PackBot was able to ascend and descend up to 55 degrees and able to traverse 45 degrees.
- Curb Height. The PackBot climbed 13 inch curbs.
- Cattle Grating. Metal pipes, 2 inches in diameter, can be moved to different positions. The PackBot traversed this obstacle at all possible gap settings (other than unreasonable ones spaced farther apart than would be expected in an actual animal guard.
- Stairs. The stairs were sets of: wooden 9 inch risers and 11 inch runs, wooden 7.5 inch risers and 11 inch runs, metal 6.5 inch risers and 12 inch runs. The PackBot was able to climb all of the stairs.
- Speed Runs. The speed tests recorded an average (cruising) speed of about 5 mph. With its power booster, the PackBot can achieve burst speeds over 8 mph.

The SwRI tests provided the PackBot designers with excellent information on the PackBot's mobility characteristics tested against precise metrics. Results of the tests were very positive and there was no critical design changes required because of mobility shortcomings.

Since disaster areas and urban terrain are covered in all types of debris, having as much mobility as possible greatly increases the success of USAR missions. Although tracks provide the core of essential mobility, having additional modes of mobility is advantageous. When negotiating rough terrain, robots often flip over. The PackBot's flippers enable it to perform self-righting. The flippers on the PackBot also provide extra mobility, since they are coupled to the main drive tracks, creating a larger adjustable contact surface. The articulated flippers help prevent the robot from being immobilized due to high-centering, enable the robot to climb taller objects, and can help propel the robot forward through dense vegetation through continuous rotation.

At the WTC disaster site, the terrain where USAR operations took place could be divided into two types, the rubble pile, see Figure 4, and buildings for clearance. The rubble pile was not something that these robots had previously encountered and the robots were not specifically designed for the rubble pile terrain. The extreme conditions presented the robots with problems in various areas. The wreckage site had such an incredible amount of debris that mobility was very difficult. The huge pile of twisted steel was challenging for humans to climb, and more difficult still for robots

Figure 4. World Trade Center Rubble Pile.

to negotiate. The mere size of the pieces of steel could be insurmountable. It was very difficult for small mobile robots to traverse such an environment. The PackBot was not able to negotiate the rubble pile except for specific places. For the most part, there were no crevasses in the rubble pile big enough for the PackBot to explore. Usefulness of the PackBot was demonstrated in the surrounding area for building clearance.

The sites requiring clearance and inspection around the rubble pile were strewn with paper and debris. A layer of dust several inches thick covered the area. The PackBot's debris rejection system on the treads was successful, allowing the PackBot to drive through large amounts of debris. This system was previously tested at SwRI with the small rock bed, dirt tracks, and rock channel. The PackBot did not detrack in the WTC operations. The PackBot was used to demonstrate building clearance in the buildings surrounding the WTC. A building clearing operation was performed in an area that had been previously cleared by rescue workers and the PackBot system was shown to be useful for clearing buildings. The PackBot moved through the environment looking for people in the buildings and inspecting structural integrity of staircases. USAR personnel at the WTC observing the demonstration deemed the building clearance capability useful. The PackBot moved through the buildings including many staircases without difficulty except for one staircase. The problematic staircase was covered with dust and the metal was slippery such that the PackBot was not able to get traction on the steps.

The WTC disaster highlighted that specific terrain encountered with USAR operations is difficult to predict, but having a well designed general mobility capability that will climb rubble, self-right, climb staircases, and is maneuverable enough to go through hallways is useful in many scenarios. The designers of the PackBot feel that the terrain such as the rubble pile could not be negotiated without a large increase in complexity and expense in the mobility mechanisms.

IV. DURABILITY

The PackBot was designed from the ground up with considerations for impact resistance, waterproofing, vibration resistance, electromagnetic resistance, low electromagnetic signature, and a wide operation temperature range. The SwRI tests examined the following metrics.

- System Shock. The system survives shocks of 400 G's. 400 G's translates to a 10 ft drop onto concrete. The system was fully operation after multiple drops from 10 ft in positions of rear, forward, and belly down.
- Waterproof. The system is rated for water depths of up to three meters. At SwRI the system was tested in a water channel just covering the PackBot, see Figure 5, and in a pond with depths of up to 5 ft. The PackBot had no problem with the water tests.
- Electromagnetic. The electromagnetic resistance capabilities of the PackBot are restricted from public release.

Figure 5. PackBot Emerging From Water Test

- Temperature Range. The known operation range of the PackBot is 20 degrees Fahrenheit to 120 degrees Fahrenheit. While the temperature range was not explicitly tested at the SwRI tests, the ambient temperature reached 116 degrees Fahrenheit.

The PackBot has an onboard health sensor suite that sends messages back to the Operator Control Unit on the status of the system. Examples of messages sent back to the operator are the thermal sensor readings throughout the system. The system automatically scales back power to motors if the motor is in danger of damage from overheating. The operator can override the thermal protection in the case of a critical mission.

The waterproof capability makes the PackBot more practical for use in the field. The system can be used in rain and can be cleaned with a water hose. The system is also sealed against dust. Many of the combat situations where a robot would be used, such as in Afghanistan, are very dusty environments.

At the WTC, the PackBot's durability contributed to the systems usefulness. The general ruggedness of the PackBot translates to less maintenance and more readiness. The results from the SwRI tests indicated that the PackBot would be a system with excellent durability and throughout the WTC deployment, the PackBot proved to be a durable system.

V. COMMUNICATIONS

The PackBot requires a single 802.11b digital link from the Operator Control Unit to the PackBot vehicle. This link carries the real-time digital video stream as well as the other status information from the robot. In testing, the PackBot's communications link has reached distances greater than one kilometer line of sight. For missions where the system will not be able to maintain line of sight or in an electro-magnetically sensitive environment such as an ordnance deactivation mission, the PackBot system has a fiber-optic spooler that releases fiber optic cable and draws the cable back in. The PackBot also has a payload for RF amplifiers for extended range RF missions. The payload system allows other communication systems to be developed and integrated in a payload slot with ease.

The WTC area, in particular the area directly on the rubble pile, presented significant obstacles for RF communication. The rubble was heavily strewn with attenuating metallic debris and the airwaves were awash with RF radiation from a multitude of radios and equipment. For these reasons, and the fact that tether operations guarantee full frame rate video feedback, the tethered robot systems were used almost exclusively on the WTC rubble pile and were inherently more reliable during operations. Tests that demonstrate a robots ability to pay out its tether and keep the tether from becoming ensnared would be useful. Radio Frequency interference was anticipated as a major and crippling issue once the robots penetrated deep within the rubble.

Exercises were conducted with RF-controlled robots in the area directly surrounding the rubble pile. These areas consisted of blown out, unsafe buildings, wrecked vehicles, and rubble-and-dust-strewn streets. Most of the buildings in this area had not collapsed and, as a result, the areas of robot operation were not as densely congested with metallic debris. This permitted the freedom of RF operation well inside many buildings that were structurally unsound or not yet deemed safe. Although the robots operated freely within many areas of these structures, the operations were conducted with the knowledge that any robots losing communications within unsafe structures were to be considered irretrievable. The dynamic and intermittent nature of RF communications highlights the need for robot-based autonomy to assist the operator during communication blackouts. iRobot is working on autonomous behaviors that detect these situations and react with algorithms designed to navigate or backtrack the robot platform to areas of better communications. Test ranges testing this ability would be of value. In addition, iRobot is working on the ability to use multiple robots relaying communications one-to-another from deep within a RF-impenetrable building. Tests that evaluate this capability would be useful.

VI. SITUATIONAL AWARENESS

Situational awareness, in the context of PackBot missions, refers to the ability of the operator to understand the environment that the PackBot is exploring. This understanding depends on the particular mission and may include:

- Presence of disaster victims, enemy fighters, friendly fighters, civilians.
- Medical condition of detected people.
- Location of Booby traps and mines.
- Integrity of building structure.
- Layout of the area.
- Location of items of interest within the area.

Test courses specifically designed for the above aspects of situational awareness, would be useful.

Selecting the most appropriate sensors for robot situational awareness and understanding how to exploit, merge and interpret the various data provided by the sensors is an extensive area of research. The PackBot can be equipped with various sensors including: cameras, sonars, infrared sensors, and laser scanners. The primary source of information for situational awareness on the PackBot has typically been standard, low-light, or infra-red video cameras.

The PackBot is equipped with a differential GPS system. At the test course in Rockville, autonomous waypoint navigation was demonstrated, see Figure 7. Using only the GPS system, the Packbot demonstrated back-tracking through maze-like courses resembling minefields.

The PackBot is equipped with a compass, roll sensor, tilt sensor, and 3-axis accelerometers. These sensors

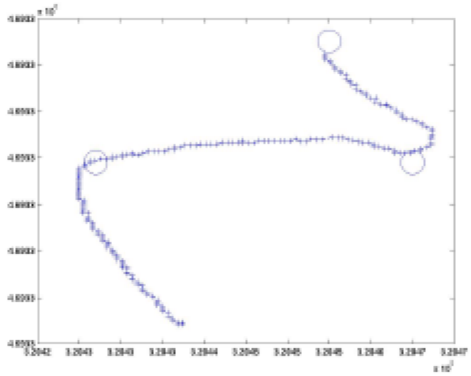

Figure 7. GPS Waypoint Autonomous Navigation

increase situational awareness by providing the operator with additional information on the PackBot's status and position

Many of the tests conducted at SwRI indirectly tested some aspects of situational awareness. For example, the vegetation test, examined the PackBot's ability to determine where it was so that it could move through the vegetation course.

At the WTC disaster, the PackBot used cameras as the main source of data for situational awareness. Both color and b/w video was used. As expected, the color was beneficial for the operator's understanding of the PackBot's environment. The PackBot also used a forward-looking infrared (FLIR) camera. The FLIR was useful in both dark and light environments. Since the environment at the WTC was covered in a thick dust, trying to discern various objects and details of the environment became difficult. The gray dust tended to mute all colors, but having a thermal based view of the world provided an alternate perspective on the immediate environment. Certain aspects of the environment were not readily evident using visible light or low light cameras; however, thermal imaging made these details apparent. The FLIR was particularly useful in detecting the presence and location of people in low-light environments. Tests examining the operator's ability to discern details through a camera would be useful.

VII. DEPLOYMENT

The deployment of a robot system can be broken down into:

- Delivering the robotic platform to the deployment area
- Setting up the control system
- Operating the robot

All of these areas must be well thought out for an Unmanned Ground Vehicle's mission to be successful. The PackBot was developed for ease of deployment. The PackBot is shipped in a padded case that can be lifted by a single person. The Operator Control Unit (OCU) and battery chargers are shipped in a separate case. The robot is deployed by pulling the base chassis out of the case and pushing the flippers onto the chassis. The deployment does not require any tools. The base chassis without batteries weighs 28 pounds so the pieces of the robot can be distributed among a team for carrying to the operation site. Ease of deployment of the PackBot was not tested in a formal setting.

Our experience at the WTC served as an education in the deployment issues associated with real emergency situations. A wide range of scenarios was present at the disaster site, requiring different deployment strategies. Automobiles were used to transport the robot systems and operators from the Javitts Convention Center to the WTC site. At other times automobiles were used to transport the robot systems and operators to a standoff point from which the operators then transported the system to the operation area. Not all areas were easily accessible and some required the PackBot to be carried on foot for long distances (up to approximately one mile). The robot systems needed to be carried over debris and rubble that the robot themselves could not traverse. This highlights the need for robot systems to be lightweight, compact, and man-portable. In other cases, operators carried equipment and robots in their arms and strapped to their backs while riding on ATVs that ferried them to the operation area. The robots did not deliver themselves to the operation area to conserve battery life and because some of the operating areas were not directly accessible.

After arriving at the area of operation, the control system had to be set up. Control stations for the PackBot at the WTC consisted of a human-machine interface of joysticks and buttons for sending commands to the robot. At the time of the WTC effort, the OCU hardware was not rugged or weather-resistant. This resulted in instances where the robot was not used for fear that the system's components were inherently unreliable. Since that time, the OCU software has been ported to more rugged OCU hardware, including a wearable OCU that has been used in military exercises. Having a man-portable OCU was shown to increase the type of missions where the PackBot could be used.

Experience at the WTC illustrated the need to transport the PackBot, OCU, and any other equipment, by foot to the area of operation and the necessity for it to be setup in a short time. A well thought-out container with intuitive locations for each piece of equipment is a necessity. These containers should be capable of being roughly transported in the back of a truck and carried easily. Minimizing the number of cables and plugs is also important. Every piece of equipment and tool needed at the control site must be included in the deployment plan.

During a deployment, the operation of the robot requires an operator's undivided attention. Additional people are needed at the control station to alert the robot operator if the operation area becomes too dangerous. All of the robots were driven under direct tele-operation without any additional autonomous behaviors aiding the operator.

One of the lessons learned at the WTC was the need for a rugged, waterproof robot system that is man-portable and easily set up. As a result, the development of well-packaged rugged OCUs has been mandated for all Tactical Mobile Robots. In order to be effective during these operations and flexible enough to adapt to the varied and extreme conditions associated with USAR missions, the robot systems should require a minimal amount of well-packaged support gear and cannot be limited by the logistics of their support or deployment.

VIII. MODULARITY

The PackBot platform is a versatile platform that can deliver a wide range of payloads that sense and manipulate the environment. Modularity is central to the PackBot design, see Figure 8. Each robot has eight payload interface connectors providing a variety of standard buses and system power. Each standard payload port contains 10/100 full/half duplex Ethernet, FARnet (an iRobot networking protocol), two differential analog video channels, two general purpose digital pins (serial, if needed), USB, and power sourcing or sinking. Payloads that have been designed or are being designed include cameras and lighting units, manipulators, fiber optic spoolers, and hybrid-electric generators. The on-board computer is a 700 MHz, Mobile Pentium III Processor with a 100 MHz system bus and 256 MB of SDRAM. The computing power of the onboard computer is available for running software required for controlling payloads.

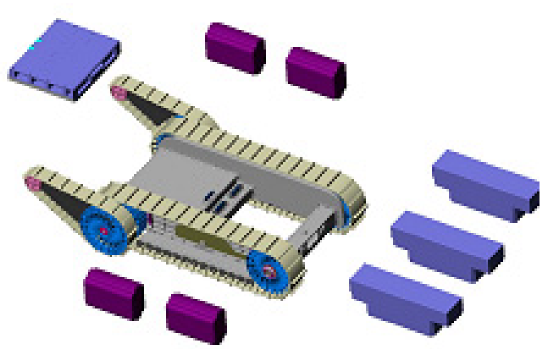

Figure 8. PackBot Modularity.

The PackBot implements a methodology for "snap-on" modular payloads that are quickly and easily interchanged to suit the particular or unique mission at hand. The flexibility and importance of this concept was proven at the WTC site when robots were able to change cameras, lights and tethers as the buildings and areas that were searched presented various technical and physical challenges.

Due to the modular design of iRobot's PackBot, a payload was developed that specifically addressed challenges that were anticipated for the WTC and USAR operations in general. Despite being designed with MOUT operations in mind, the PackBot was adapted to address USAR missions. The payload developed had multiple cameras, infrared illumination, 2-way audio, and a lens cleaning system. In addition to the payloads that were developed in preparation for deployment to the WTC, the standard buses provided on the PackBot payload connectors allowed for several technologies to be incorporated on site. This allowed the robot to make use of sensors and equipment specific to USAR missions. The experiences at the WTC demonstrated the flexibility of a modular architecture and the necessity for robot configuration on a per mission basis.

Payloads used at the WTC were limited to stationary cameras (including a FLIR), light sources (IR and Halogen), up to four battery packs, and Cat 5 cable spoolers. But the versatility, the advantages, and the disadvantages of the overall modular concept were apparent. Even though all payloads were developed for harsh environmental exposure, great care had to be taken when attempting to replace, adjust, or modify payload configurations. Fine concrete dust and debris covered every square inch of the robots' surfaces after every deployment.

Useful metrics for modularity include the amount of time and cost required to add a simple payload to the system.

IX. ENDURANCE

A critical metric for field operations is the maximum length of a mission that can be performed. At the SwRI tests, the PackBot demonstrated run times of 2 hours with constant activity. The maximum mission times can be extended to over 10 hours if the robot is stationary for most of the mission. These mission times represent the standard usage of two batteries. Four batteries can be used to increase the mission time. Endurance tests at SwRI demonstrated that the PackBot can carry payloads more than doubling its 35-pound base weight without significant impact to its mission time. The PackBot achieves its long run times with the selection of power saving components throughout the vehicle.

At the WTC, the lengthier mission times translated to less down time for the robot returning to swap batteries. Although the mission length was not an issue on the specific PackBot missions, there were scenarios at the WTC where a long mission length would be advantages. For example, in conducting extensive building clearance, the operation may be slowed down by the robot returning to the home base every two to three hours for a battery exchange.

X. CONCLUSION

The PackBot performed well at the World Trade Center disaster site in each area of mobility, durability, situational awareness, communications, deployment, modularity, and endurance. Many of the characteristics of the PackBot were well understood from the testing conducted at SwRI, iRobot, and other exercises such as the Fort Drum MOUT city. The application of PackBot technology at the WTC disaster demonstrated that technology developed for MOUT is transferable to and useful in USAR missions although these operations presented unique challenges. The robust mobility and the flexibility provided by the modular nature of the PackBot enabled the robots to operate effectively and adapt to new situations.

The widely varying conditions and environments encountered at the WTC disaster site confirmed that no single size or configuration of robot could address all of the difficulties that an USAR mission can present, however the PackBot provides a useful capability for many situations encountered. The TMR program has made great progress in advancing robot technology and much of what it has done is applicable to areas outside of MOUT missions. The experiences at the WTC show that there is great benefit in using robotic technology in search and rescue operations, yet there remains work to be done in developing specific USAR robot technology.

Additional metrics specifically designed for USAR applications would be helpful. For example, metrics could measure mobility over rubble and building debris, as well as communications range in indoor environments (both intact and damaged). Metrics could also test the ease of deployment by measuring weight and time to setup. The performance metrics developed by SwRI for testing mobile robots provided valuable information about the PackBot's capabilities. The SwRI metrics indicated that the PackBot would perform well in a wide variety of rugged environments, and our experiences at the WTC confirmed the SwRI tests.