



Response Robot Evaluation Exercise

TX-TF1 Training Facility - Disaster City
College Station, TX
April 4-6, 2006
(with a standards meeting April 7, 2006)

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Executive Summary

The Department of Homeland Security, through the Science and Technology Directorate Standards Program, is developing performance standards for robots applied to urban search and rescue (US&R). The National Institute of Standards and Technology (NIST) is leading this effort with collaboration from subject matter experts within the Federal Emergency Management Agency (FEMA) US&R Task Forces and other response organizations, along with robot manufacturers and robot researchers intent on this application domain. The resulting standard test methods are being developed within the Homeland Security Applications Committee of ASTM International.

Due to the breadth and complexity of urban search and rescue missions, and the diverse and evolving technologies present within robotic systems, the definition of performance requirements and associated test methods is an ambitious undertaking. The robot providers and eventual end-users need to reach common understandings of the envisioned deployment scenarios, environmental conditions, and specific operational capabilities that are both desirable and possible for robots applied to US&R missions. Toward that end, NIST organizes events that bring emergency responders together with a broad variety of robots and the engineers that developed them to work within actual responder training facilities. These informal response robot evaluation exercises provide collaborative opportunities to experiment and practice, while refining stated requirements and performance objectives for robots intended for search and rescue tasks. The most recent event was held April 4-6, 2006 at Disaster City[®], FEMA's Texas Task Force 1 training facility built and operated by the Texas Engineering Extension Service, part of the Texas A&M System. Disaster City is considered by many to be the most comprehensive emergency response training facility presently available.

Responders from the FEMA Task Forces, along with members of other response organizations who are active in the associated standards committee, were able to experiment with a wide range of robotic platforms: 16 models of ground vehicles, 2 models of wall climbers, 7 models of aerial vehicles including a helicopter, and 2 underwater vehicles. Ten different deployment scenarios were used around the Disaster City facility. In each of these scenarios, responders used the robots to search areas of interest for simulated victims and other embedded tests. Thirteen emerging test methods and their associated test artifacts were available to support robot/operator practice and training. These reproducible test methods, which are intended to help guide developers toward effective solutions while providing responders with known practice, training, and evaluation methods, will be refined based on the experiences and feedback from these events. The resulting these test methods will be submitted to ASTM International for balloting in the coming months.

A standards committee meeting was held on the day after the exercise to distill the lessons learned. Numerous useful comments were noted, and will drive the standards development process. The key decisions made were to focus on three of the possible thirteen robot categories when developing the first set of test methods and associated robot usage guides. The responders selected small throw-able "peek bots;" wide-area ground survey robots; and aerial loiter/survey robots for near-term standard test methods leading to deployment.

Extensive data was collected throughout the event. Responders were asked to formally and informally provide feedback on the scenarios, test methods, and robots. Videos and images were captured of all robots in action. Feedback regarding the test methods being piloted was also captured. Additional data collection efforts support new performance measurement infrastructure being developed by NIST: 3-D laser scans of scenarios to support ground-truth analysis and rubble characterization, simulation tools for robot development, and operator training; A robot tracking system, which uses active radio tags and surrounding antennas, to capture quantitative performance data within complex training environments.

This report provides a summary of all the activities and results from this event. Highlight images and video of the robots can be downloaded from the NIST project home page:
http://www.isd.mel.nist.gov/US&R_Robot_Standards.

Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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1.0 Introduction

Response robot evaluation exercises introduce emerging robotic capabilities to emergency responders while educating robot developers regarding the performance requirements necessary to be effective, along with the environmental conditions and operational constraints necessary to be useful. They also provide an opportunity to refine emerging test methods and associated test artifacts being developed to measure robot performance in ways that are relevant to emergency responders. Conducting these events in actual US&R training scenarios helps correlate the proposed standard test methods with envisioned deployment tasks and lays the foundation for the usage guides which will identify which robot categories appear best suited for particular response tasks. The resulting standard test methods and usage guides for US&R robots will be generated within the ASTM International Homeland Security Committee through the E54.08 Subcommittee on Operational Equipment.

The second in an ongoing series of response robot evaluation exercises for FEMA US&R teams was hosted at the Texas Task Force 1 (TX-TF1) training facility known as Disaster City®, which is located at Texas A&M University, College Station, TX. Applicable robots and supporting technologies (e.g., sensors), purchasable and/or developmental, were invited to take part in this exercise which highlighted operationally relevant US&R scenarios specifically devised for ground, aerial, and underwater response robots. The robots themselves were not formally evaluated during this exercise.

Disaster City® is a 52-acre training facility designed to deliver the full array of skills and techniques needed by urban search and rescue professionals. As part of the Texas Engineering Extension Service (TEEX) at Texas A&M University and a training site for TX-TF1, the facility features full-size collapsible structures that replicate community infrastructure, including a strip mall, office building, industrial complex, assembly hall/theater, single family dwelling, train derailment and three rubble piles.



Figure 1.1: Images from the response robot evaluation exercise at Disaster City® April 4-6, 2006

The event included three days of robot evaluations in available US&R training props. The first two days allowed the assembled responders to deploy the robots within the training props, become familiar with emerging technologies likely to provide benefits in the near term, and provide feedback to developers regarding realistic usage. On the third day, the emergency responders chose the most successful robots from the previous two days to perform targeted (and practiced) tasks in a four hour mock incident response exercise, which included several canine teams as well. The robot developers acted as advisors/observers for the US&R teams during this exercise. An informal after action briefing was held on the morning of the fourth day to distill applicable knowledge gained during the event and to refine the design parameters for the test methods proposed for standardization. All stakeholders were encouraged to provide feedback on the proposed test methods.

2.0 Background

The event held at Disaster City® is part of an ongoing program funded by the Department of Homeland Security and conducted by the National Institute of Standards and Technology to develop performance standards for robots applied to urban search and rescue. During the initial phase of the program, FEMA Task Force members participated in a series of workshops in which the performance requirements for US&R robots were defined. During these workshops, potential robot deployment categories and employment roles were also enumerated. Roughly one hundred requirements were defined and organized into a systematic structure, along with thirteen robot deployment categories. The output of the program is to be a set of standard test methods complemented by usage guides to help responder entities decide which robot categories are best suited to which response scenarios. The performance test methods will provide a common language, reproducible test artifacts, and performance objectives defined by the responders to help robot developers refine their system designs and objectively measure performance. The usage guides will provide recommended performance ranges for different deployment scenarios. ASTM International is the host organization for the resulting standards, under the Operational Equipment subcommittee within the Homeland Security Applications Committee (E54.08)¹.

Due to the multi-disciplinary nature of robotics and the complexity of the urban search and rescue application, the derivation of performance test methods from the initial requirements is a multi-stage, iterative process. An initial attempt at prioritization of requirements was performed based on the responders' input regarding which requirements applied to the greatest number of robot deployment categories; in other words, the requirements deemed most essential to any robot deployment, were selected. This initial list of requirements comprise the candidate set of "Wave 1" requirements for which performance test methods are being developed and standardized this year. Subsequent standardization waves will occur periodically as the technologies and robots mature enough to address the additional performance requirements. Along the way, regular response robot evaluation exercises will further understanding of how robots can augment responder capabilities within a variety of urban search and rescue scenarios, and will allow responders as well as robot developers to gauge progress in the maturity of the various component technologies as well as the integrated robotic systems.

¹ <http://www.astm.org/>

3.0 Participants

NIST's team of test engineers and support personnel worked closely with the TEEX/TX-TF1 personnel throughout the planning, setup, and administration of this event, which accommodated roughly seventy people and more than thirty robots across ten different scenario props at Disaster City. The TEEX/TX-TF1 personnel very ably managed the overall logistics on site, which contributed greatly to the success of this event and ensured safe operations throughout.

The primary participants from the emergency responder community were representatives from FEMA US&R Task Forces, as has been the case throughout the DHS/NIST performance standards program for US&R robots. Some non-FEMA responders who are members of the ASTM standards task group also participated. One canine team participated throughout the event and was joined by several more canine teams for the final day mock incident response.



Figure 3.1: Responders Operating Robots and Exploring US&R Training Props

As for robot participation, there were 16 different models of ground vehicles, 2 models of wall climbers, 7 models of aerial vehicles including a helicopter, and 2 models of underwater vehicles. Two dynamic simulation environments were also available for visualization of high-fidelity robot models within realistic practice environments (including props at Disaster City[®]). The robots represented 9 of the 13 envisioned US&R deployment categories identified in earlier workshops.² The Table below lists each model of robot available on site for the responders to use. There were multiple instances of some of the more mature models available. Representatives from the robot developers/manufacturers typically deployed their own robots, but some were deployed by the Alliance for Robotic Assisted Crisis Assessment & Response (ARACAR), a non-profit group that has a large cache of robots and is collaborating on the overall robot performance standards effort.

Although not affiliated with any specific robot, several additional participants from the Department of Homeland Security, Department of Defense, Technical Support Working Group, and other government agencies, as well as academics from Texas A&M, were present during all or part of the exercise.



Figure 3.2: A) The assembled emergency responders and NIST personnel. B) Ground, aerial, and underwater robots along with their associated developers and operators.

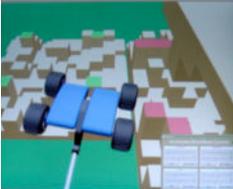
² Statement of Requirements for Urban Search and Rescue Robot Performance Standards (Preliminary Version), May 2005. [http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements Report \(prelim\).pdf](http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements%20Report%20(prelim).pdf)

Table 3.1: Participating Robots

IMAGE (Roughly by size)	NAME	DEVELOPER (Brought by)	DEPLOYMENT CATEGORY
WALL CLIMBERS			
	Nanomag (magnetic)	Inuktun Services (ARACAR)	4. Ground: Wall Climber
	VRAM Mobile Robot Platform (VMRP) (suction)	Vortex HC, LLC	4. Ground: Wall Climber
GROUND			
	ToughBot	OmniTech Robotics, LLC (ARACAR)	1. Ground: Peek Robot
	Eye Ball	Remington Technologies (TX-TF1)	1. Ground: Peek Robot
	Variable Geometry Tracked Vehicle (VGTV)	Inuktun Services (ARACAR)	1. Ground: Peek Robot 6. Ground: Confined Space Shape Shifters
	Sneaky Robot	M-Bots, Inc.	1. Ground: Peek Robot
	Bombot	West Virginia High Tech Foundation	3. Ground: Non Collapsed/Wide Area Survey
	MARCbot	Exponent, Inc. (ARACAR)	3. Ground: Non Collapsed/Wide Area Survey

	Chaos	Autonomous Solutions, Inc.	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey 6. Ground: Confined Space Shape Shifters
	PackBot Scout	iRobot Corp.	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey 6. Ground: Confined Space Shape Shifters
	PackBot Explorer	iRobot Corp. (ARACAR)	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey 6. Ground: Confined Space Shape Shifters
	PackBot EOD (w/ manipulator)	iRobot Corp. (ARACAR)	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey 7. Ground: Retrieval Robot
	MARV	Mesa Robotics, Inc.	3. Ground: Non Collapsed/Wide Area Survey
	MATILDA	Mesa Robotics, Inc.	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey
	MATILDA (w/ manipulator)	Mesa Robotics, Inc.	2. Ground: Collapsed Structure/Stair Climber 3. Ground: Non Collapsed/Wide Area Survey 7. Ground: Retrieval Robot
	TALON (w/ manipulator)	Foster-Miller, Inc. (NIST)	3. Ground: Non Collapsed/Wide Area Survey 7. Ground: Retrieval Robot
	Mini-ANDROS (w/ manipulator)	Northrop Grumman Remotec	3. Ground: Non Collapsed/Wide Area Survey 7. Ground: Retrieval Robot

	ANDROS F6A (w/ manipulator)	Northrop Grumman Remotec	3. Ground: Non Collapsed/Wide Area Survey 7. Ground: Retrieval Robot
AERIAL			
	Wasp	AeroVironment, Inc.	8. Aerial: High Altitude Loiter
	Nighthawk	Applied Research Associates, Inc.	8. Aerial: High Altitude Loiter
	Raven	AeroVironment, Inc.	8. Aerial: High Altitude Loiter
	Evolution-XTS	L-3 BAI Aerosystems, Inc.	8. Aerial: High Altitude Loiter
	CyberBug	Cyber Defense Systems, Inc.	8. Aerial: High Altitude Loiter
	Flying Bassett (helicopter)	University of Alabama - Huntsville	8. Aerial: High Altitude Loiter 9. Aerial: Rooftop Payload Drop
	Tethered Blimp (20ft)	ARACAR	8. Aerial: High Altitude Loiter

AQUATIC			
	Pro III	VideoRay, LLC	11. Aquatic: Variable Depth Sub
	SeaSprite (w/ scanning sonar)	VideoRay, LLC	11. Aquatic: Variable Depth Sub
SIMULATIONS			
	Symonym	Acroname, Inc.	Dynamic 3-D Simulation Environment
	USARsim	Unreal Tournament Epic Games, Univ. of Pittsburgh, NIST	Dynamic 3-D Simulation Environment

4.0 Scenarios

This section briefly describes the training scenarios, or props, that were used during this exercise. Responders identified access points within each scenario during the initial orientation, but had some flexibility regarding how to approach the search mission once they had a robot in hand. Some scenarios had multiple entry points.

The responders were organized into four different teams that rotated across each scenario. Similarly, four teams of robots were created, primarily based on compatibility of their wireless communications. One of the challenges of deploying robots is the fact that many use the same radio communication frequencies, which can cause debilitating interference on site. Some robots used tethered communications at times to avoid these issues. The robot teams rotated through two different scenarios each day. The responder teams rotated twice as fast, through four scenarios each day, to work with as many different combinations of robots and scenarios as possible over the three days. Responders rotated to each scenario for 90 minutes, spending 45 minutes at two different start points within the scenario working with two different robots. During aerial operations, all interested responders were at that scenario to work with the aerial robots sequentially. Ground robots that could run tethered to avoid any radio conflicts with the aerial vehicles were allowed to operate simultaneously on any other scenario. Every possible combination of responders/robots/scenarios was not quite achieved given the limited time available. The Figure below shows an overview of the rotation schedule.

A mock incident response on the afternoon of the last day allowed the responders to focus on specific scenarios employing the robots of their choice. Tethered operations were encouraged to limit radio interference and to ensure that responders had experience with the benefits and challenges of using tethered robots.

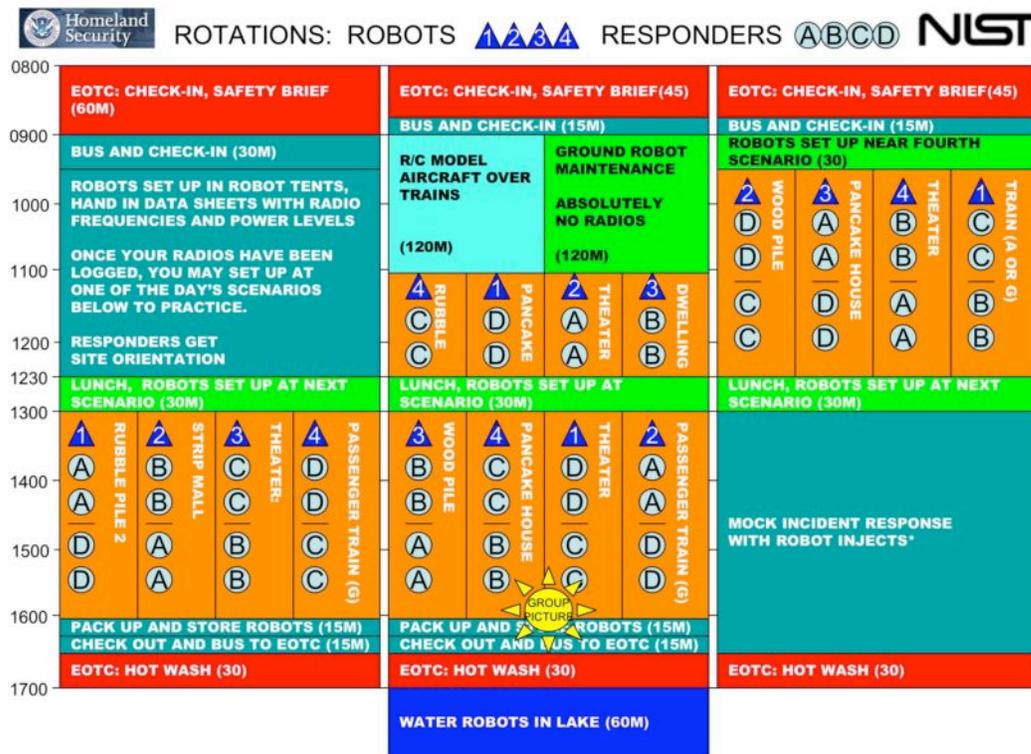


Figure 4.1: The three-day schedule of responder and robot rotations across all available scenarios.

In each of these scenarios, NIST embedded simulated victims, or “victim props,” that the responders were to locate using the robots. These simulated victims emitted assorted combinations of signs of life: human form (mannequin parts), thermal signature (heating blankets and pads stuffed into clothing), movement (waving or shifting), sound (yelling or moaning), CO₂ (in confined spaces). Examples of victims emplaced in the scenarios are shown in the Figure below.



Figure 5: Simulated victims embedded into various scenarios included partially visible victims in the ground based robot scenarios and entirely visible victims (from the proper vantage point) in the aerial scenario.

House of Pancakes (Prop #130)



Description: Partially collapsed building of unknown use with a roof almost in contact with the ground on the only accessible side. Enter through confined access under the metal roof or through breach, explore overall maze of obstacles and debris to look for simulated victims and hazardous materials stored inside (read visual acuity charts with hazardous materials placards) or identify cracks in walls when found.

Single Family Dwelling (Prop #129)



Description: Partially collapsed dwelling due to earthquake. Main entrances are compromised, so the exterior wall has been breached. Enter the maze of rooms either through the door under a leaning collapse or through the breach to perform a pattern search of the entire dwelling for simulated victims and hazardous materials stored inside (read visual acuity charts and hazardous materials placards). Negotiate various rubble and debris including a large breach in the floor, perform a thorough search for simulated victims, move through and interact with the environment where necessary, and map the rooms to provide responders with all necessary information pertaining to victims, hazards, entrances/exits. There is also a basement accessible from the outside down steep stairs.

Strip Mall (Prop #131)



Store A: V shaped ceiling collapse. Robot access to Store B, which is closed off and as dark as possible.

Store B: Vertical insertion through breach in pancake collapsed concrete slab. Maneuver under the slab from one end to the other over various rubble and debris to search for simulated victims and hazardous materials stored inside (read visual acuity charts and hazardous materials placards).

Store D: The responder must carry the robot up the leaning collapsed roof surfaces of Store D and vertically insert (lower, drop, or throw) the robot over the side to explore the partially collapsed space of Store E. This was a known hazardous material store, so in addition to locating and mapping simulated victims, it must identify any hazardous materials stored inside (read visual acuity charts and hazardous materials placards).

Rubble Pile #2 (Prop #132 near #133 platform)



Description: Fully collapsed structure with subterranean voids. The likely entrances found are supported somewhat loosely by concrete barriers (not pipes), have variable but confined dimensions, and contain problematic rubble, so are unsuitable for responder entry. Responders should deploy robots into these subterranean voids to perform primary search for simulated victims under the rubble and look for any potential hazards

Wood Rubble Pile #3 (Prop #136)



Description: Fully collapsed wood structure with possible voids. Responders should deploy robots over the perimeter of this pile, either by climbing, throwing, or launching into the central area to look for simulated victims, map the area, and convey situational awareness. A nearby steel structure under construction provides an elevated vantage point if a robot can scale the exterior to provide a contributing overview of the wood rubble pile.

Passenger Trains (Prop #126 and #127)



Description: Passenger rail cars were hit by industrial hazmat tanker cars of unknown substance and both trains partially derailed. Ground robots should circumnavigate all trains over tracks, various debris, and rubble. The robots should 3-D map the perimeter along with the location and positions of each car, including under elevated car (used in advanced shoring class). Robots should search the Sleeper Car ramping up from the ground, and search each curtained alcove on both sides looking for simulated victims. For the Crew Car on its side, robots should be inserted to explore the interior to locate any simulated victims or read the placards on hazardous canisters that may be in the mailroom. Access to the mailroom is too small for a responder in Level A suit.

Industrial Hazmat Trains (Prop #116 and #117)



Description: Some of the hazardous tanker cars are also derailed, and apparently leaking fluids in places. Simulated surface victims appear incapacitated in/around the cars. Aerial robots should loiter over the area to scan the perimeter, map the location of all rail cars (see targets of interest), simulated victims, and the source and extent of all leaks. They should also read the hazardous materials placards (aerial visual acuity test) to identify tanker contents.

Water Scenario (Prop #000)



Description: Shallow, turbid pond with underwater features to be investigated. Use side-scan sonar and visual sensors to determine the shapes and sizes of the features on the sonar resolution test artifacts.

5.0 Emerging Test Methods

A set of test methods designed to address specific responder-defined robot requirements were set up in and around the theater building (#134) and embedded into several scenarios. This provided an opportunity to refine these test methods based on feedback from responders and developers as they used them for practice and operator training. The initial test methods and artifacts are described briefly below. Another iteration will take place late Summer 2006 to incorporate feedback from the Disaster City event and the resulting test methods will be introduced into the standardization process through the ASTM International E54.08.01 task group.

Logistics – Cache Packaging – Volume

This simple test method addresses the requirement that the robot and all associated components (such as the operator control unit and spare parts) must fit within the responders' cache packaging and transportation system. Based on responders' definitions of the metric, three standard packing cases were available for the manufacturers to determine which ones were required to contain the entire robotic system.

Logistics – Cache Packaging – Weight

This simple test method addresses the requirement on the part of the responders that they be able to move and store all equipment using existing methods and tools. A scale was available for robot manufacturers to weigh their robotic system.



Figure 5.1: Reference test artifacts for Logistics – Cache Packaging – Volume and Weight

Sensing – Vision System – Acuity (Near Field)

This test method captures the responders' expectation to use video for key tasks such as maneuvering (hence the real-time emphasis), object identification (hence the color emphasis), and detailed inspection (hence the emphasis on short-range system acuity). The responders noted the need to consider the entire system, including possible communications signal degradation and display quality, when testing this capability. They also noted that this requirement is closely tied to the need for adjustable illumination to avoid washing out the image of close objects. The responders made no distinction regarding tethered or wireless implementations to address this requirement. The near and far field tests are implemented together below.

Sensing – Vision System – Acuity (Far Field): This test method captures the responders' expectation to use video for key tasks such as maneuvering (hence the real-time emphasis), object identification (hence the color emphasis), and path planning (hence the emphasis on long-range system acuity). The responders noted the need to consider the entire system, including possible communications signal degradation and display quality, when testing this capability. They also noted that the limiting case for long-range system acuity is probably assessment of structural integrity of buildings. This requires identifying and measuring cracks in walls, inspecting the tops/bottoms of load bearing columns, and generally assessing the squareness of walls, ceilings, and floors. The responders made no distinction regarding tethered or wireless implementations to address this requirement. The associated reference test artifacts are shown below.

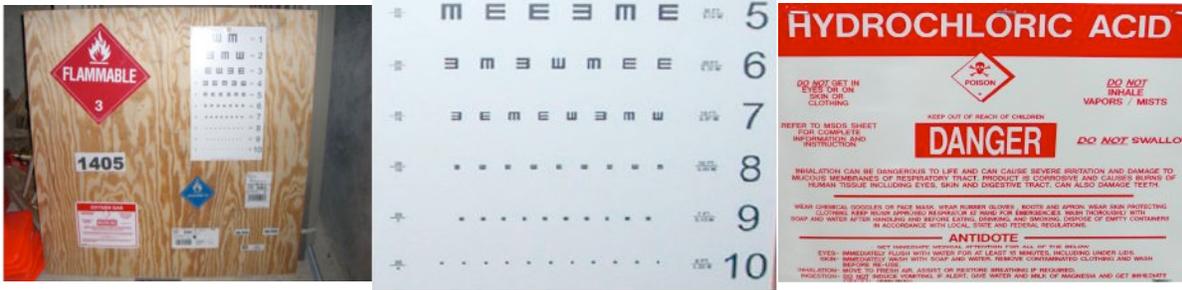


Figure 5.2: Reference test artifacts for Sensing – Vision System – Acuity (Far Field)

The visual acuity test method used both near and far field charts and hazard labels in view from a single viewing location for the robot. The robots would either position themselves at the defined viewing location or was placed at the locations to save time. The operator was correctly read the smallest line possible, which corresponds to certain lines on the real-life hazard and shipping labels.

Sensing – Vision System – Acuity (Aerial)

This test method addresses the responder requirement to visually identify features of interest, in this case from aerial robots. The same principles guiding the other visual acuity tests are applied to this test. Eye charts are scaled up to be comparable in size to, and much larger than, hazardous materials identification placards found on rail cars. The charts are positioned vertically to simulate the orientation that hazmat placards have normally on tanker cars. Test targets are marked with 1.2 m square black panels with white Xs to help the robot operators find and focus on specific targets of interest within the scenario. The Xs are placed on the ground in unique groupings. The aerial operators identify such groupings by reporting the number of Xs and overall pattern and then proceed to investigate the target of interest. The associated reference test artifacts are shown below.



Figure 5.3: Reference Test Artifacts for Sensing – Vision System – Acuity (Aerial)

Sensing – Vision System – Acuity (Underwater):

This test method was conducted using underwater targets designed to measure sonar resolution. In this case, however, the operator was instructed to identify the shape and measure the size of features found on the various underwater targets. Due to the murky water, the robot needed to almost touch the target to visually identify the features. The operator was also instructed to draw the pattern seen, which in the case of the grid based circular cutouts, required stations keeping, indexing from grid to grid, and keeping track of grids already identified. The associated reference test artifacts are shown below.



Figure 5.4: Reference test artifacts for Sensing – Vision System – Acuity (Underwater):

Payload – Manipulation – Maximum Reach

This test method addresses the responder requirement to use robotic manipulators to perform a variety of tasks in complex environments. This directed perception test captures discrete ranges of useful manipulator reach with a payload, which in this case is a camera and a light (variable illumination was very helpful in this test). The test consists of four levels of stacked boxes (46 cm tall x 46 cm deep x 61 cm wide) with 15 cm diameter access holes on all sides. Each box contains targets inside, including a near field visual acuity chart mounted to the rear of the box and a colored light stick in a known orientation centered and affixed to the bottom of the box. The access holes are vertically centered on each box, and located either on the right or left quarter line, requiring a skewed view to identify both targets inside. Robot operators identify and report the smallest readable line of the visual acuity chart along with the color and orientation of the glowing light stick. Other uses of these box stacks include canine units training with explosive ordnance sample targets inside the boxes; dogs can typically clear the lower three levels of all boxes encountered. Large robots can reach the top-level access holes but often exhibit balance issues, which are exacerbated by so-called orange (half-cubic) random stepfields surrounding three sides of the test stack. There is always one side of the stack approachable from flat flooring. The associated reference test artifacts are shown below.



Figure 5.5: Reference test artifacts for Payload – Manipulation – Maximum Reach. The artifacts surrounding the boxes are orange (half-cubic) random stepfields.

Payload – Manipulation – Retrieval

This test method addresses the responder requirement to retrieve objects, not necessarily configured for robot manipulators, within complex environments. This manipulator dexterity test setup is similar to the directed perception test in that it involves a stack of four shelves at 46 cm incremental elevations (the third shelf is roughly at table height) and surrounded on three sides by so-called orange (half-cubic) stepfields, with one side of the shelving stack accessible from flat flooring. Each shelf contains nine wooden blocks centered on a 3x3 grid, with consistent orientations to challenge particular gripping approaches. The blocks are 4x4 posts cut into three cubic lengths, so are larger than most grippers can grab in at least one dimension. Robot operators approach the shelf stack from a flat flooring side and remove as many blocks as possible from as many shelf levels as possible. They repeat the task from a stepfield side to complicate robot orientations and mobility. The number and locations (x, y, z) of all blocks removed from any given side are noted. The associated reference test artifacts are shown below.



Figure 5.6: Reference test artifacts for Payload – Manipulation – Retrieval

Human/System Interaction – Acceptable Usability

This test method addresses the responder requirement to operate robotic systems simply and effectively. The metric measures the percent of timed tasks operators can successfully complete. The operators are to navigate a maze-like course and locate specific visual cues that identify candidate “gates” in the maze. They have to judge whether the robot can fit through the gates and then attempt to navigate the robot through the gates. The dimensions of the overall maze (width of aisles and gates) are proportional to the size class of the robot. The associated reference test artifacts are shown below.



Figure 5.7: Reference test artifacts for Human/System Interaction – Acceptable Usability

Communications – Range – Beyond Line of Sight

This test method addressed the responder requirement to project remote situational awareness around corners of buildings and into compromised or collapsed structures. During this test, the operator navigated a robot down the length of a reinforced concrete building (the Strip Mall was roughly 30 m long), while maintaining a path within 1 m of the building. At the far end of the building, the robot turned 90 degrees to drive along the far side of the building. The distance beyond line of sight, traversed along the far side of the building, was measured until communications was lost. The building used for this test is shown below.



Figure 5.8: Path along building walls used for Communications – Range – Beyond Line of Sight

Mobility – Locomotion – Sustained Speed

This test method measures robot speeds and basic maneuverability on different surfaces while maintaining a proscribed course. The courses required predictable changes in direction (zig-zags) over three different ground surfaces: grass, pavement, and NIST’s random stepfields as an abstracted, but repeatable, rubble-like terrain. The associated reference test artifacts are shown below.



Figure 5.9: Reference test artifacts for Mobility – Locomotion – Sustained Speed. Overview of the zig-zag course (left), on grass (middle), and on pavement (right).



Figure 5.10: Reference test artifacts for Mobility – Locomotion – Sustained Speed. The abstracted rubble course is made of red (full cubic) random stepfields.

Mobility – Aerial – Path Following

This test method addressed a new requirement identified in the course of designing the aerial portion of this exercise. As a qualification event for participating in the hazmat train scenario, aerial vehicles had to follow a defined course. Measuring the ability of an aerial vehicle to track a known path and navigate over particular ground locations is essential for ensuring that the aerial vehicle is controllable and predictable, which is especially necessary for navigating within urban settings. The associated reference test artifacts are shown below.



Figure 5.11: Reference test paths and artifacts for the Mobility – Aerial – Path Following

Mobility – Aerial – Station-keeping

This test method addressed the responder requirement to maintain stationkeeping around a target of interest. In the case of aerial vehicles, fixed diameter orbits were required to maintain focus on a target of interest. For vertical take-off and landing (VTOL) aerial platforms, the test method involves maintaining a fixed position and orientation on near a target in order to read visual acuity charts or identify other targets of interest. The operator is allowed to do so manually, however, hands free stationkeeping is preferable and will eventually be incorporated into the metric. The associated reference test artifacts are shown below.



Figure 5.12: Mobility – Aerial – Stationkeeping tests were performed by a helicopter around the train wrecks. Reference test artifacts for Sensing – Vision System – Acuity (Aerial) are shown in the right picture at the base of the light pole, although the targets are located on the far side (down-range).

Mobility – Stair Climbing, Ramps, and Confined Space Access

These test methods address responder requirements for mobility on stairs, ramps, and through confined spaces. These test methods used artifacts that were readily available within the various scenarios. These specific test artifacts will not be formally submitted to the standards process. However, fabricated versions of such test artifacts,

which can be easily proliferated to robot developers, will be included in proposed performance test methods. The tests were conducted using the features shown below.



Figure 5.13: Several test methods were conducted using features already available in the environment. For example, Mobility – Stair Climbing, Ramps, and Confined Space Access.

6.0 Data Collection

This event provided a focused opportunity to capture feedback from responders and manufacturers. Questionnaires regarding the scenarios and the test methods captured the impressions of all the stakeholders. Further feedback was collected from the responders only during a “Hot Wash” review meeting immediately following the event. Copious images and video of the robots in action were also collected. This section describes briefly the data collected.

6.1 Images and Video

The organizers collected images and videos of robots and personnel participating in the event. Each robot developer will receive all media related to their robots. Highlight images and generally successful robot videos can be found on the NIST project home page: http://www.isd.mel.nist.gov/US&R_Robot_Standards/.

6.2 Responder Questionnaires

Responder feedback was captured regarding the relevance of the scenarios as training props and the operation of robots within the scenarios. The focus was on how effective different robots were within the scenarios to get a general sense of how well the responders felt they operated as a team with the robots. The form used is shown in the figure below. The numeric responses to the questionnaire shown were averaged. These averages are references in the general discussion below. Analysis of the feedback from the responders suggested certain trends:

Concerning how representative the scenarios were perceived to be:

- Hazmat Train (6.0)
- House of Pancakes (5.8)
- Rubble Pile (5.7)
- Dwelling (5.5) and Wood Pile (5.5)
- Passenger Train (5.4)
- Strip Mall (5.0)

Concerning how representative the tasks within each scenario were perceived to be:

- Rubble Pile (6.0) and House of Pancakes (6.0)
- HazMat Train (5.3)
- Passenger Train (5.2)
- Dwelling (5.0) and Wood Pile (5.0)
- Strip Mall (4.5)

As for ratings of team performance at each scenario, the scores were:

- HazMat Train (approximately 5.3)
- House of Pancakes (5.19)
- Strip Mall (5.14)
- Dwelling (4.74)
- Wood Pile (4.65)
- Passenger Train (4.62)
- Rubble Pile (4.4)

Robot capabilities:

- HazMat Train (5.5)
- Strip Mall (5.0) and Wood Pile (5.0)
- House of Pancakes (4.5)
- Passenger Train (4.1)
- Dwelling (4.0)
- Rubble Pile (3.2)

Scenario utility:

- HazMat Train (5.8)
- Wood Pile (5.0) and House of Pancakes (5.0)
- Strip Mall (4.9)
- Dwelling (4.0)
- Rubble Pile (3.5)
- Passenger Train (3.2)

Time required to complete:

- Dwelling (5.8)
- House of Pancakes (5.5)
- Wood Pile (4.8)
- HazMatTrain (4.3)
- Strip Mall (4.1)
- Passenger Train (3.9)

Robot-responder performance:

- Strip Mall (5.2)
- Wood Pile (5.0) and House of Pancakes (5.0)
- HazMat Train (4.1)
- Passenger Train (4.0) and Rubble Pile (4.0)
- Dwelling (3.8)

Ratings for quality of operator interface:

- HazMat Train (5.8)
- Dwelling (5.7)
- Wood Pile (5.0) and House of Pancakes (5.0)
- Rubble Pile (4.6)
- Strip Mall (4.5)
- Passenger Train (3.6)

**Responder/Robot Evaluation Exercise
Responder Evaluation Form**

SCENARIOS AND ROBOTS

Site: _____ Scenario: _____
 Robot: _____ Responder: _____

Each participant on a team should fill out a questionnaire. You will be asked to fill out one for each scenario you do and for each robot you use. So if you do scenario #1 three times with different robots we will ask you to fill out a questionnaire each time.

1. Concept of operations used in scenario?

1	2	3	4	5	6	7
Not at all representative					very representative	

2. Concept of operations used in scenario?

1	2	3	4	5	6	7
Not at all representative of what would be done					very representative of what would be done	

3. Assessment of responder team performance

1	2	3	4	5	6	7
Substandard					excellent	

4. Capabilities of robot

1	2	3	4	5	6	7
Inadequate for scenario					completely sufficient	

5. Utility of robot in scenario

1	2	3	4	5	6	7
Not at all useful					extremely useful	

6. Length of time needed to accomplish the scenario

1	2	3	4	5	6	7
Too long					just right	

7. Overall performance of scenario (responders and robot)

1	2	3	4	5	6	7
substandard					excellent	

8. If you were the robot operator please rate the operator interface for use in the scenario

1	2	3	4	5	6	7
Difficult to use					easy to use	

Please indicate your expertise in using the robot

1	2	3	4	5	6	7
First attempt	novice			medium		expert

Figure 6.1: A scenario and robot evaluation form. The questions and scales are shown. Each question also had space for comments (not shown).

Requirement Operating Range Data Capture				
Number: 38 * Type: LOGISTICS Sub-Type: CACHE PACKAGING Requirement: VOLUME PER CONTAINER Metric: SCALE 1-5 1 = Pelican 1650 box 3 = Hardigg box checkable on commercial aircraft 5 = Ropack model 4048, 4039 with drop door Description: This requirement captures the responders' expectation to move and store all equipment using existing methods and tools. Test Method: SELF-DECLARED				
Robot		Category		
Metrics & Units	A Scale (1, 3, 5)	B Number of Boxes	C	D
				COMMENTS
S				
Operator		Test Results		COMMENTS
E				
E				
E				
E				
E				
Responder/TF		Test Results		COMMENTS
R				
R				
R				
R				
R				
R				
R				

Figure 6.2: Example Form from Proposed Test Method. This particular one is for a self-declared test method, so only the "S" portion would be filled out.

Results of the piloted test methods were also captured during the exercise. Some metrics were self-declared while others were measured using the test artifacts described previously. The self-declared tests included many of the “yes/no” logistics requirements, wherein the manufacturer is expected to fill out the appropriate responses to the

questions. During data collection NIST also wanted to differentiate between expert and novice users of the robots. Expert user data can serve as a baseline of performance against which to measure novices and also capture their relative improvement towards “expert” status when they undergo training. With few exceptions, the responders were considered novices in terms of robot usage. We do not include the data captured in this category because it was purely intended as a trial collection of data and whatever data was collected is used to provide statistical trends – not measure performance of individual robots at this time.

6.3 “Hot Wash” Discussions

At the end of the third day, a “hot wash”³ was conducted, wherein NIST staff debriefed the responders to get their impressions of the overall exercise, scenarios, and robots. In particular, NIST was interested in gauging the responders’ prioritizations of robot categories in terms of technical maturity. In other words, which categories were closest to being fieldable in a disaster response? Some of the issues brought up in the hot wash were explored further on the final day during the standards committee meeting. The initial categories of robots help determine the operating ranges for the test method designs.

The responders felt that the following categories of robots were nearly ready to field:

- Small, throwable, so-called “peek bots.” Robots that are able to be deployed into very confined spaces and send video or potentially sensor data back to the operators.
- Aerial survey robots that could “look over the hill” to assess the situation and determine at least which roads are passable. US&R teams can save valuable time if they can determine whether a roadway is blocked. They don’t necessarily expect aerial robots to assess structural integrity or even detect victims. They would like to be able to monitor atmospheric conditions from these platforms as well.
- Wide-area survey robots, which could support a Type II downrange reconnaissance mission. These robots don’t necessarily have to enter confined spaces or traverse rubble piles, but they do need to be able to climb stairs or at least curbs and modest irregular terrain. They need GPS tracking with info overlaid onto a map. They would typically move quickly down range (at least 1 km) to assess the situation and deploy multiple sensors (chemical, biological, radiological, nuclear, explosive) with telemetry.

There is growing interest in seeing what sensors are available, or will be available, to mount on the different robots. The target sensor package to install first is a four gas monitor that the responders currently use.

Several other constructive comments covered other aspects of robot capabilities and performance. This summary includes observations during the course of the event, as well as those that were noted during the hot wash. The responders identified the following improvements for current implementations:

Sensors

- Thermal/infrared capabilities, to help locate victims as well as to identify fires and hot spots. This is particularly critical when there is smoke.
- Onboard mapping of environments when navigating through smoke.
- Better navigation aids, such as GPS with the ability to show the robot coordinates and direction of view.
- Better placement of cameras, so they provide better depth perception. Responders sometimes view the same location from two different camera perspectives in an attempt to gain depth perception. Cameras should view the robot’s own tracks or wheels to help with situational awareness.
- Better far field visual acuity, up to 1000 feet, to help with planning.

Mobility

- Better mobility over loose debris. Random stepfields provide reasonable abstracted rubble, but should be looser to allow displacing individual steps. Wires and strings should be added to snag tracks.
- Continuous driving after throwing a track, especially if throwing tracks is a periodic.
- Minimum speed of four miles per hour.

Communications

- Better radio communications, should allow choices of frequencies if one becomes problematic.
- Indication of radio communications signal strength and/or bandwidth – maybe even automatically detected to change frequencies and improve signal quality.

³ A performance review, particularly after a training exercise or combat operation.

- Longer radio communications ranges both in-sight and beyond line-of-sight.
- Tethered communications presented a clear signal for long range and beyond line-of-sight problem, but the tether implementations introduced mobility complications and the additional workload for the operator to remember the tether, not run over it, and spool it in our out.

Human/System Interaction

- Easier operator interfaces. Some are too complex (too many modes), while others were easier to learn. There was a lot of variation in the “usability” of the controllers for the robots.
- Better feedback on the robot state, such as arm position and runtime remaining, etc. The amount of information available to the operator at the control station also varied.
- Better OCU displays for daylight conditions. Responders resorted to draping their jackets over their heads and the OCU at times.
- Better audio feedback to the operator, to listen to the robot’s actions more than to search the environment. Directional audio (stereo) and headphones were very helpful.
- The usability test method should be modified to separate out camera manipulation (which was part of the procedure in the version piloted at this exercise).

Manipulation

- Independent base rotation joints for manipulators, to remove reliance on mobility (tracks or wheels) to rotate the manipulator. Especially helpful when the robot is on uneven terrain.
- Test methods for opening doors, which are important tasks for conducting searches.

Logistics

- Easier track replacement in the field, especially if the tracks get thrown periodically.
- Easier wash-down and decontamination when necessary. Many of the robot designs would pool fluids in body features. Smoother designs would allow fluids to run off.

Concepts of Operation

Several responder teams paired up different robots in their scenarios. They used them collaboratively in the following manners:

- A larger robot carried a smaller robot to a particular location and released it. The smaller robot then conducted the search in more confined spaces.
- Multiple robots were positioned to provide multiple views of a location, or one robot’s cameras observed a second robot as it moved for better remote situational awareness.
- One robot assisted another robot, either by opening a door or removing debris from the robot’s tracks.

7.0 Scenario Descriptions Using 3D Imaging

An essential element in defining performance metrics is the ability to clearly understand and describe the operating environment of the system under test. For US&R robots, both qualitative and quantitative measures of the environments in which platforms are tested and deployed are of great interest⁴. To address this need, NIST researchers are developing a building collapse taxonomy to support the emerging US&R robot performance standards. The effort will focus on developing a framework for integrating building classification, disaster type, and collapse type to provide general descriptions of probable operating environments. NIST personnel are also researching the use of 3D imaging sensors and range image analysis to characterize rubble (2.5D approach) and confined space voids (3D approach).



Figure 7.1: A robot shown approaching a tunnel passage under the rubble pile (left). The laser scanner captures high-resolution geometry data of all surfaces in the area (middle). The resulting “point cloud” of range data from that single scan location provides a ground-truth model of the actual rubble (right). Multiple scans from many different scan locations can be combined to produce overall images of large, complex environments.

To support these efforts, NIST researchers teamed with Optira, Inc.⁵ to produce laser scan data of three of the training scenarios at Disaster City. These scenarios included the rubble pile (prop #132 near #133 platform), the wood pile (prop #136), and the passenger train derailment (prop #126 and #127). 3D image data sets were collected using two commercially available laser scanners over the course of three days. Each scenario was scanned from multiple locations and each scan location was registered using targets placed in the environment. These targets were independently measured to provide survey control. Figures below show elements of the 3D imaging process.

A laser scanner is a 3D imaging device that uses a laser to measure the distance to an object. The laser beam is scanned both horizontally and vertically over time to image the operator-designated field of view. The distance, azimuth, and elevation information collected from each measurement in the scan is used to create high-resolution point clouds containing hundreds of thousands of points. Individual scans are then merged through a process called registration to create accurate point clouds of the scenes. The figures below depict screen captures of the scenes generated in point cloud viewing software. Camera viewpoints can be changed to examine the 3D data from multiple viewing angles and measurements such as point-to-point distance can be readily determined.

⁴ For examples of qualitative measures of an environment consider trail rating systems for ski slopes or the Beaufort Wind Force Scale for estimating wind speed from sea state. A quantitative metric in the US&R context could be a specific measure of the ‘roughness’ or ‘bumpiness’ of the terrain surface derived using techniques such as fractal dimension analysis or wavelet energy statistics. An interesting approach would be to develop a method to evaluate the impedance of an environment to being traversed. This would be similar to the Yosemite Decimal System (YDS) for evaluating climbing routes. Although subjective, the YDS has evolved into an effective method for quantifying route difficulty, albeit for only one mobility platform – humans. From this discussion one can imagine a specific robot platform with an UDS (US&R Decimal System) number of x for an environment with fractal dimension of y . A different platform may – and likely will – have a different UDS number for the same environment. The two measures taken together would provide comparable and verifiable information about the mobility of the robot platform.

⁵ Optira, Inc. (www.optira.com) specializes in providing as-built documentation for historic preservation, new construction, facilities engineering and numerous other applications. Optira is a partner with NIST in the FIATECH Laser Scanning Measurement Assurance project.



Figure 7.2: Since the laser scanner is a line-of-sight device, obtaining sufficient information for a complex environment such as the rubble pile requires several scan locations around and on top of the rubble. Scan locations are carefully chosen to capture sufficient scene data while enabling tie in to prior scans using pre-positioned targets.

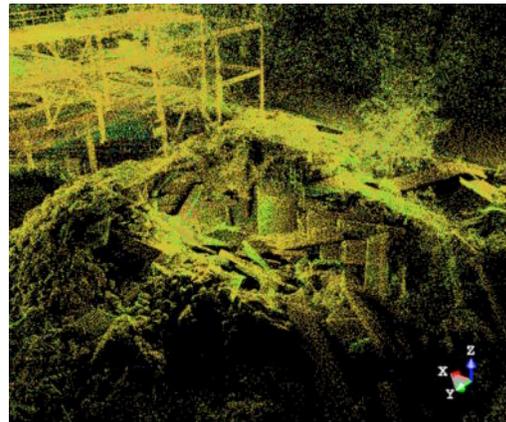


Figure 7.3: An image of the rubble pile (left). A registered perspective view of the point cloud that describes the rubble pile, generated from multiple scan locations (right).

There are many potential uses for such data. First, NIST will investigate means of representing the types of environments and specifically the complexities within the environment (especially for rubble) to see if there are predictable and consistent ways of representing rubble or other difficult terrain quantitatively. Second, NIST, along with partner organizations, is investigating how to represent the point clouds and/or derivative terrain models within simulation environments. Importing point, polygonal, or surface models of realistic training scenarios into simulation systems can make the training scenarios themselves accessible to a wider set of robot developers. Robots can also be modeled within these simulation environments, which support vehicle physics and scene interaction capability. Responders, developers, researchers, and other interested personnel will be able to practice navigating robots within the scenarios at Disaster City – to some degree of fidelity. Intelligent behaviors for semi-autonomous robots can also be virtually tested within these simulated environments.

This type of sensed data can also provide a preview of the kinds of data that may become available through sensors mounted on robots. Whereas the sensors used to capture this data are large, heavy and can require up to an hour to capture a scan; smaller, lighter 3D imaging sensors that generate data at sufficient rates to support real-time robot operations are starting to enter the market. These devices will not provide as high a resolution nor cover as large an area, but they will be able to give responders a much clearer understanding of the configuration of interior spaces searched by robots than 2D images alone. As 3D mapping algorithms become more capable, robots deploying 3D imaging sensors will provide critical information for emergency response.



Figure 7.4: Left: NIST researchers capturing one scan around the passenger train wreck. Right: A bird's-eye-view of the full 3D point cloud of the passenger train wreck.



Figure 7.5: An image of the wood pile taken from a man-lift (left). The 3D point cloud combining three 'overhead' scans and several ground-level scans (right).

The 3D image data collected during the response robot evaluation exercise will be made available to researchers to foster complex environment classifications, practice simulations environments, and robot development.

8.0 Asset Tracking within a Training Scenario

NIST researchers have been working with an asset tracking system, developed by Multi-Spectral Solutions, Inc.⁶, to capture continuous location data for robots, personnel, and/or dogs operating within training scenarios. This tracking system requires equipping the perimeter of the scenario with antennas in carefully measured locations to receive signals and triangulate the position of active radio tags affixed to moving assets within the scenario. It also requires one or more reference tags placed at known locations within the scenario for calibration. NIST uses this tracking system to capture quantitative performance data (2D or 3D positions over time) during training operations to compare particular technologies, approaches, and/or methods of deployment. This kind of quantitative data capture enables performance metrics such as: deviations from intended paths, dwell locations and durations, percent of area searched, completeness of collaborative searches, etc.



Figure 8.1: Asset tracking system components include multiple receivers (shown without attached antenna), active badge tags (1000mW), and smaller active tags (30mW). (Not shown is the network hub, computer, and cabling.)

NIST has performed system characterization tests in ideal conditions to determine the best possible 2D accuracy of the system, which was roughly 15-20 cm (6-8 inches). This tracking system has been used successfully for a few years within fabricated robot test arenas to capture 2D paths of individual robots, teams of collaborative robots, and dogs. Efforts to track assets within realistic training scenarios have produced mixed results. At a previous event, we tracked several responders moving through an intact building structure pre-equipped with antennas to produce data and videos of each responder's 2D path overlaid onto the building floor plan. We also tracked assets in line-of-sight of the antennas across a large concrete rubble pile. However, attempting to track assets located in tunnels under the concrete rubble pile, or within surface voids on the pile, was unsuccessful due to the overall density of concrete rubble along with the limited power levels of the active radio tags (30mW) at that time. At Disaster City, we deployed the tracking system around the wood pile, which provided a more porous prop than the concrete rubble, and used higher power radio tags (1000mW).



Figure 8.2: The wood pile scenario at Disaster City (left), with an overall size as shown of approximately 40m long x 30m wide, has its highest elevation around the perimeter with a sunken interior. Access to the interior is either through buried culverts (shown in close-up in middle), or over the elevated perimeter (right).

Four receivers with antennas were attached to tripods located on the street surrounding the wood pile, forming a 50m (160ft) by 37m (120ft) rectangle at an elevation of about 3m (9ft). Two additional receivers and antennas were placed at ground level of the two tripods located in opposite corners. All receiver antennas were pointing toward the

⁶ Fontana, R., Recent System Applications of Short-Pulse Ultra-Wideband (UWB) Technology (*Invited Paper*), *IEEE Microwave Theory & Tech.*, Vol. 52, No. 9, Sept. 2004.

center of the pile. Two reference tags were placed at elevated points within the wood pile for calibration of the system.

Once the system hardware was placed, measured, and calibrated, several tests were conducted to see if robots, responders, and/or canines could be tracked. Due to limited time and our inability to get antennas to a conveniently elevated vantage point, we initially focused on 2D tracking, although some 3D data was obtained. To allow filtering and averaging of resolved location data, we placed two or more active radio tags on each asset to be tracked - one on either side of a responder helmet, for example.



Figure 8.3: Tracking system receivers and antennas (shown in blue) were mounted to tripods around the perimeter of the wood pile. Robots with active radio tags affixed (shown in orange) were tracked around the wood pile, but they demonstrated limited mobility within the complex interior of the pile. Canines and their responder handlers, however, could traverse most of pile and provided much more interesting tracking subjects.

Robots could be tracked as they performed initial reconnaissance on the street surrounding the wood pile, although the robots could not see the interior from the street because the highest points of the pile are around the perimeter. As the robots entered the wood pile through buried concrete culverts, the tracking data disappeared, probably due to the robot's inability to exit the culvert into the complex interior of the pile. Similarly, all attempts to track robots within the interior of the pile failed, probably due to signal attenuation from the very low robot positions within the pile, which required a straight-line path through the densely packed wood pile perimeter to reach the ground level receivers outside. Elevated antenna positions would certainly have helped, but we were unable to fit it into the schedule.

Our efforts to track responders and dogs as they maneuvered in and around the pile were more successful. The radio tags placed around the dog's collar and on the responder's helmet could communicate with the tracking system receivers outside the pile because they were at some modest elevation above the interior rubble. They produced relatively clean 2D tracks while generally waling/climbing across the pile, but their tracking data disappeared when burrowing down into a void or culvert (similar to the robot's typical position within the pile).

Further system characterization experiments to determine 3D accuracy will contribute to the next response robot evaluation exercise, which will focus on tracking assets within conventional "stick-built" dwelling structures and multi-floor structures. Although this technology holds promise for tracking emergency responders at actual disaster sites, and several research organizations and commercial entities are working toward such eventualities, our focus remains on equipping training scenarios to capture and compare practice performance data to help establish and improve robot capabilities within complex environments.

9.0 Standards Committee Meeting (ASTM - E54.08.01)

On the morning after the exercise, a meeting was held to focus on applying the lessons learned to the standard test methods in progress. As noted above, the key determination was which of the thirteen potential robot categories or deployment scenarios on which to focus. The three robot categories are shown in Table 9.1 below, and are further explained in the Preliminary Requirements Report⁷. Note that the terminology in “Category 8: Aerial High-Altitude Loiter Robots” does not precisely capture the type of capability the responders have now seen in action, and want to see included in Wave 1. All the aerial vehicles demonstrated at Disaster City operated under 300 feet above ground level (AGL) to avoid regulated airspace, and had flight durations of roughly 1 hour maximum. The responders noted that these systems clearly fit their Wave 1 expectations for deployment. So at the next formal standards meeting, we will propose to clarify the terminology describing the category to better reflect the standard test methods piloted at Disaster City.

Table 9.1: Three robot deployment categories to focus Wave 1 standards test methods

	Robot Category	Employment Role(s)	Deployment Method(s)	Tradeoffs
1	Ground: Peek Robots	Provide rapid audio-visual situational awareness, provide rapid HAZMAT detection; data logging for subsequent teams	Tossed, chucked, thrown pneumatically or with surgical tubing; marsupially deployed	Trade mobility, duration, sensing for increased expendability
3	Ground: Non-collapsed Structure – Wide Area Survey Robots	Long range, human access stairway and upper floor situational awareness; contaminated area survey; site assessment; victim identification; mitigation activities; stay-behind monitoring	Backpacked; self-driven; marsupially deployed	Experienced form factor for increased mobility, sensing, manipulation; mapping variant; spraying variant; breaching variant
8	Aerial: High-Altitude Loiter Robots	Provide overhead perspective and situational awareness; provide HAZMAT plume detection; provide communications repeater coverage	Released; balloon or fixed-wing; tethered	Trade penetration capacity for vertical perspective

Regarding Category 1: Ground Peek Robots, the discussions centered on the visual acuity test methods since the so-called “peekbots” demonstrated at Disaster City were essentially remote cameras and microphones. The emphasis was on discussion of trade-offs between camera field of view (FOV), zoom capabilities, and illumination. Some of the comments were:

- Peekbots need to be able to see a minimum of 10 feet; this means they have to be able to illuminate at that distance.
- Peekbots need to be able to see a minimum 10° FOV, but 10-30° is desirable.
- Cameras with 30° FOV and 10X zoom seemed like a good tradeoff of field of view for image detail.
- The visual acuity tests, which currently include various hazmat label sizes correlated to eye chart lines to emphasize real world uses, need to be augmented to clearly associate other more general scenario images. This would help responders identify performance objectives and thresholds for long range planning of routes, or example, and recognition of objects that are not textual.

Regarding Category 3: Non-Collapsed Structure – Wide Area Survey Robots, the discussions centered on the immediate need for down-range deployment of hazmat sensors. Toward that end, NIST is working to have representative sensors available on robots at the next response robot exercise for responders to work with, and to begin devising test methods specifically addressing hazmat requirements. Sensors that responders are looking for (or equivalent capabilities) included:

- Multi-gas detectors (O₂, H₂S, CO, Lower Explosive Limits of Volatile Organic Compounds, etc.)
- Gamma detector for radiological incidents
- Photo-ionization detectors (PID) toxic industrial chemical detector
- Ion Mobility Spectrometer or flame photometry for weapons of mass destruction

Regarding Category 8 Aerial High-Altitude Loiter Robots, the discussions centered on the perceived readiness of the UAVs demonstrated at Disaster City for Wave 1 standard test methods and deployment. These discussions included relevant input from Dave Lund, Director of the Aerospace Vehicle Systems Institute at Texas A&M University. He

⁷ Statement of Requirements for Urban Search and Rescue Robot Performance Standards (Preliminary Version), May 2005. [http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements_Report_\(prelim\).pdf](http://www.isd.mel.nist.gov/US&R_Robot_Standards/Requirements_Report_(prelim).pdf)

was the key person in charge of enabling and conducting the operation of SUAV's at Disaster City. The emphasis of the discussion was on how these SUAVs would be incorporated into field operations and modifications to make them more useful in the near term:

- Remote situational awareness over a larger area (1-5 km) is the key objective, so repeated hand launching and easy recover is a must.
- Deployments of SUAVs would always be above obstacles and buildings. They are not expected to navigate in urban canyons.
- Vocabulary definitions are needed. For instance, "station-keeping" versus "orbit diameter" (which could be equal to 0 for a helicopter), "loitering," and "recovery point."
- SUAV cameras with higher resolution than the ones demonstrated are available and need to be tested. The aerial visual acuity tests highlighted the need to read hazmat labels on tanker trains, but none of the SUAVs could resolve such detail.
- Image stabilization would improve clarity of aerial images.
- Infrared and multispectral cameras are necessary also on SUAVs to see through smoke.
- A "telestrator" capability as demonstrated, with video recording, playback, drawing overlays, image capture, and printing is essential. It is difficult to note features of possible interest in moving images, but backing up and freezing the image can mitigate this.
- Maintaining a fixed gaze on a target of interest is an important capability, either through a well-defined altitude/orbit, or by an independently controlled pan/tilt/zoom camera.
- Mosaics of images taken from aerial perspectives would also be useful.

Other general items discussed at the standards meeting:

- The need to be able to associate GPS and geographic information systems (GIS) data with survey data regarding both visual and hazmat sensors.
- Ideally, the operator control unit would have access to recent maps of the region showing roadways. The operators could command aerial and/or ground robots to follow a known roadway for reconnaissance.

10.0 Technology Gaps

Based on feedback from the responders and technical robotics experts involved in this response robot evaluation exercises, there appear to be several technological gaps that hinder fielding capable and useful robots in urban search and rescue missions. This is not surprising since application of robots within this difficult domain is relatively new. Several technology gaps are outlined in this section. They are driven by responder performance expectations, captured informally through observations and comments, and filtered by experienced robotics engineers. Underlying all the following discussions it is clear that robots, regardless of their onboard technologies, need to be made more rugged in order to withstand the rigors of deployments in disaster response. This need for ruggedness is inherent in all, and so not specifically discussed. There is no attempt in this report to assess the required efforts to close such gaps, or to note related activities already working to do so. Some advanced robotic systems exist that address at least some of the requirements listed, but they are (a) not generally available to the community at large, (b) not yet scalable to smaller platforms, and/or (c) would, in their current form, add too much to the cost of the robots.

Communications

Most robots rely on wireless communications for command signals as well as for sensor feedback to the operator control unit (OCU). There are issues in terms of the limitations of the wireless range and susceptibility to interference and tampering. In general for good performance, there must be line of sight between the OCU and the robot's antennas, which is unrealistic in a cluttered, collapsed structure. Although the maximum line of sight distance attainable was not measured in this environment, even the manufacturers' specifications do not typically claim the range required by the responders for ground robots, which can be more than a kilometer beyond line of site.

There have been cases where, due to the lag in communications and actuation response by the robot, a robot has moved beyond communications range. At this point, the robot will not respond to any further commands or worse, may begin moving randomly. At minimum, robots should have an automatic behavior that backs up to the last known location where it could send and receive signals, or simply stops prior to losing communications.

In every large-scale event, there is a lot of signal interference among the different robots. This exercise was conducted in a relatively benign electromagnetic environment, with minimal radio or other interfering equipment active as compared with a real response situation. Yet many robots suffered performance degradation due to radio conflicts. Some were incapacitated. Robot communications – both the command and the feedback signals – must avoid using the most popular frequencies (2.4 GHz, for example). At minimum, the OCU should include an indication of signal strength so that the operator can observe degradation before losing communications with the robot. Specific frequencies for response robots should be sought, to allow better management of multiple channels and generally higher power transmitters than typical commercial equipment.

Tethers provide a well-known alternative to radio communications and resolve many key requirements that the responders have articulated: clear image and video resolution, beyond line-of-sight operations, security of command signals, security of video return signals, etc. However, tethers as typically implemented have often introduced mobility problems in cluttered environments. Passive tethers dragging along behind a robot get snagged quickly. Active tether spools on the robots often require the operator to be cognizant of the tether to know when to pay out more line or retract it. Robots stepping on their own (fragile) tether can be another liability, resulting in damage to the tether and/or get caught up in the robot's wheel/tracks. More innovative tether management schemes should be developed and incorporated into robots of all sizes. Large robots can allow tension controlled release and automatic retrieval when backing. Smaller robots, whose weight can be supported by a tether, can use a powered tether spool to augment maneuverability or deployment strategies in cluttered environments. Tethers that provide power, even as an auxiliary remote charging capability, as well as communications, can provide additional advantages. Some ideas may require that the tether be cut and the spool replaced once the robot emerges from the scenario through any exit (cost of deployment). In general, innovative tether management can provide many potential advantages:

- Tethers can provide the only known visual reference for a remote operator working in a complex, unknown environment. A known reference such as this can help to avoid getting lost, which is extremely easy to do. The tether can also mark the direction from which the robot came, and help identify areas already searched.
- Tethers can provide responders the exact route to a victim, should the robot send back any promising signals that a victim has been found. This is beneficial whether the robot can maintain power, becomes disabled, or is simply lost and can't convey an accurate location (which is likely).
- Tethers can provide a clear path to an exit for victims in the environment that come across either the robot or the tether, especially if the tether is phosphorescent, has directional arrows and distances to the entry point (OCU), or sequenced lighting toward the entry point.

- Tethers that can be actuated to support the weight of the robot can provide a controlled descent in vertical insertions or provide a controlled descent of stairs or off other other objects. Controlled ascents can also help pull itself out of a bad position to try again. In this case, getting the tether “hooked” on something in the environment is helpful and necessary.
- Tethers can allow connection/disconnection of the OCU at the entry point to enable periodic use by different response teams (recon then primary search, for example), especially if remote charging is included.
- Tethers can allow remote charging of onboard batteries to sustain communications or enable periodic mobility after the first battery charge is exhausted.
- Tethers can allow small robot launches via hammer-toss style of throwing, using the tether itself and the weight of the robot to increase the range of an initial throw over a wall or onto a roof.

Sensors for Navigation and Mapping

More and better sensors are needed to assist remote operators in complex environments. In terms of navigation, the onboard cameras are crucial, since the robots are remotely teleoperated most of the time. Onboard cameras have to provide the “driver” with an adequate sense of what is immediately surrounding the robot (s/he has to know if the rear track is caught on an obstacle, whether it is safe to turn left, if there’s an overhead hazard, or a hole that the robot might fall into. They also have to allow longer-range planning to recognize which direction may be easiest to traverse, identify potential victim signatures in a particular area, or perform feature inspection for structural instability.

The quality of the cameras, meaning their resolution, field of view, ability to zoom, and to adjust to varying lighting conditions, varied greatly among the robots at the event. Most robots could improve their camera quality. According to the responders, longer ranges (up to 1000 feet) are desirable. However, a greater challenge is how to utilize the camera(s) in order to present information to the operator effectively. Some OCU’s contain multiple windows with the views from the different cameras; this is very confusing to some operators. Therefore a multiplicity of camera views is not necessarily the solution to this problem.

Monocular cameras make it difficult to perceive depth or to estimate distances. An obstruction may seem further or closer than it really is. Therefore, providing the operators with more of a three-dimensional sense of the world around the robot and of ranges to distant objects is a high priority. Range-imaging sensors (e.g., LADARs) that are very small, lightweight, can cope with different illumination levels and longer ranges would be helpful in providing surrounding three-dimensional geometry. Algorithms that register multiple scans and stitch together a map of the areas explored by the robot would facilitate the navigation and greatly increase the value of the robots for the responders.

Maps created by the robot as it explores an environment should also fuse information from the color cameras and other sensors (e.g., be able to tie a snapshot of an area of interest to a location on the map so it can be viewed upon request). The estimated source and intensity of a detected infrared signature can be indicated on the map, as can those from CBRNE sensors. Responders should also be able to manually annotate the maps.

On some robots at Disaster City, the cameras could be panned and/or tilted. This flexibility needs to be carefully implemented as well. Responders are working under duress, therefore the controls for the camera positions need to be as intuitive as possible. And the current orientation of the sensors ought to be clear to the operator. Navigation aids, such as GPS coordinates (where available) or an overhead map view showing where the robot currently is within either an a priori map or one acquired by the robot’s sensors, would be extremely useful.

More sensors are required in order for the robots to be more effective in disaster response. Infrared cameras need to be integrated with special emphasis on variable illumination requirements so that the scene doesn’t wash out from multiple illuminators. Switching between camera views, which have different perspectives, fields of view, or magnification, puts an additional burden on the responder. Effective means of presenting the information to the responder when s/he needs it must be developed.

Audio may be an under-utilized sensing modality. Some robots have microphones onboard the robots. In some cases, expert users rely on the microphone to detect status of the robot itself (e.g., if its motors are laboring harder than expected, or slippage is occurring). Research into how to better utilize audio for augmenting the situational awareness of the operator, both for the robot’s state and for searching the environment, may be warranted. Multiple microphones, or example, could help indicate the direction of a particular sound source.

Other sensors, such as for chemical, biological, radiological, nuclear, or explosive detection (CBRNE), must be miniaturized so as to easily fit on smaller robots. NIST will begin conducting exercises integrating CBRNE sensors with robots in the summer of 2006 and will report on the status of that technology at the appropriate time.

Integration with other Geographic Information Systems

It would be intuitive for responders to be able to command robots (either aerial or ground) to follow existing roadways on digital terrain maps within the OCU. This would require the ability to import some form of geographic information (format TBD), being able to command the robot by giving it waypoints in world coordinates, and georeferencing the position of the robot (tracking its location with respect to map positions). Elements of this capability exist in commercial equipment, and were demonstrated on some aerial robots, but were not seen within the ground robots present at Disaster City.

Mobility

Effective mobility of robots over a wide variety of challenging terrains is not yet a reality. The wood pile in particular proved to be not generally traversable by robots. This is an open research area that requires a more methodical approach in trying to understand mobility characteristics versus robot morphology and other attributes. For robots with adjustable gaits or geometries, it would be useful for the operator to simply choose from a selection of practiced initial configurations for climbing or descending, or going over or under objects. The operator should also be able to seamlessly transition to a particular gait, or try a sequence of gaits, for unknown terrain the robot is trying to traverse.

Manipulation

Some of the robots at Disaster City deployed manipulators which can be used to open doors or move objects, given enough time, skill, and patience by the operator. Those that have cameras on the arm can use the arm to gain better views of regions of interest, such as around corners or over obstacles. It is typically difficult to quickly move the gripper to a desired position and orientation using switches to control the manipulator joint by joint – which is typical of currently deployed response robot manipulators. The technological gap is the introduction of coordinated motion control techniques for manipulators onto these mobile platforms. Coordinated motion control manipulators enable the operator to move the gripper in a direction in absolute space (straight up/down, left/right, diagonal, etc.) or relative to the robot's body, often from a single multi-directional joystick. This relieves the operator from the burden of having to figure out which joints to move, and how much, to get the desired motion. Coordinated controlled manipulators are a well-known area of robotics, existing in virtually every pedestal-mounted robot in manufacturing applications today. Integration of this technology onto mobile robots should be straightforward and quick, with huge potential payoffs. For example, door-opening tasks could be performed more efficiently if an operator could control a manipulator to perform a rotational wrist turn (on a door knob) followed by a purely horizontal arcing motion to swing a hinged door open. The area of research that this opens is the combination of coordinated controlled manipulators *working together with* mobile bases to perform advanced capabilities. For example, opening exterior dwelling doors, which require that same pulling motion while negotiating a stoop and stair step or other complicated mobility.

Human/Robot Interaction

Several items above relate to the interaction between the operator and the robot through the operator control unit. These interactions include receiving information from the robot sensors, and the operator's cognitive workload while s/he attempts to maneuver the robot through complex, unknown environments. The operator is always attempting to perform remote situational assessments to negotiate the environment, and given the stressful conditions under which responders must deploy these robots, the workload can easily become unacceptably high. Presenting the responder with an integrated, easily understandable view of the situation surrounding the robot, along with the health/status of the robot, is a requirement that needs to be addressed for response robots to become effective tools for emergency response.

11.0 Summary

The exercise held at Disaster City[®] helped advance understanding of the performance issues relevant to application of robots to urban search and rescue missions. Working closely with subject matter experts within relevant training scenarios, NIST and other organizations were able to further develop and refine performance requirements and test methods for US&R robots. The responders gained insights pertaining to the current status of robotic technology as well as the future potential. They determined the three initial robot categories for Wave 1 standard test methods and deployment. The categories address small, throwable “Ground Peek Robots”; “Wide-Area Survey Robots”; and “High Altitude Loiter Robots” (which may require a change in description since effective altitudes were demonstrated at Disaster City to be 300 ft. above ground level). The responders were able to begin developing new concepts of operation, which will be essential once Task Forces and other response organizations begin to integrate robots into their deployments. The manufacturers were able to gain firsthand knowledge of the expectations that responders have for robots used in search and rescue missions. They received direct feedback from the responders on their systems, and better correlated the stated performance requirements with the expected environments. And the various working groups responsible for developing test methods under the ASTM US&R robot standards task group collected data. The test methods and artifacts will be refined as a result of the lessons learned.

As planned, the proposed test methods for Wave 1 will be submitted into the balloting process this year. The stakeholders will have an opportunity to review the test methods in their near-final incarnations in August 2006, when the next response robot evaluation exercise will be held in Maryland. At that event, responders will have an opportunity to begin experimenting with sensor payloads on the robots. Per their feedback at Disaster City[®], NIST is working with manufacturers, sensor standards groups, and others to devise scenarios wherein sensors for detecting chemicals, radiological materials, and possibly biological and other hazards are mounted on robots.

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Appendix A – Participants

Responders

Tom Haus	CA-TF1
Lee Haus	CA-TF1
Dan Kawamoto	CO-TF1
John Quinn	CO-TF1
Michael Conditt	NE-TF1
Sam Stover	IN-TF1
Michael Steed	MD-TF1
George Hough	NY-TF1
Randy Miller	NY-TF1
Billy Parker	TX-TF1
Robert McKee	TX-TF1
Mark Hundley	VA-TF2
Glenn Keller	Allentown Fire Department
Roberto Manca	Ontario Provincial Police
Alex Ferworn	Ryerson University – OPP PERT

Other Registered Participants

Steve	Richards	Acroname Inc.
Calvin	Au	AeroVironment Inc.
Ricky	Rogers	AeroVironment Inc.
Nowell	Siegel	AeroVironment Inc.
Alan	Lawson	Applied Research Associates
Adam	Sloan	Applied Research Associates
Bou	Baldwin	ARACAR
John	Blitch	ARACAR/Blitz Solutions Inc.
Blake	Douglas	ARACAR
Dave	Grilley	ARACAR
Chris	Nagelvoort	ARACAR
Mike	Pierce	ARACAR
Romario	Wallace	ARACAR
Eric	Poulson	Autonomous Solutions
Omar	Salas	Autonomous Solutions
Ryan	Robinson	Cyber Defense Systems
Satoshi	Tadokoro	Intl Rescue System Inst / Tohoku Univ
Robert	Smith	iRobot Corp.
John	Evans	JOHN M EVANS LLC
Bruce	Billian	JOUSTER / Virginia Tech
Rodney	Brown	JOUSTER / Virginia Tech
Kirk	Jenkins	L-3 BAI Aerosystems Inc.
Matt	Lister	L-3 BAI Aerosystems Inc.
Mike	Stevens	L-3 BAI Aerosystems Inc.
Lisa	Diamanti	L-3 Communications - BAI Aerosystems

Sridhar	Lakshmanan	M-Bots, Inc.
Vin	Varghese	M-Bots, Inc.
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Mike	Cole	Mesa Robotics, Inc.
Don	Jones	Mesa Robotics, Inc.
Sameer	Savant	Mesa Robotics, Inc.
Brian	Antonishek	NIST
Geraldine	Cheok	NIST
Hui-Min	Huang	NIST
Adam	Jacoff	NIST
Galen	Koepke	NIST
Elena	Messina	NIST
Craig	Schlenoff	NIST
Jean	Scholtz	NIST
Brian	Stanton	NIST
Ann	Virts	NIST
Brian	Weiss	NIST
Joel	Criswell	Northrop Grumman Corp - Remotec, Inc.
Jim	Daniels	Northrop Grumman Corp - Remotec, Inc.
Eric	Thompson	OnSight Consulting
Nathan	Gray	Optira
Mitchell	Schefcik	Optira
Travis	Gray	Optira
Sanjeev	Swarup	Skeyes Unlimited
Tamas	Kalmar-Nagy	Texas A&M University Vet Teaching Hosp
Anthony	Detrick	TSWG/BATTELLE
Joe	Alexander	U.S. Army TARDEC-RDECOM
William	Smuda	U.S. Army TARDEC-RDECOM
James	Lawrence	University of Alabama in Huntsville
Stephen	Phillips	University of Alabama in Huntsville
Kenneth	Horton	Unknown
Michael	Fleming	Virginia Tech University
Ronald	Cochran	WVHTC Foundation
Robert	Bean	WVHTC Foundation