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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,
ISBN 978-3-902613-16-5, pp.546, October 2007, Itech Education and Publishing, Vienna, Austria

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.

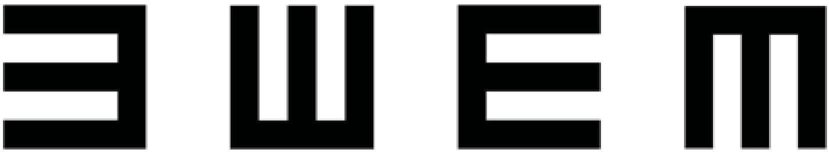

Fig. 1. Tumbling E's

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

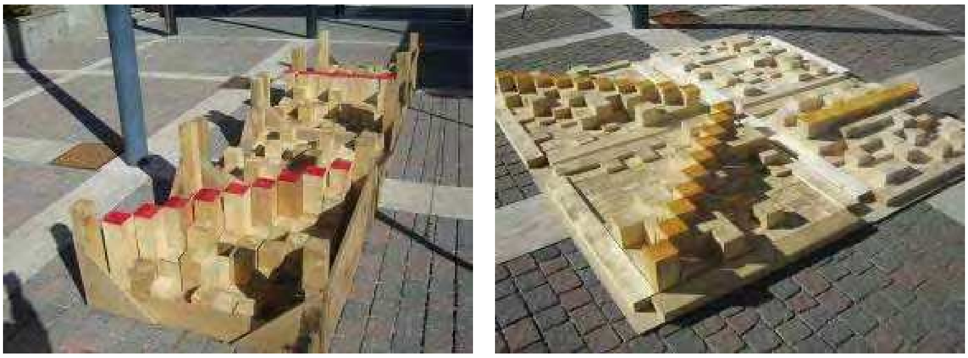

Fig. 2. Step Fields Provide Reproducible Terrain Challenges

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 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.

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

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.

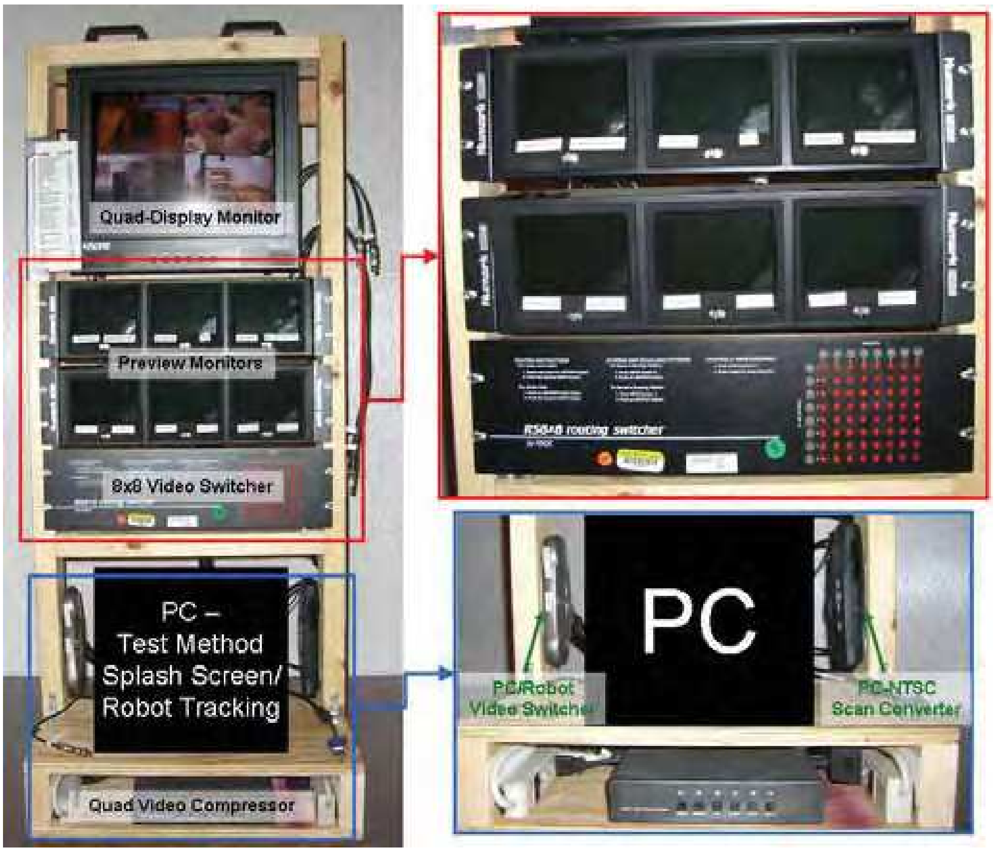

Fig. 4. Quad Audio/Video Control and Display Hub

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

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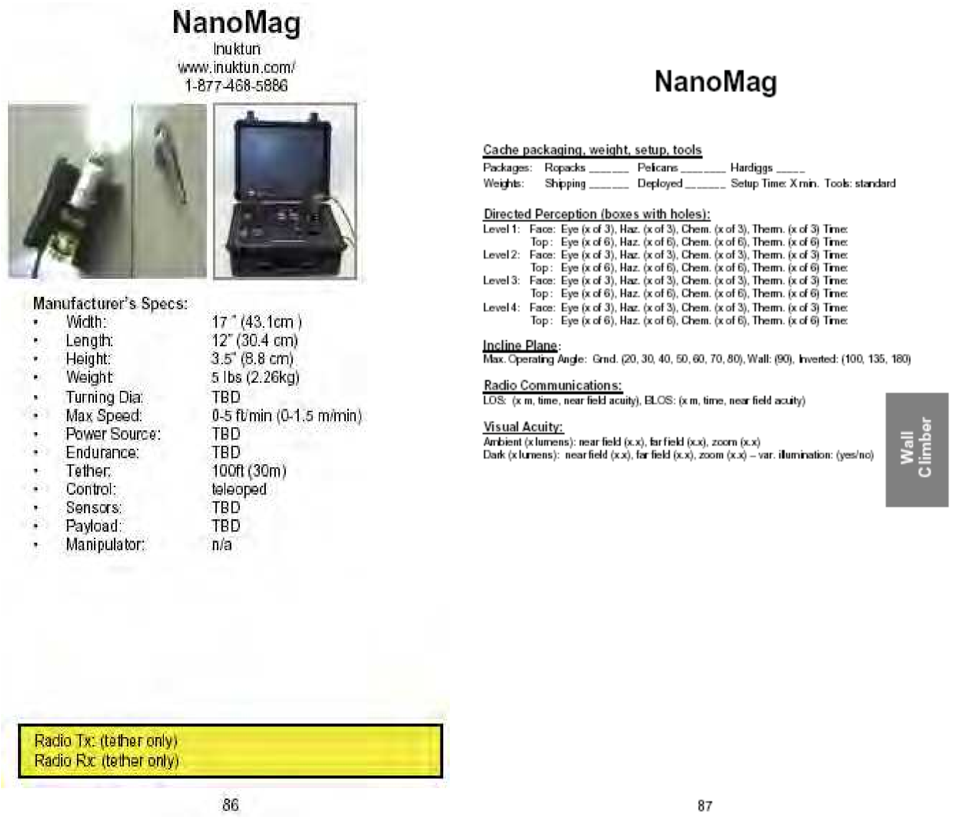
[1] Certain commercial software and tools are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the tools identified are necessarily the best available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



NanoMag

Inuktun
www.inuktun.com/
1-877-468-5886

Manufacturer's Specs:
- Width: 17 " (43.1cm)
- Length: 12" (30.4 cm)
- Height: 3.5" (8.8 cm)
- Weight: 5 lbs (2.26kg)
- Turning Dia: TBD
- Max Speed: 0-5 ft/min (0-1.5 m/min)
- Power Source: TBD
- Endurance: TBD
- Tether: 100ft (30m)
- Control: teleoped
- Sensors: TBD
- Payload: TBD
- Manipulator: n/a

Radio Tx: (tether only)
Radio Rx: (tether only)

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NanoMag

Cache packaging, weight, setup, tools
Packages: Ropacks ______ Pelicans _______ Hardiggs _____
Weights: Shipping ______ Deployed ______ Setup Time: X min. Tools: standard

Directed Perception (boxes with holes):
Level 1: Face: Eye (x of 3), Haz. (x of 3), Chem. (x of 3), Therm. (x of 3) Time:
Top : Eye (x of 6), Haz. (x of 6), Chem. (x of 6), Therm. (x of 6) Time:
Level 2: Face: Eye (x of 3), Haz. (x of 3), Chem. (x of 3), Therm. (x of 3) Time:
Top : Eye (x of 6), Haz. (x of 6), Chem. (x of 6), Therm. (x of 6) Time:
Level 3: Face: Eye (x of 3), Haz. (x of 3), Chem. (x of 3), Therm. (x of 3) Time:
Top : Eye (x of 6), Haz. (x of 6), Chem. (x of 6), Therm. (x of 6) Time:
Level 4: Face: Eye (x of 3), Haz. (x of 3), Chem. (x of 3), Therm. (x of 3) Time:
Top : Eye (x of 6), Haz. (x of 6), Chem. (x of 6), Therm. (x of 6) Time:

Incline Plane:
Max. Operating Angle: Grnd. (20, 30, 40, 50, 60, 70, 80), Wall: (90), Inverted: (100, 135, 180)

Radio Communications:
LOS: (x m, time, near field acuity), BLOS: (x m, time, near field acuity)

Visual Acuity:
Ambient (x lumens): near field (x.x), far field (x.x), zoom (x.x)
Dark (x lumens): near field (x.x), far field (x.x), zoom (x.x) – var. illumination: (yes/no)

Wall Climber

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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.*