Test Methods and Knowledge Representation for Urban Search and Rescue Robots

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1. Introduction

Urban Search and Rescue (USAR) is defined as "the strategy, tactics, and operations for locating, providing medical treatment, and extrication of entrapped victims." (Federal Emergency Management Agency 2000) USAR teams exist at national, state, and local levels. At the national level, the Federal Emergency Management Agency (FEMA), which is part of the Department of Homeland Security, has Task Forces that respond to major disasters. There are many challenges in diverse disciplines entailed in applying robots for USAR. Examples include range and penetration limitations for wireless radio signals that send commands to the robots from the operator control station, the ability of the platforms to withstand moisture, dust, and other contaminants, and the resolution of onboard navigation cameras.

NIST is working with FEMA Task Force members to define performance requirements and standard test methods as well as to assess the deployment potential of robots applied to the USAR domain. The development process being employed during this effort is driven by user-defined requirements, which were initially articulated by FEMA responders during an initial set of workshops hosted by NIST. Responders also identified different deployment categories for robots within USAR missions. These deployment categories describe types of capabilities or features the robots should have, along with tradeoffs. Thirteen different categories were defined, which may not necessarily map to thirteen different robot types (i.e., a particular robot may serve within more than one category).

Supporting efforts are detailing robot capabilities and deployment environments in unambiguous computer-usable formats. An ontology is being used as the neutral representation format for the robot characteristics. A complementary effort is attempting to quantify and characterize the environment into which the robots will be deployed. Taxonomies of buildings (pre and post-collapse) are being developed, as well as methods of deriving mathematical representations of the surfaces which the robots must cross. This chapter discusses all of these efforts in depth, as they are key enablers in the quest to match robot capabilities to the deployment environments.

Source: Climbing & Walking Robots, Towards New Applications, Book edited by Houxiang Zhang,
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Several requirements for robots applied to USAR involve mobility capabilities. Aerial, ground, and aquatic robots can all play a part in USAR operations and have unique mobility challenges and requirements. It is clear, however, that the usefulness of robots in USAR is highly dependent on their mobility capabilities as they must be able to negotiate highly unstructured environments. This chapter will highlight aspects of mobility that are relevant to robots that can walk or climb. The chapter is structured as follows. Section 2 describes the initial requirements-gathering phase for this project and details the requirements that were produced. This is followed by a discussion in Section 3 of the test method development and standardization approach, including descriptions of some of the more fully-developed test methods. Section 4 discusses the tools and techniques that have been created to capture performance data as robots are tested. Response robot exercises are described in Section 5. Section 6 covers the knowledge representation efforts, including the robot specifications and ontology and the structural collapse taxonomy. Conclusions are presented in Section 7.

2. Defining the Performance Requirements for USAR Robots

Although the potential for utilizing robots to assist rescuers in USAR operations was recognized prior to this project's inception, a methodical capture of responders' views of how they would use robots and what the detailed performance requirements were for robots had not occurred previously. Beginning in Fall 2004, NIST worked closely with DHS Science and Technology and FEMA to initiate a series of workshops that defined the initial set of performance requirements for robots applied to USAR. The first three workshops deliberately did not include robot technologists and vendors, so as to not initially bias the input from the end users with knowledge of existing technologies or approaches. Once a substantial body of requirements was gathered from responders, in subsequent workshops, robot technology providers (researchers, vendors, other government programs) were encouraged to participate.

The requirements definition process during the initial set of workshops was comprised of identifying and describing individual requirements, defining how a robot's performance with respect to a given requirement is to be measured, and, where possible, specifying the objective (desired) and threshold (minimum or maximum) performance values. The resulting list of requirements totaled over 100. These were grouped into several broad major categories. One major category, 'System', was further decomposed into sub-categories. These categories as well as the other major categories are shown in Table 1. A draft report detailing the process, the initial set of requirements, and the robot deployment categories is found at the NIST web site (Messina et.al. 2005).

Human-System Interaction	Pertaining to the human interaction and operator(s) control of the robot
Logistics	Related to the overall deployment procedures and constraints in place for disaster response
Operating Environment	Surroundings and conditions in which the operator and robot will have to operate
Safety	Pertaining to the safety of humans and potentially property in the vicinity of the robots
System:	Overall physical unit comprising the robot. This consists of the sub-components below:
- Chassis	The main body of the robot, upon which additional components and capabilities may be added. This is the minimum set of capabilities (base platform).
- Communications	Pertaining to the support for transmission of information to and from the robot, including commands for motion or control of payload, sensors, or other components, as well as underlying support for transmission of sensor and other data streams back to operator
- Mobility	The ability of the robot to negotiate and move around the environment
- Payload	Any additional hardware that the robot carries and may either deploy or utilize in the course of the mission
- Power	Energy source(s) for the chassis and all other components on board the robot
- Sensing	Hardware and supporting software which sense the environment

Table 1. Major requirements categories

Responders defined the requirements, the metrics for each, and for most of them provided objective and threshold values. The performance objectives and thresholds are dependent on the specific mission in some cases. For instance, the resolution of the onboard cameras depends on the range at which objects must be observed and on the types of objects. An aerial robot may need to provide responders information about whether a roadway ahead is blocked or clear. Another robot, aerial or ground-based, may be required to help the structural specialist assess the size of cracks in the structure.

As noted, there is no typical USAR scenario. FEMA teams (and other organizations) may respond to hurricanes, explosions, or earthquakes. The buildings may be wood frame, concrete, brick, or other construction. They may have to search subterranean, wet, confined spaces and tunnels or they may have to climb up the sides of buildings whose facades have fallen away. During the initial three requirements definition workshops, potential robot deployment categories (which could correspond to different disaster types or aspects of a response) were enumerated. Twelve categories were defined, which detailed the capabilities that the robot should have, along with the deployment method, and tradeoffs. Ground, aerial, and aquatic robot deployments are represented. The deployment categories are listed in Table 2. In some cases, the requirements therefore need to be defined according to mission or deployment type.

Robot Category	Employment Role(s)
Ground: Peek Robots	Provide rapid audio-visual situational awareness; provide rapid HAZMAT detection; data logging for subsequent team work
Ground: Collapsed Structure--Stair/Floor climbing, map, spray, breach Robots	Stairway & upper floor situational awareness; mitigation activities; stay behind monitoring
Ground: Non-collapsed Structure--Wide area Survey Robot	Long range, human access stairway & upper floor situational awareness; contaminated area survey; site assessment; victim identification; mitigation activities; stay behind monitoring
Ground: Wall Climbing Deliver Robots	Deliver Payloads to upper floors; provide expanded situational awareness when aerial platforms are unavailable or untenable
Ground: Confined Space, Temporary Shore Robots	Adaptive, temporary shoring; provide stay behind monitoring; victim triage & support
Ground: Confined Space Shape Shifters	Search; provide stay behind monitoring
Ground: Confined Space Retrieval Robots	Retrieve objects from confined spaces; provide stay behind monitoring
Aerial: Survey/Loiter Robots	Provide overhead perspective & sit. awareness; provide HAZMAT plume detection; provide communications repeater coverage
Aerial: Rooftop Payload Drop Robots	Payload delivery to rooftops; provide overhead perspective; provide communications repeater coverage
Aerial: Ledge Access Robot	Object retrieval from upper floors; crowd control with a loudspeaker object attached, provide situational awareness
Aquatic: Variable Depth Sub Robot	Structural inspection; leak localization/mitigation; object (body) recovery
Aquatic: Bottom Crawler Robot	Water traverse; rapid current station keeping; object recovery

Table 2. Robot Deployment Categories

Correlations were performed of the first set of requirements versus the deployment types. Responders were asked to note which requirements applied to which deployments. The data were analyzed to uncover which requirements affected the greatest number of missions, hence would be the most commonly-needed. An initial set of requirements was thus selected for conversion to test methods. After responders had opportunities to experiment with a wide variety of different robot platforms within various scenarios and deployments, they selected three of the twelve deployment categories as being highest priority. This selection reflected both their opinion that these were missions in which robots could provide the best utility and for which the robots seemed most technologically mature:

- Ground: Peek robots. Small, throwable robots that are able to be deployed into very confined spaces and send video or potentially sensor data back to the operators.
- Aerial, Survey/Loiter Robots. These robots could "look over the hill" to assess the situation and determine at least which roads are passable. USAR Teams 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.
- Ground: Non-collapsed Structure--Wide area Survey Robots. These robots could support a downrange reconnaissance mission. They 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 would typically move quickly down range (at least 1 km) to assess the situation and deploy multiple sensors (chemical, biological, radiological, nuclear, and explosive) with telemetry.

3. Measuring Robots Performance Against the Requirements

Among the key products of this program are standard test methods and metrics for the various performance requirements and characteristics defined by the responders. The test methods should be objective and clearly defined, and ideally, they will also be reproducible by robot developers and manufacturers to provide tangible goals for system capabilities. This will enable robot and component developers to exercise their systems in their own locations in order to attain the required performance.

The resulting standard test methods and usage guides for USAR robots will be generated within the ASTM International Homeland Security Committee through the E54.08 Subcommittee on Operational Equipment.

Draft test methods are evaluated several times by the responders and the robot developers to ensure that both communities find them representative and fair. Test methods measure performance against a specific requirement or set of requirements. The complementary usage guides help interpret the test method results for a given type of mission or deployment.

In this section, we will discuss the test methods to assess visual acuity, field of view, and maneuverability over uneven terrain, pitch/roll surfaces, ramps, stairs, and confined spaces.

To illustrate the effect of different deployment categories on the performance requirements, we will start by discussing the visual acuity and field of view test method. This test method assesses performance to address the responders' requirements listed in Table 3. The specifics of the test set up were designed to address specifically the three types of robot deployments selected as highest priority, noted above.

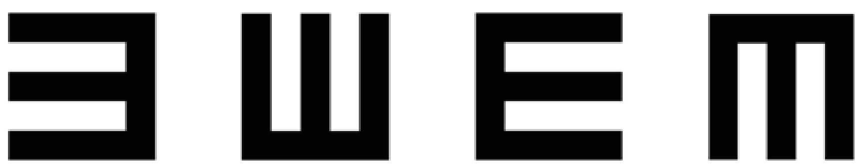


Fig. 1. Tumbling E's

The test method utilizes the Tumbling E optotype (character) in eye charts that are to be viewed by the operator at the control station remotely located from the robot, which is positioned at specified distances from two eye charts (near and far). Far Vision Visual Acuity is important for both unmanned air vehicles (UAVs) and ground vehicles for wide area survey. Zoom is required for ground vehicles for wide area survey. Near Vision Visual Acuity is important for ground vehicles for wide area survey in examining objects at close range and also for small robots that operate in constrained spaces. Figure 1 shows a sample line of tumbling E's. The operator is to indicate which side of the letter E is open (top, left, right, bottom) for each letter in a row. The smallest row that is correctly read in its entirety is the one that is noted on the form. The test is conducted in both ambient light and dark conditions (both of which are measured and noted). If the robot is traversing dark areas (which is likely in USAR missions), onboard illumination is necessary. However, if the illumination is not adjustable, close by objects will be "washed out" by the strong lighting. This case will become evident if the robot illumination enables reading the far-field chart, but precludes viewing the near-field one.

Type	Sub-Type	Requirement
Chassis	Illumination	Adjustable
Sensing	Video	Real time remote video system (Near)
Sensing	Video	Real time remote video system (Far)
Sensing	Video	Field of View
Sensing	Video	Pan
Sensing	Video	Tilt

Table 3. Requirements addressed by Visual Acuity Test Method

Common terrain artifacts are used in multiple test methods and are specifically aimed at representing a world that's not flat. They are meant to provide reproducible and repeatable mobility or orientation challenges. Step Field Pallets (Figure 2) provide repeatable surface topologies with different levels of "aggressiveness." Half-cubic stepfields (referred to as "orange") provide orientation complexity in static tests, such as Directed Perception. Full-cubic step fields ("red") provide repeatable surface topologies for dynamic tests, such as for locomotion. The sizes of the steps and width of the pallets are scaleable according to the robot sizes. Small size robots can use pallets that are made of 5 cm by 5 cm posts. Mid-sized robots can use pallets made of 10 cm by 10 cm posts. Large-sized robots use pallets made of clusters of four 10 cm by 10 cm posts. The topologies of the posts can be biased in three main ways: flat, hill, and diagonal configurations. Ž

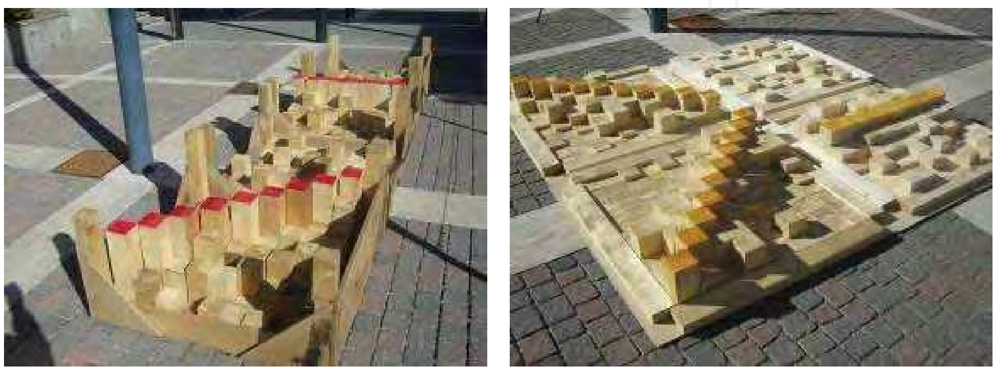


Fig. 2. Step Fields Provide Reproducible Terrain Challenges

Pitch/Roll Ramps provide non-flat flooring for orientation complexity. As implied by the name, the orientation of the ramp can be along the direction of robot travel or perpendicular to it. Different types of ramps are concatenated as well. The angles of the ramps can be 5°, 10°, or 15°.

In terms of how the performance is measured in these test methods, there is a wide variance in the abilities and levels of experience of the operators. Therefore each test method's data capture form includes a selection of the operator's self-declared experience level (novice, intermediate, or expert). When the "official" data is collected for a robot (once the test method is a standard), the robot manufacturer will supply the operator(s) that will conduct the test. We expect to strive for statistically significant numbers of trials, so that the data is averaged over numerous repetitions. Ideally, the performance data will include the level of expertise and can thus be further analyzed for disparities by this particular demographic.

Basic robot speeds and maneuverability on different terrains are measured in a series of tests. To measure basic locomotion abilities and sustained speeds, the robots are to traverse a prescribed course. The terrain types may be paved, unpaved (including vegetated), or a variant of abstracted, but repeatable, rubble-like terrain. The course may be a zig-zag pattern or a figure 8 pattern. For a zig-zag course, the test proctor notes the time it takes the robot to reach the end in one direction, and then proceed back to the origin. For a figure 8 course, the robot may be required to complete a given number of laps. A variant of these mobility tests is one that measures the ability of a robot to traverse confined spaces. In this test, step field pallets are inverted and placed over another set of pallets (see Fig. 3). This test measures the ability of robots to maneuver in very small spaces.

Special cases of mobility are tested using ramps and stairs. A pattern of way points is marked on a ramp (at a variable angle), which the robot is to follow on an inclined plane. Ability to do so and time to complete is noted for each angle, which is gradually increased until the robot may no longer accomplish this safely. For robots that are able to climb walls or move while inverted, the test can be extended to accommodate these configurations. For the mobility on stairs, the ability of the robot to ascend and descend several flights of stairs

Fig. 3. Example Mobility Tests. Left: Confined Space Cubes; Right: Inclined Plane with waypoint pattern

of different steepness is measured. Whether the stairs have enclosing walls or just railings, as well as whether they have risers or are open, are among the variables.

Other test methods, not described in this chapter, measure the robot packaging volume and weight, the situational awareness afforded by the operator control station and sensors, aerial station-keeeping, the ability to access different spatial zones with visual and mission-specific sensors, the ability to grasp and move objects at different locations, and wireless communications range.

The next section describes the infrastructure that is in place to capture data during the implementation of the test methods.

4. Data Collection – Audio/Visual

When a robot attempts a test method, performance data is captured through both quantitative measurements and Audio/Visual (A/V) data collection. The data collected in the former varies based upon the specific test method, while the latter is somewhat constant. A quad video and single audio collection system is managed throughout each test method to capture a clear representation of both the operator's and robot's actions during these performance evaluations. This A/V data collection system is composed of the control and display hub (shown in Figure 4) and supported by in-situ cameras and an operator station-based microphone. A PC-output splash screen showing the pertinent run information initiates the A/V collection and displays the robot name, operator's skill level, test method, etc. While a robot operates within a test method, video is captured of the robot from multiple perspectives (includes a combination of ground-based and ceiling mounted cameras), the operator's hand interactions with the robot's control system, the robot's visual user interface, and the PC display output of the robot tracking system (maze test method, only). A microphone in the operator room captures all the sounds the operator is exposed to throughout their performance which might include audible user interface feedback or operator comments.

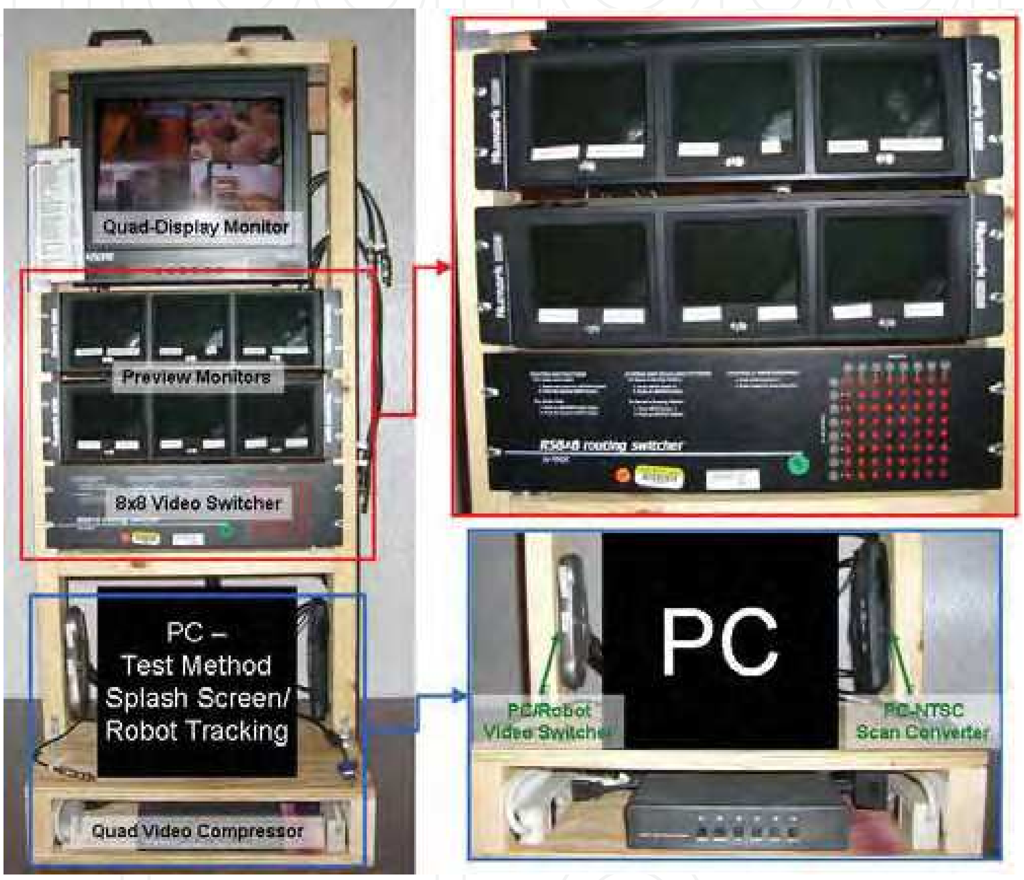


Fig. 4. Quad Audio/Video Control and Display Hub

The video and audio feeds are sent into the control and display hub. While the audio output is sent directly to the digital recording device, the video signals go through preview monitors and switchers before the final four video outputs are fed into the quad compressor and split out to a large display monitor and the digital recording device. Typically, the A/V manager has more than four video sources per test method, but only has the discretion to pick the two opportune robot video sources (displayed in the upper-right and upper-left quadrants) while the other two video sources default to the operator's control station (lower-left quadrant) and robot visual user interface (lower-right quadrant).

5. Response Robot Exercises

The robot manufacturers and researchers 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 USAR 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. In each instance, search scenarios are devised using facilities available at the training facility. NIST-built simulated victims are placed within the scenarios. These may exhibit several signs of life, including human form (typically partial), heat, sound, and movement. Robot providers are encouraged to work closely with responders to determine the best way to deploy robots into these scenarios. Operation of the robots by the responders by the end of the exercise is a key goal. This enables responders to familiarize themselves with the capabilities of the robots and to provide direct feedback to the robot manufacturers and researchers about strengths and weaknesses of robots applied to this domain. Three exercises have been held to date at FEMA USAR Task Force training facilities and are briefly described in this section.

In August of 2005, the first response robot exercise for this project was held in the desert training facility for Nevada Task Force 1. Fifteen ground (including throw-able, wall-climbing, confined space, complex terrain reconnaissance, and other sub-categories), 3 aerial, 2 aquatic, and 2 amphibious robots participated. FEMA Task Force members from the local team, as well as from several other areas of the country devised search scenarios and operated robots through them. At this time, there was one nascent test method - visual acuity - that was piloted.

The second exercise was hosted by Texas Task Force 1 at Disaster City in April 2006. (Jacoff and Messina 2006) More than 30 robots participated in 10 scenarios at this 21 hectare facility. The robot demographics spanned 16 models of ground vehicles, 2 models of wall climbers, 7 models of aerial vehicles including a helicopter, and 2 underwater vehicles. The scenarios included aerial survey of a rail accident using a variety of small and micro aerial vehicles (primarily fixed wing). Fig. 7 shows some of the scenarios. At this point, there were several emerging test methods available to be evaluated. A standards task group meeting was held after the exercise to gather input and test method critiques from the responders and vendors. At a separate meeting, the responders selected the three focus robot categories discussed above and provided an assessment of the robot maturity levels and relative strengths and weaknesses.

Maryland Task Force 1 hosted an exercise in August 2006·. This event placed heavy emphasis on evaluation of the eleven draft test methods. This exercise included 24 models of ground robots, 2 models of wall climbers, and 2 models of aerial robots, which had to run through all relevant test methods before proceeding to the scenarios. In addition to the search and rescue training scenarios, there was an *ad hoc* experiment integrating portable radiation sensors with robots.

Collaborating with NIST researchers who are working on radiation sensor standards, sensor vendors participated, providing sensors that were integrated with robots and deployed in a test method (directed perception) and in a scenario. Standards working group meetings for the communications, human-system interaction, and sensor teams were held, to capture lessons learned during the piloting of the test methods.

After conducting four such exercises, several salient observations emerged. There are many useful roles that robots can play in helping responders in USAR missions. In particular, the three high priority deployment types selected by responders can fulfill useful functions. There are some additional technological and engineering improvements still generally needed. For instance, robots must be able to withstand very harsh conditions, including submersion in water. Some of the robots developed for military applications are ready to confront these challenges, but most others are not.

One current limitation present in most robots that have participated in the exercises pertains to the wireless communications between the robot and the operator control unit (OCU). Commands are sent from the OCU to the robot and telemetry or sensor data is sent back. There are issues with limitations in the range for line of sight communications as well as for non-line of sight. Responders would like to be able to send a robot a kilometer downrange or into a collapsed concrete structure and still be able to communicate with it. Adding autonomy to the robots, so that they may continue their mission even when out of range, or at least return to the last location where they had radio contact would greatly increase their robustness. Interference between robot radios and other communications equipment also is a common problem.

Better and more sensors are desired. Responders would like better navigation aids, such as Global Positioning System (GPS) and the ability to show the robot coordinates and direction of view. They would like to have onboard mapping of environments when navigating through smoke. The cameras currently used for navigation could be better-placed to afford a higher perspective to improve path planning and obstacle avoidance. Assistance in gauging depth is needed.

The mobility of ground robots, in general, needs improvement. There are very few platforms that can even attempt to traverse rubble piles, such as those commonly found at FEMA USAR training facilities. Tracks on robots (which are commonly used) can easily come off or catch loose debris and become disabled. Stairs can foil some robots, especially if they are dusty or otherwise slippery. A robot locomotion design based on walking, if complemented with semi-autonomous gaits, could adapt to a wide variety of terrains and conditions. Search dogs regularly participate at the response robot exercises, and their ability to traverse rubble piles and other challenging terrain is unsurpassed. Wall-climbing robots have been favorably received. Responders like the ability to peer over the tops of buildings or use the ceiling, which may be intact, to survey a collapsed area. Figure 5 shows examples of wall-climbers in action. The wall-climbers need to improve their robustness and be able to deal with changes in the wall or ceiling surfaces. Discontinuities or protuberances can cause them to lose contact with the wall and fall.

Fig. 5. Examples of wall-climbing robots

6. Knowledge Representation Efforts

As mentioned earlier, knowledge representation is a key enabler in the quest to match robot capabilities to the deployment environments. With the large number of disparate robots that are currently available, responders need an easy way to quickly determine which robot is most appropriate for their current mission. This section describes three efforts which are currently underway to represent robot capabilities and structural collapse types with the goal of providing various tools to assist responders in choosing the best robot for their mission. They are the Robot Pocket Guide, the Robot Capability Ontology, and the Structural Collapse Taxonomy.

6.1. The Robot Pocket Guide

Over the past year, NIST has been developing a robot pocket guide to provide responders with easy access to high-level specifications of robots. The guide is designed to fit in a responder's pocket and currently contains information about 28 robots that have participated in the aforementioned exercises. Robots are classified as either ground, wall-climbed, aquatic, or aerial. Sample pages of the pocket guide are shown in Figure 6. The NanoMag[1] is classified as a wall climbing robot (as shown by the tab on the right). Information that is included about the NanoMag on the left page along with a picture of the robot and its operator control unit include its width, length, height, weight, turning diameter, maximum speed, etc. On the right page, there is information about how the robot performed in the test methods described earlier. Because the test methods have not yet been

[1] Certain commercial software and tools are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the tools identified are necessarily the best available for the purpose.

finalized, all that is shown is how the information will be represented. Similar information is included about the other 27 robots. As more robots participate in the upcoming exercises, information about them will be added to the pocket guide.

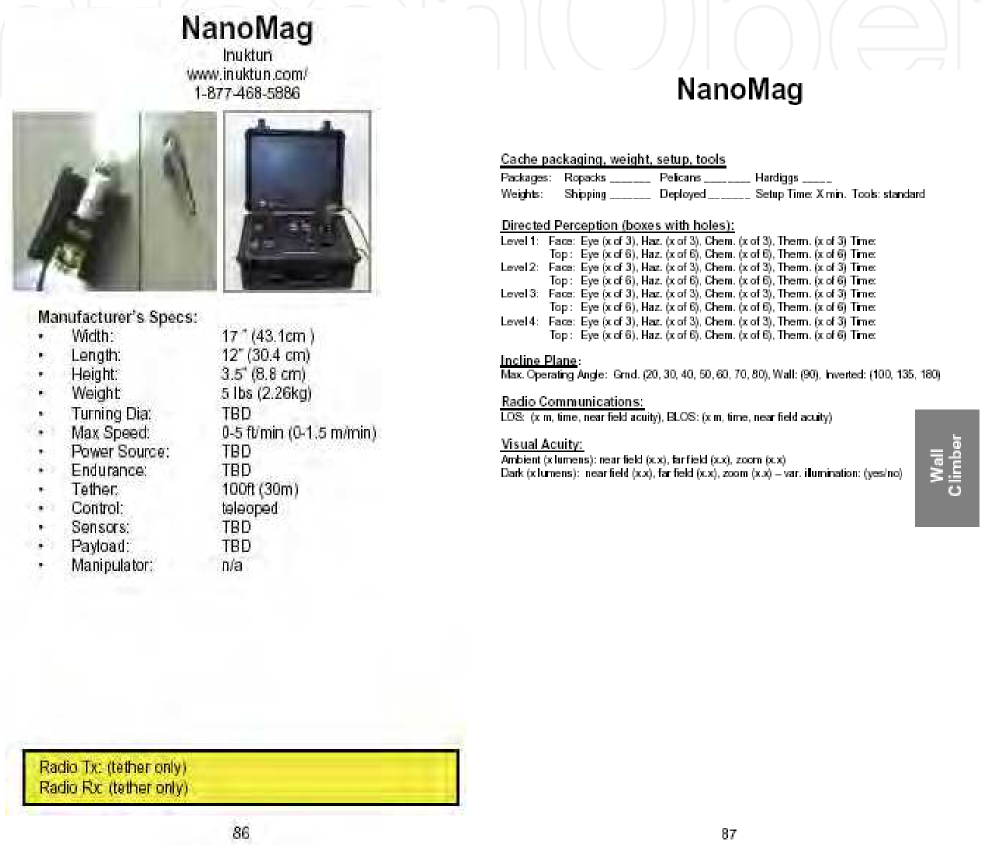


Fig. 6. The NanoMag page in the robot pocket guide

6.2. The Robot Capability Ontology

6.2.1. Overview

The goal of this Robot Capabilities Ontology effort is to develop and begin to populate a neutral knowledge representation (data structure) capturing relevant information about robots and their capabilities. This ontology will help to assist in the development, testing, and certification of effective technologies for sensing, mobility, navigation, planning, integration and operator interaction within search and rescue robot systems. It is envisioned that a first responder would query this knowledge representation using a graphical front end to find robots that meet the criteria (e.g., size, weight, heat resistance, etc.) they need to perform a desired mission in a disaster site. This knowledge representation must be flexible enough to adapt as the robot requirements evolve. As such, we have chosen to use an ontological approach for representing these requirements.

6.2.2. Sample Scenario

Passenger rail cars were hit by industrial hazmat tanker cars of unknown substance and both trains partially derailed, as shown in Figure 7. After initial analysis, it was determined that ground robots should circumnavigate all trains over the tracks, various debris, and rubble. The robots should map the perimeter along with the location and positions of each car, including under the elevated car. 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 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.

Fig. 7. Train Wreckage Scenarios

The first responders need to decide which robots to use out of their available cache of robots. They go to their laptop and enter their requirements for the robots. They use pull-down boxes and text entry boxes to state that they need a robot that can traverse rubble 15 cm (6 inches) in diameter, has sensor capabilities that can develop a 3-D map of the environment, can withstand various hazmat conditions, and can fit into alcoves as small as 1 meter (3 feet) in width and height. They must also have sensors that can identify victims by heat signatures. Lastly, they must have vision capabilities that read signs with 2.5 cm (1 inch) lettering from a distance of 3.2 meters (7 feet) away. Based on their requirements, two robots are returned that are acceptable. However, one of the robots also has heat resistance up to 90 degrees celsius (200 degrees Fahrenheit), which is not important for this scenario but is very important for another disaster site nearby which partnering first responders are addressing. The first responder decides to use the robot without the heat resistance and requests that specific robot through the user interface.

6.2.3. Related Work

To the best of the authors' knowledge, only a handful of projects exist that have addressed the challenge of developing a knowledge representation for Urban Search and Rescue (USAR). One such effort is being performed at the University of Electro-Communications in

Tokyo, Japan (Chatterjee and Matsuno 2005). This work intends to identify the necessity and scope of developing ontology standards for describing the rescue robot features and for describing the disaster scenarios in the context of search and rescue effort coordination. It is intended to support the decision process of assigning any particular robot platform to any specific disaster site and to prioritize allocation of available robot-aided rescue teams to specific disaster areas among many demanding sites. At the time that this paper was written, a list of requirements existed for the information that should be contained in the ontology, but no effort had been performed to model them within a formal data structure.

SPAWAR (Space and Naval Warfare Systems Command) has developed the Mobile Robot Knowledge Base (MRKB) (Joint Robotics Program 2005), which provides the robotics community with a web-accessible, centralized resource for sharing information, experience, and technology to more efficiently and effectively meet the needs of the robot system user. The resource includes searchable information on robot components, subsystems, mission payloads, platforms, and Department of Defense (DOD) robotics programs. In addition, the MRKB website provides a forum for technology and information transfer within the DOD robotics community and an interface for the Robotic Systems Pool (RSP). The RSP manages a collection of small teleoperated and semi-autonomous robotic platforms, available for loan to DOD and other qualified entities. The objective is to put robots in the hands of users and use the test data and fielding experience to improve robot systems. Minimal information about the robots is contained on this website itself (it primarily includes a picture, overall characterization, and cost). Each robot site also contains a link to the robot manufacturer's page where more detailed information can be found out.

There have been efforts at the Center for Robot Assisted Search and Rescue (CRASAR) in the development of taxonomies for robot failures (Carlson et.al. 2004) and issues pertaining to social interactions between robots and humans (Burke et.al. 2004). A failure is defined as the inability of the robot or the equipment used with the robot to function normally. Both complete breakdowns and noticeable degradations in performance are included. The effort developed a taxonomy to gain insight into how and why mobile robots fail. *Failures* are categorized based on the source of failure and are divided into *physical* and *human* categories, following dependability computing practices. *Physical failures* are subdivided into classes based on common systems found in all robot platforms, these being *effector*, *sensor*, *control system*, *power*, and *communications*. *Effectors* are defined as any components that perform actuation and any connections related to those components. This category includes for example, *motors*, *grippers*, *treads*, and *wheels*. The control system category includes the on-board computer, manufacturer provided software, and any remote operator control units (OCU). *Human failures* (also called human error) are subdivided into *design* and *interaction* subclasses. Mistakes are caused by fallacies in conscious processing, such as misunderstanding the situation and doing the wrong thing. Slips are caused by fallacies in unconscious processing, where the operator attempted to do the right thing but was unsuccessful. Each failure, regardless of physical or human, has two attributes, repairability and impact. The severity of the failure is evaluated based on its impact on the robot's assigned task or mission. A terminal robot failure is one that terminates the robot's current mission, and a non-terminal failure is one that introduces some noticeable degradation of the robot's capability to perform its mission. The repairability of the failure is described as either field-repairable or non-field-repairable. A failure is considered field-repairable if it can be repaired under favorable environmental conditions with the equipment that commonly accompanies the robot into the field. This work focuses solely on robot failure, while the work that is described in the remainder of this section also takes a classification approach but focuses on robot capabilities in a more general sense.

6.2.4. Ontology Overview

Using the requirements discussed earlier in this chapter [Section 2] as the underlying basis, a knowledge representation was developed to capture the requirements. The goal was to develop a knowledge representation that would allow for:

- Less ambiguity in term usage and understanding
- Explicit representation of all knowledge, without hidden assumptions
- Conformance to commonly-used standards
- Availability of the knowledge source to other arenas outside of urban search and rescue
- Availability of a wide variety of tools (reasoning engines, consistency checkers, etc.)

To address this, we used an ontological approach to represent these requirements. In this context, an ontology can be thought of as a knowledge representation approach that represents key concepts, their properties, their relationships, and their rules and constraints. Whereas taxonomies usually provide only a set of vocabulary and a single type of relationship between terms (usually a parent/child type of relationship), an ontology provides a much richer set of relationship and also allows for constraints and rules to govern those relationships. In general, ontologies make all pertinent knowledge about a domain explicit and are represented in a computer-interpretable fashion that allows software to reason over that knowledge to infer additional information.

The benefits of having a robot ontology are numerous. In addition to providing the data structures to represent the robot requirements, the robot ontology can allow for:

- The selection of equipment and agents for rescue operations
- Assistance in the exchange of information across USAR teams
- The ability to find the available resources that address a need
- The identification of gaps in functionality that can drive research efforts

The following sections describe the infrastructure that was used to develop the robot ontology as well as the current status of its development.

6.2.5. Infrastructure

The Robot Ontology has been developed to ensure compliance with existing formal and *de facto* standards as well as ensuring compatibility with existing tools and software infrastructures. More specifically, the Robot Ontology leverages the Protégé ontology development tool and the OWL/OWL-S specification, as described below.

Before an ontology can be built, a decision must be made as to which tool (or set of tools) should be used to enter, capture, and visualize the ontology. For this work, we decided to use Protégé (Schlenoff et.al. 2004). Protégé is an open source ontology editor developed at

Stanford University. It supports class and property definitions and relationships, property restrictions, instance generation, and queries. Protégé accommodates plug-ins, which are actively being developed for areas such as visualization and reasoning.

Protégé provides a suite of tools to construct domain models and knowledge-based applications with ontologies. At its core, Protégé implements a rich set of knowledge-modeling structures and actions that support the creation, visualization, and manipulation of ontologies in various representation formats. It supports class and property definitions and relationships, property restrictions, instance generation, and queries. Protégé can be customized to provide domain-friendly support for creating knowledge models and entering data. Further, Protégé can be extended by way of a plug-in architecture and a Java-based Application Programming Interface (API) for building knowledge-based tools and applications. Protégé was chosen due to its strong user community, its ability to support the OWL language, its ease of use (as determined by previous experience), and its ability to be extended with plug-ins such as visualization tool.

We decided to use the OWL-S upper ontology (The OWL Services Coalition 2003) as the underlying representation for the Robot Ontology in order, among other reasons, to leverage the large and ever-growing community and to ensure compatibility with the XML (eXtensible Markup Language) format. OWL-S is a service ontology, which supplies a core set of markup language constructs for describing the properties and capabilities of services in an unambiguous, computer-intepretable format. OWL-S, which is being developed by the Semantic Web Services arm of the Defense Advanced Research Projects Agency (DARPA) Agent Markup Language (DAML) program, is based on OWL (Harmelen and McGuiness 2004). OWL is an extension to XML and RDF (Resource Description Framework) schema that defines terms commonly used in creating a model of an object or process. OWL is a World Wide Wide Consortium (W3C) recommendation, which is analogous to an international standard in other standards bodies.

OWL-S is structured to provide three types of knowledge about a service, each characterized by the question it answers and shown in Figure 8:

- What does the service require of the user(s), or other agents, and provide for them? The answer to this question is given in the ``profile.'' Thus, the class *SERVICE* presents a *SERVICEPROFILE*
- How does it work? The answer to this question is given in the ``model.'' Thus, the class *SERVICE* is describedBy a *SERVICEMODEL*
- How is it used? The answer to this question is given in the ``grounding.'' Thus, the class *SERVICE* supports a *SERVICEGROUNDING*.

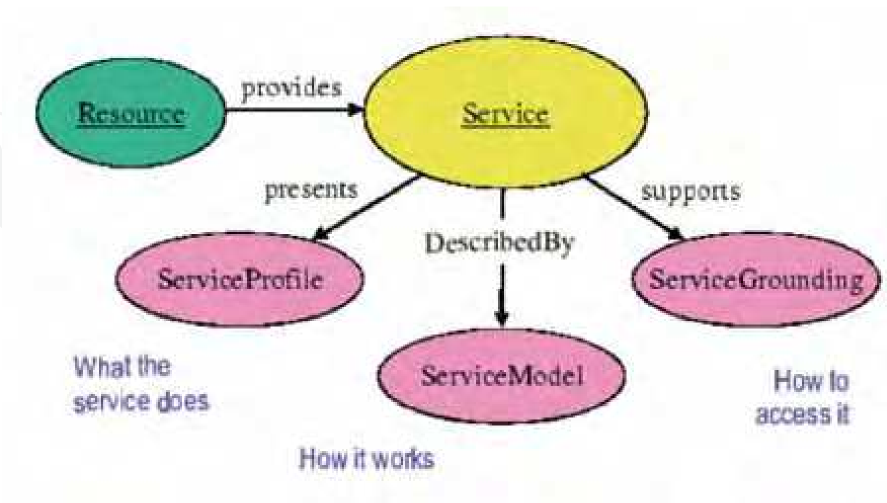


Fig. 8. OWL-S Ontology Structure

6.2.6. Ontology Structure

To capture the requirements described earlier in the paper, an initial structure for the Robot Ontology has been developed. A screenshot of the ontology in Protégé is shown in Figure 9. The column on the left shows the classes that are represented in the ontology (e.g., *Capability*, *Robot*, *User Interface*). The box on the right shows the attributes that are associated with the highlighted class (*Robot*). Robots have attributes such as hasCommunicationCapability, hasHumanFactorsCapabilities, hasLocomotionCapabilities, etc. Each one of these attributes may point to a class (shown in parenthesis next to the attribute name) which contains more specific information about the value of that attribute.

The main concept in the ontology is *Robot*, where a robot can roughly be defined as a mechanism with locomotion and sensing capability which a human user may interact with from a remote location. A Robot can be thought of as having three primary categories of information, namely:

- Structural Characteristics – describes the physical and structural aspects of a robot
- Functional Capabilities – describes the behavioral features of the robot
- Operational Considerations – describes the interactions of the robot with the human and the interoperability with other robots

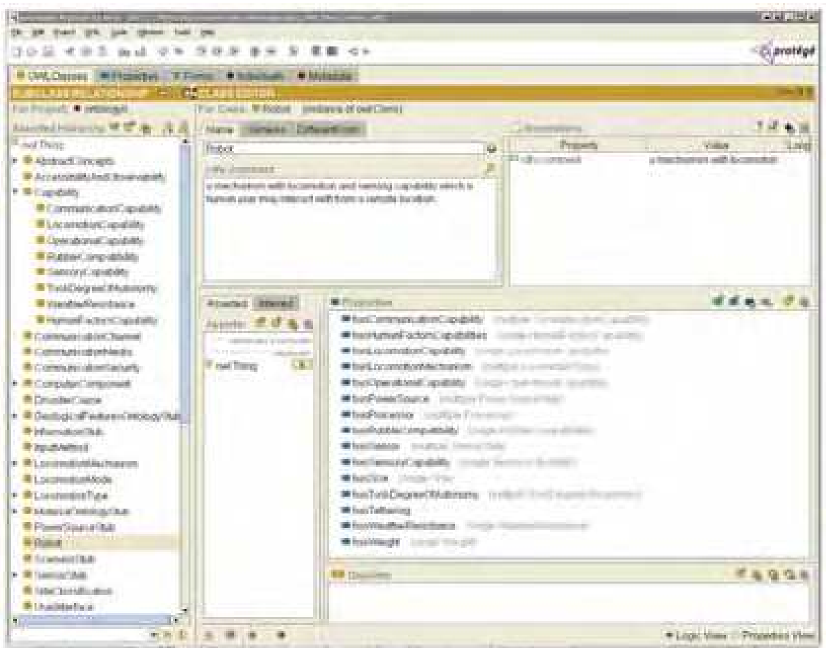


Fig. 9. The Robot Capabilities Ontology

In the Robot Ontology, structural characteristics are primarily captured in the definition of the robot itself. These characteristics include (but are not limited to):

- Size –(e.g., minimum and maximum length, width, and height (depending on robot configuration))
- Weight
- Tethering (i.e., yes or no)
- Power Source
- Locomotion Mechanism (e.g., wheeled, walking, crawling, jumping, flying, etc.)
- Sensors (e.g., camera, FLIR, LADAR, SONAR, GPS, Audio, Temperature Sensor, etc.)
- Processors

Many of the above are direct attributes of the Robot class. The Robot class and its attributes are shown in Figure 9. Another important thing to notice in Figure 9 are the classes that end in the word "stub". These are meant to be placeholders to integrate in more established (and hopefully standardized) representations. Examples of these "stubs" include GeologicalFeatureOntologyStub, InformationStub, MaterialOntologyStub, PowerSourceStub, ScenarioStub, and SensorStub.

Examples of knowledge captured in the functional capabilities category include (but are not limited to):

- Locomotion Capabilities (e.g., max. speed, max. step climbing, max. slope climbing, etc.)
- Sensory Capabilities (e.g., min. visibility level, map building capability, self-localization, system health, etc.)
- Operational Capabilities (e.g., working time, setup time, max. force available to push, mean time before failure (MTBF), mean time between maintenance (MTBM), required tools for maintenance, run time indicator, sustainment (spares and supplies), etc.)
- Weather Resistance (e.g., max. operating temp, max. submergibility level, etc.)
- Degree of Autonomy (e.g., joint level dependency, drive level dependency, navigation level dependency, etc.)
- Rubble Compatibility (e.g., ability to historically operate well in certain terrains)
- Communications (e.g., communication media, communication channel frequency, content standards, information content, communication locking, communication encryption)

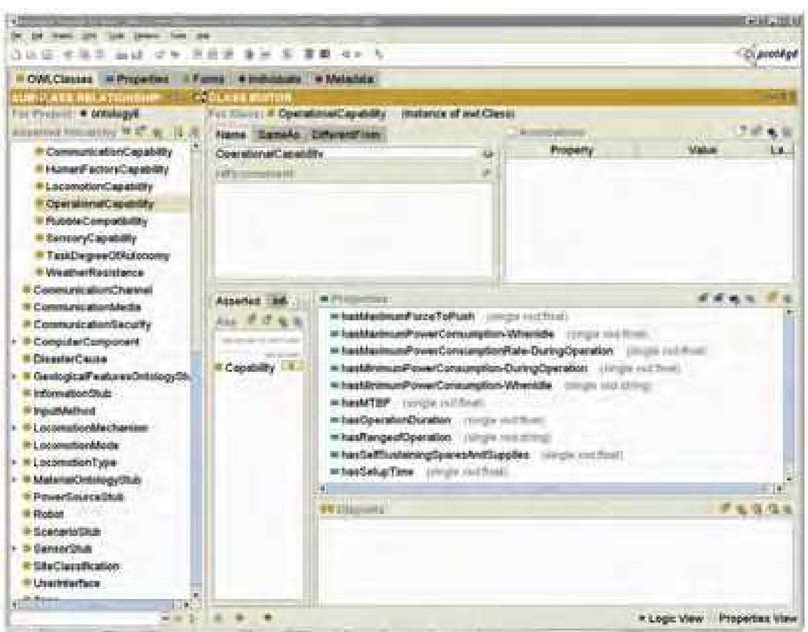


Fig. 10. Operational Capability Attributes

Figure 10 shows an example of the operational capabilities that may be associated with a robot. Note in this figure that some attributes have "primitive" attributes as their type (e.g., float, string, Boolean). This implies that, instead of pointing to another class of object to capture the data associated with that attribute, the data is captured directly in that primitive type.

Examples of knowledge captured in the operational considerations category include (but are not limited to):

- Human Factors (operator ratio, initial training, proficiency education, acceptable usability, auto-notification, display type, packaging)
- Intra-Group Interaction (i.e., interaction with other similar robots)
- Inter-Group Interaction (i.e., interaction with other 3rd party robots or computers)

Figure 11 shows an example of the human factors attributes that may be associated with a robot.

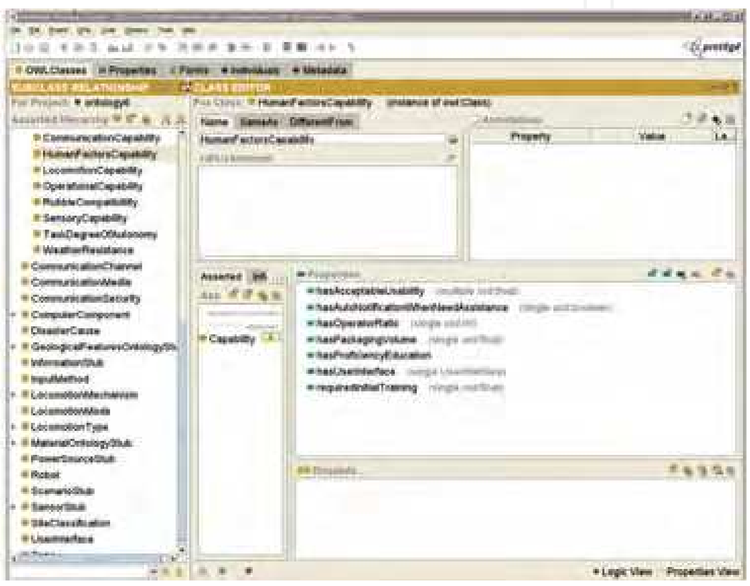


Fig. 11. Human Factors Attributes

6.2.7. Future Work

This section describes our progress in developing a robot ontology for USAR. To date, the Robot Ontology contains 230 classes, 245 attributes (properties), and 180 instances. As the project progresses, it is expected that the ontology will grow considerably. Although strong progress has been made, there is still quite a lot of work to be accomplished. Future work will focus on (in no particular order):

- Continue to specialize the robot ontology structure to provide greater level of detail in the areas that have already been addressed
- Explore other standards efforts and existing ontologies that can be leveraged, such as ontologies for sensors, power sources, materials, and environment.
- Continue to incorporate the requirements from the requirements workshops into the robot ontology structure
- Develop a user interface to help the end user query the ontology. A simple user interface is shown in Figure 12.

Fig. 12. Sample User Interface to Ontology

6.3. Structural Collapse Taxonomy

6.3.1. Overview

When a disaster occurs, previously benign terrain may become difficult or impossible to traverse. Buildings collapse, roads and bridges are destroyed, and previously smooth, obstacle free terrain may contain large obstacles and discontinuities. In order to perform search and rescue operations, responders must know what form of mobility they must use to traverse affected areas. For operational scenarios, the terrain must be assessed in order to employ assets that posses the correct mobility techniques to get to desired locations. In a research and development scenario, a description and classification of potential operating environments is necessary to effectively guide system development. This is particularly true for the development of performance-based standards for Urban Search And Rescue (USAR) robots.

An essential element in defining performance metrics is to be able to clearly understand and describe the operating environment of the system under test. For USAR robotics, both qualitative and quantitative measures of the environments in which platforms are tested and deployed are of great interest. 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 USAR context could be a specific measure of the traversibility of the terrain surface derived using techniques such as height, slope, and roughness estimation from plane fitting, fractal dimension analysis or wavelet energy statistics. Traversibility is a well-studied discipline, particularly in the context of unmanned ground vehicle path planning. The challenge is to standardize a universallyaccepted measure for system evaluation. An interesting qualitative approach would be to develop a method to score USAR environments 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 (USAR Decimal System) number of x for an environment with terrain characterization 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.

To address the performance metric need, NIST is conducting research in characterizing terrain traversability for USAR robots (Molino et.al. 2006). The desired result is a set of algorithms that are capable of analyzing a terrain surface and predicting which robots would be able to successfully navigate the terrain. To support this research effort, NIST has gathered high-resolution point clouds of several training disaster scenarios and made those available for all interested researchers. In addition to characterization algorithms, there is also a desire to develop representative models of these training scenarios for use in simulation environment discussed in Section 5. The difficulty is to provide models of sufficient fidelity that the collapsed terrain is correctly simulated for mobility physics and maintains important features such as void spaces and terrain roughness, without overwhelming the current generation of game engines. A related effort involves developing a framework for integrating building classification, disaster type, and collapse type to provide general descriptions of probable operating environments.

6.3.2. Structural Collapse Taxonomy

In the context of emergence response and disaster estimation, buildings are normally classified by model building type and occupancy class. For building types, primary factors include the building materials used for constructing the structural frame, the lateral-force-resisting system, and the height of the structure. A simplified classification system is shown in Table 4.

Type of Construction[1]	Wood, Masonry[2], Steel, Concrete[3]
Type of Structure	Shear Wall[4] or Moment Frame
Height	Low-rise (≤ 6 stories) [5], Mid–rise (6-10 stories), High (>10)

Notes:

(1) Refers to materials making up structural frame;

(2) Masonry is typcially further divided into reinforced or unreinforced

(3) Concrete is typically further divided into cast-in-place or pre-cast

(4) Masonry is only shear wall;

(5) Masonry is usually never > 6 stories and wood is usually never > 4 stories. Therefore masonry and wood default to low-rise

Table 4. Simplified Building Type Schema

The American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI) issued a standard for the seismic evaluation of existing buildings (ASCE SEI 2003)}. ASCE/SEI 31-03 publication defines 15 base building types with subcategories resulting in 24 separate building descriptions. The building types are organized by the building material and the lateral-force-resisting system. Building height is not a factor. A complete listing of the 24 types is provided in Table 5.

W1	Wood Light
W1A	Multi-Story, Multi-Unit Residential Wood Frames
W2	Wood Frames, Commercial and Industrial
S1	Steel Moment Frames with Stiff Diaphragms
S1A	Steel Moment Frames with Flexible Diaphragms
S2	Steel Braced Frames with Stiff Diaphragms
S2A	Steel Braced Frames with Flexible Diaphragms
S3	Steel Light Frames
S4	Steel Frames with Concrete Shear Walls
S5	Steel Frames with Infill Masonry Shear Walls and Stiff Diaphragms
S5A	Steel Frames with Infill Masonry Shear Walls and Flexible Diaphragms
C1	Concrete Moment Frames
C2	Concrete Shear Wall Buildings with Stiff Diaphragms
C2A	Concrete Shear Wall Buildings with Flexible Diaphragms
C3	Concrete Frames with Infill Masonry Shear Walls and Stiff Diaphragms
C3A	Concrete Frames with Infill Masonry Shear Walls and Flexible Diaphragms
PC1	Precast/Tilt-up Concrete Shear Wall Buildings with Flexible Diaphragms
PC1A	Precast/Tilt-up Concrete Shear Wall Buildings with Stiff Diaphragms
PC2	Precast Concrete Frames with Shear Walls
PC2A	Precast Concrete Frames without Shear Walls
RM1	Reinforced Masonry Bearing Wall Buildings with Flexible Diaphragms
RM2	Reinforced Masonry Bearing Wall Buildings with Stiff Diaphragms
URM	Unreinforced Masonry Bearing Wall Buildings
URMA	Unreinforced Masonry Bearing Wall Buildings with Stiff Diaphragms

Table 5. Common Building Types (from ASCE / SEI 31-03)

A more detailed building classification system is used in the FEMA Hazards U.S. Multi-Hazard (HAZUS-MH) system (FEMA 2007; Schneider et.al. 2006). This system is a standard methodology and associated software program for estimating potential losses from earthquakes, floods, and hurricane winds. HAZUS-MH not only includes model building types based upon structural systems (material and design) but also occupancy class and height. There are 28 different occupancy classes (e.g., hospital, school, apartment building, etc.) and 36 different model building types. The model building types are an extension of those shown in Table 4, factoring in low-, mid-, and high-rise classifications. In HAZUS-MH, estimates of potential damage are modeled from building type, while occupancy class is solely used for estimating loss (Kircher et.al. 2006). For USAR robotic system design and deployment, occupancy class is an important consideration to understand potential human occupancy, potential obstacles and void spaces due to interior elements, and the potential for other hazards (e.g., toxic or explosive atmospheres).

Another building classification system of note is from the FEMA 154 Rapid Visual Screening of Buildings for Potential Seismic Hazards manual. This manual adopted the model building types used the FEMA 310 Prestandard for Seismic Evaluation, which was the precursor to ASCE/SEI 31-03. As a result, FEMA 154 uses just the base 15 model building types used in ASCE/SEI 31-03. FEMA 154 is the second edition of a document first published by the Advanced Technology Council in 1988 of the same name and known in the response community as ACT-21. In ACT-21, there were 12 base building types as shown in Table 6. This is important because the FEMA USAR community adopted the ACT-21 designations and those designations are described responder training materials (FEMA 2006). Responders will be familiar with the ACT-21 designations, but may not be aware of the expanded classifications developed in ASCE/SEI 31-03 and HAZUS-MH.

W1	Wood Buildings (All Types)
S1	Steel Moment Resisting Frames
S2	Braced Steel Frames
S3	Light Metal Buildings
S4	Steel Frames with Concrete Shear Walls
C1	Concrete Moment Frames
C2	Concrete Shear Wall Buildings
C3/S5	Concrete/Steel Frames with Infill Unreinforced Masonry
TU/PC1	Precast/Tilt-up Concrete Shear Wall Buildings
PC2	Precast Concrete Frames
RM	Reinforced Masonry
URM	Unreinforced Masonry

Table 6. Common Building Types (from ATC-21)

In addition to building type and occupancy class, other parameters which should be taken into consideration are the type of structural loading causing the collapse and the type of collapse itself. Basic structural loading categories include earthquakes, windstorms, explosions, fire, flood, failure of construction bracing, urban decay, overload, and vehicle impact (e.g. cars, trains, planes, etc.). Overall types of collapses include partial, total, and progressive collapse. Often, specific building types collapse in familiar ways for various structural loads, yielding several categories of collapse patterns. An example would be the pancake, v-shape, lean-to, and cantilever earthquake collapse patterns. Structural loading categories and basic collapse patterns are discussed in .

6.3.3. USAR Terrain Characterization Data Collection

To support the development of mobility performance metrics, characterization algorithms, and simulation environments, NIST research engineers teamed with a 3D imaging service provider to produce high resolution laser scan data of three of the operational scenarios at the TX-TF1 Disaster City training facility at College Station, TX. These scenarios included the rubble pile (#2), the wood pile (#3), and the train wreck. 3D image data were collected using two commercially-available terrestrial laser scanners over the course of three days. Each scenario was scanned from multiple locations and each scan location was registered using targets. These targets were independently measured with a total station to provide survey control. Figures 13 (A & B)and 14 (A & B) show elements of the 3D imaging process

(A) (B)

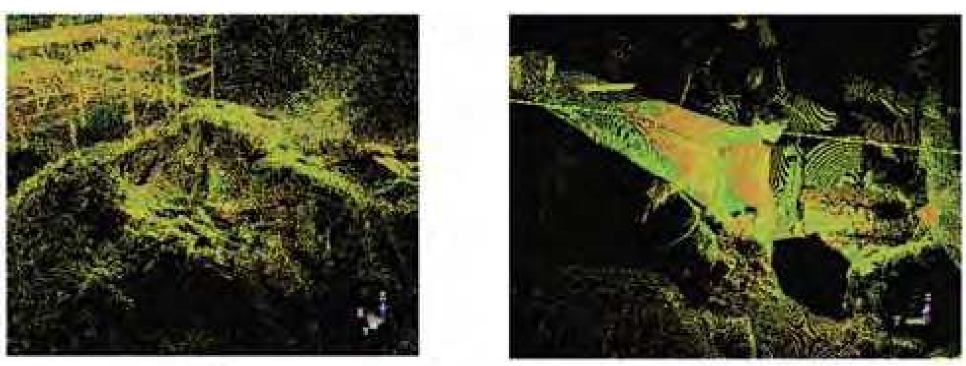
Fig. 13. (A) Setting up a scan of the rubble pile. Scan locations must be carefully chosen to obtain sufficient scene data to capture the existing conditions and enable tie in to prior scans using pre-positioned targets. (B) Since the laser scanner is a line-of-sight device, obtaining sufficient information for a disordered scene such as the rubble pile requires numerous scan locations throughout the environment.

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 geometrically accurate point clouds of the scenes.

(A) (B)

Fig. 14. (A).The wood pile was imaged using three 'overhead' scans and several ground-level scans. This view was taken from a scissors-lift. (B) Imaging the train wreck.

Figures 15 (A & B) and 16 (A & B) depict screen captures of the scenes from a point cloud viewing package. Within the point cloud 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.



(A) (B)

Fig. 15. (A) Registered perspective view of rubble pile.(B) Single scan from the rubble pile. The long 'tube' structure is made of two jersey barriers which form a tunnel through the pile. The scanner was placed at the entrance to the tunnel. The point cloud viewpoint was rotated in the 3D viewing software to show the tunnel.

There are many potential uses for these 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 such as USARSim. 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 developers. As an example, several robots are being modeled within USARSim with vehicle physics and scene interaction capability. Responders, researchers, developers, and other interested personnel will be able to navigate the scenarios at Disaster City – to some degree of fidelity – without having to physically travel to the location. Intelligent behaviors for semi-autonomous robots can also be virtually tested within the Disaster City models. The three images shown in Figure 17 depict this progression.

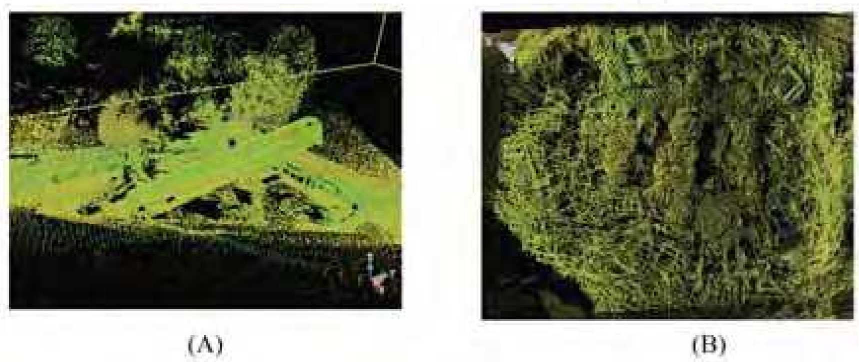


Fig. 16. (A) A bird's-eye-view of the full 3D point cloud of the train wreck. (B) A plan view of the wood pile.

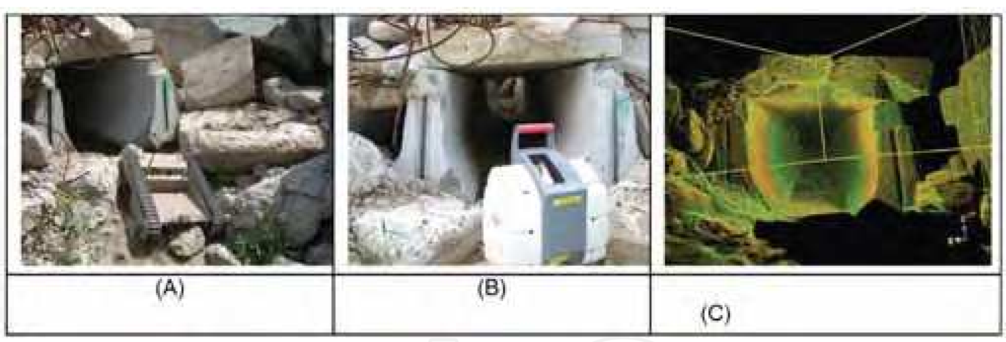


Fig. 17. A) Robot approaching a tunnel passage under rubble pile. B) Laser scanner captures high-resolution geometry data of all surfaces. C) Resulting "point cloud" of range data provides extremely accurate (ground-truth) model of actual rubble to support rubble classification and high-fidelity simulation environments for robot development and training.

Finally, this type of sensed data can 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 rather than 2D images alone. As automated or semi-automated algorithms to create maps of areas explored by robots become more capable, sensors that provide rich range information will be crucial.

The 3D image data collected during the responder event has been made available to researchers worldwide to foster development USAR robot development.

7. Conclusion

In this paper, we described an effort in which NIST is working with FEMA Task Force members to define performance requirements and standard test methods as well as to assess the deployment potential of robots applied to the USAR domain. This process has resulted in draft test method specifications based upon a well-defined set of robot requirements, which are currently making their way through the standardization process. This chapter also describes a set of knowledge representation efforts that are underway to make it easier for responders to easily determine the best robot for the environment in which they are confronted. These knowledge representation efforts range from fairly informal – a paper-based robot pocket guides which give high-level specification of robot characteristics to more formal – an ontology-based representations which allow users to search for the most appropriate robot based on a more comprehensive set of the robots characteristics. A complementary effort is attempting to quantify and characterize the environment into which the robots will be deployed. Taxonomies of buildings (pre and post-collapse) are being developed, as well as methods of deriving mathematical representations of the surfaces which the robots must cross.

Though much progress has been made, there is still much work to be done. The existing test methods still need to be further refined (with continual input from the responders) and continue through the standards development process. Additional test methods will be developed to address some of the additional requirements as the current ones continue to mature.

From the knowledge representation perspective, the pocket handbook is by far the most mature and has been given to the responders that have been involved in the previous evaluations. It will continue to evolve as feedback comes back from the responders and as more robots participate in future exercises. The structural collapse taxonomy and the robot capabilities ontology are earlier in the development process, and are still in the process of being populated with relevant information. Recent efforts in the robot capabilities ontology effort are focusing on developing/enhancing a front-end user interface (UI) to the ontology that would allow a responder to interact with the system using terminology that is familiar to them. A search engine will be developed that links the UI to the ontology to allow the responder to quickly find the best robot that meets his/her requirements.

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Climbing and Walking Robots: towards New Applications
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With the advancement of technology, new exciting approaches enable us to render mobile robotic systems more versatile, robust and cost-efficient. Some researchers combine climbing and walking techniques with a modular approach, a reconfigurable approach, or a swarm approach to realize novel prototypes as flexible mobile robotic platforms featuring all necessary locomotion capabilities. The purpose of this book is to provide an overview of the latest wide-range achievements in climbing and walking robotic technology to researchers, scientists, and engineers throughout the world. Different aspects including control simulation, locomotion realization, methodology, and system integration are presented from the scientific and from the technical point of view. This book consists of two main parts, one dealing with walking robots, the second with climbing robots. The content is also grouped by theoretical research and applicative realization. Every chapter offers a considerable amount of interesting and useful information.