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A Robot Ontology for Urban Search and Rescue

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ABSTRACT
The goal of this Robot Ontology effort is to develop and begin to populate a neutral knowledge representation (the data structures) capturing relevant information about robots and their capabilities 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. This knowledge representation must be flexible enough to adapt as the robot requirements evolve. As such, we have chosen to use an ontological approach to representing these requirements. This paper describes the Robot Ontology, how it fits in to the overall Urban Search and Rescue effort, how we will be proceeding in the future.

Keywords
Robot ontology, urban search and rescue, OWL, Protégé

1. INTRODUCTION AND RELATED WORK
The goal of this Robot Ontology effort is to develop and begin to populate a neutral knowledge representation (the data structures) capturing relevant information about robots and their capabilities 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. This knowledge representation must be flexible enough to adapt as the robot requirements evolve. As such, we have chosen to use an ontological approach to representing these requirements.

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 (US&R). These efforts have been leveraged in this work and include:

- Efforts to determine the information requirements for a US&R ontology performed at the University of Electro-Communications in Tokyo, Japan [5],
- Efforts to develop a Mobile Robot Knowledge Base at SPAWAR [8],
- Efforts at the Center for Robot Assisted Search and Rescue (CRASAR) in the development of taxonomies for robot failures [4] and issues pertaining to social interactions between robots and humans [3].

This paper is organized as follows. Section 2 describes the goal of the overall Department of Homeland Security (DHS) Urban Search and Rescue (US&R) effort and shows how the robot ontology fits in. Section 3 describes the requirements generated from a series of workshops that serve as the basis for the robot ontology. Section 4 summarizes the building blocks that were used in developing the ontology shows some related efforts. Section 5 discusses the structure of the ontology. Section 6 discusses the ontology status and Section 7 concludes the paper.

2. BACKGROUND OF US&R EFFORT
In an effort to accelerate the development and deployment of robotic tools for urban search and rescue responders, the National Institute of Standards and Technology (NIST) has begun the process of developing test methods for robotic technologies applied to US&R requirements. This effort will foster collaboration between US&R responders and technology developers to define performance metrics, generate standard test methods, and instrument test sites to capture robot performance in situationally relevant environments. The results of these standard performance tests will be captured in a compendium of existing and developmental robots with classifications and descriptors to differentiate particular robotic capabilities. This, along with ongoing efforts to categorize situational US&R constraints such as building collapse types or the presence of hazardous materials, will help responders match particular robotic capabilities to response needs. In general, these efforts will enable responders to effectively use robotic tools to enhance their effectiveness while reducing risk to personnel during disasters.

There are several possible ways to enhance the effectiveness of emergency responders through technology. Standardized test methods generated directly from responder requirements can ensure that applicable technologies are relatively easy to use, integrate efficiently into existing infrastructure, and provide demonstrable utility to response operations. Studies on ways to improve effectiveness of US&R and other responders have identified robots as potentially high-impact solutions. The DHS Federal Emergency Management Agency (FEMA) and the National Institute of Justice (NIJ) co-sponsored an effort to identify and define functional requirements for new and/or improved technologies that meet the needs of both US&R teams as well as law enforcement agencies. The report [1] listed high priority needs, which included: "Reliable non-human, non-canine search and rescue systems - robust systems that combine enhanced canine/human search and rescue capabilities without existing weaknesses (i.e., robots)"

Table 1: Potential Robot or Deployment Categories

	Robot Category	Employment Role(s)	Deployment Method(s)
1.	Ground: Peek Robots	Provide rapid audio visual situational awareness; provide rapid HAZMAT detection; data logging for subsequent team work	Tossed, chucked, thrown pneumatically, w/surgical tubing; marsupially deployed
2.	Ground: Collapsed Structure--Stair/Floor climbing, map, spray, breach Robots	Stairway & upper floor situational awareness; mitigation activities; stay behind monitoring	Backpacked; self driven; marsupially deployed
3.	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	Backpacked; self driven; marsupially deployed
4.	Ground: Wall Climbing Deliver Robots	Deliver Payloads to upper floors; provide expanded situational awareness when aerial platforms are unavailable or untenable	Placed; thrown pneumatically, w/surgical tubing; marsupially deployed
5.	Ground: Confined Space, Temporary Shore Robots	Adaptive, temporary shoring; provide stay behind monitoring; victim triage & support	Placed: lowered via tether
6.	Ground: Confined Space Shape Shifters	Search; provide stay behind monitoring	Placed; lowered via tether
7.	Ground: Confined Space Retrieval Robots	Retrieve objects from confined spaces; provide stay behind monitoring	Placed; lowered via tether
8.	Aerial: High Altitude Loiter Robots	Provide overhead perspective & sit. awareness; provide HAZMAT plume detection; provide communications repeater coverage	Released: balloon or F/W; tethered LTAF (kite)
9.	Aerial: Rooftop Payload Drop Robots	Payload delivery to rooftops; provide overhead perspective; provide communications repeater coverage	Launched F/W; tethered LTAF (kite)
10.	Aerial: Ledge Access Robot	Object retrieval from upper floors; crowd control with a loudspeaker object attached, provide situational awareness	Launched Vertical Take-off and Landing (VTOL)
11.	Aquatic: Variable Depth Sub Robot	Structural inspection; leak localization/mitigation; object (body) recovery	Dropped into water; lowered via tether
12.	Aquatic: Bottom Crawler Robot	Water traverse; rapid current station keeping; object recovery	Driven across water; lowered via tether
13.	Aquatic: Swift Water Surface Swimmer	Upstream access and station keeping; payload delivery; object recovery	Dropped into water; marsupially deployed

Standard test methods generated from explicit requirements for US&R robots, with objective performance metrics and repeatable performance testing, will accelerate the development and deployment of mobile robotic tools for US&R responders. Currently, no such standards or performance metrics exist, although some guidelines for performance, capabilities, and human-system interactions have been identified [2,6].

In order to address this need, the DHS Science and Technology (S&T) Directorate initiated an effort in fiscal year 2004 with NIST to develop comprehensive standards to support development, testing, and certification of effective robotic technologies for US&R applications. These standards will address robot mobility, sensing, navigation, planning, integration into operational caches, and human system interaction.

Such standards will allow DHS to provide guidance to local, state, and federal homeland security organizations regarding the purchase, deployment, and use of robotic systems for US&R applications.

The NIST team working toward developing these standard test methods is closely following the guidance provided by the above-mentioned studies. This effort builds on requirements voiced by US&R responders and focuses on fostering collaboration between the responders, robot vendors, and robot developers to generate consensus standard tests for task-specific robot capabilities and interoperability of components.

3. REQUIREMENTS DEFINITION

The process to define US&R robot performance requirements began by assembling a group of subject matter experts, primarily FEMA Task Force leaders and specialists. Representatives from most FEMA Task Forces participated in some or all three workshops held to define initial performance requirements for the robots.

Urban search and rescue teams are comprised of a large number of individual specialists who perform specific functions. The search and rescue operation itself is divided into several phases, which are roughly sequential in order, although some may be carried out in parallel. Basic responsibilities during a rescue effort were identified as reconnaissance, primary search, structural assessment, stabilization, medical, rescue, monitoring, hazardous materials, and others. During the course of the first workshop, the working group identified two particular roles, reconnaissance and primary search, as the two highest priorities for applying robots.

By the third workshop, a more detailed set of situations was needed to stimulate the responders to fully consider how the robots would be used in reality, and to make sure everyone was envisioning the same thing. Thirteen initial robot categories were adopted to provide this focus. The number of categories and their definitions are expected to change as the program evolves. A version is shown in Table 1.

Table 2: Main Requirement Categories

Requirements Category	Number of Individual requirements	Category Definition
Human-System Interaction	23	Pertaining to the human interaction and operator(s) control of the robot
Logistics	10	Related to the overall deployment procedures and constraints in place for disaster response
Operating Environment	5	Surroundings and conditions in which the operator and robot will have to operate
System		Overall physical unit comprising the robot. This consists of the sub-components below
- Chassis	4	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	5	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	12	The ability of the robot to negotiate and move around the environment
- Payload	7	Any additional hardware that the robot carries and may either deploy or utilize in the course of the mission
- Power	5	Energy source(s) for the chassis and all other components on board the robot
- Sensing	32	Hardware and supporting software which sense the environment

These are not necessarily meant to define specific robotic implementations desired for US&R, since it is premature to make these decisions. However, some of them may in fact provide reasonable approximations of robotic capabilities that will be identified by responders as “high priority” while being considered “fieldable” in the near term by developers. This combination of high priority and technical availability will be targeted for Wave 1 test methods.

In addition to the robot categories, the workshops produced a total of 103 performance requirements by the responders. The requirements fit into the major categories listed in Table 2. The requirements will grow and change with further input from responders and vendors.

Through a series of detailed analysis (outside the scope of this paper), 26 of the 103 performance requirements were identified as high priority, and therefore became the initial focus of the effort. These 26 performance requirements are listed below:

- **Adjustable Illumination** - expectation to use video in confined spaces and for short-range object identification, which can wash out from excessive illumination of the scene.
- **Beyond Line Of Sight Range** - expectation to project remote situational awareness into compromised or collapsed structures or to convey other types of information.
- **Secure Communication** - expectation to use this system in sensitive public situations where maintaining control of remotes systems is imperative and limiting access to video images and other communications to authorized personnel is prudent.
- **Line-Of Sight Communications** -expectation to project remote situational awareness or to convey other types of information down range within line of sight.
- **Initial Training Requirements** - expectation to minimize the initial training necessary to become proficient in operation of the system.
- **Proficiency Education** - expectation to minimize the annual proficiency training necessary to maintain certification.
- **Operator Ratio** - expectation to minimize the number of operators necessary to operate any given system and perform the associated tasks effectively.
- **Acceptable Usability** - expectation to operate any given system to perform the associated tasks effectively.
- **Lighting Conditions** - expectation to view and use the operator console in different lighting conditions.
- **Use With Protective Clothing** - expectation to be operating the system while wearing personal protective equipment such as gloves, helmet, eye protection, ear protection, etc.
- **Effectiveness of Dashboard** - expectation to monitor general system health and status (e.g. orientation, communication strength, power level, etc.).
- **Weight** - expectation to move and store all equipment using existing methods and tools.
- **Mean Time Between Failures** - expectation to use all equipment for the entire duration of a deployment
- **Setup Time** - expectation to move, unpack, and assemble all equipment to a ready state using existing methods and tools.
- **Volume Per Container** - expectation to move and store all equipment using existing methods and tools.
- **Spares and Supplies** - expectation to be self-sustaining for 72 hours without re-supply from outside the base of operations.
- **Maintenance Duration -** expectation to minimize the amount of time required to perform routine maintenance operations in the field, potentially in-situ on a rubble pile or other awkward location.
- **Maintenance Tools** - expectation to minimize the need for specialized tools to perform field maintenance at the base of operations.
- **Maintenance Intervals** - expectation to minimize the mean time between required field maintenance performed at the base of operations.
- **Water Operation** - expectation to minimize the mean time between required field maintenance performed at the base of operations.
- **Working Time** - expectation to maintain operations beyond basic mobility requirements within a given terrain type.
- **Power Sustainment** - expectation to maintain operations in the field before re-supply of power is needed.
- **Power Runtime Indicator** - expectation to manage power resources to effectively plan mission durations, points of no return, and other important power considerations.
- **Color Video System Acuity (Near)** - expectation to use video for key tasks such as maneuvering (hence the real-time emphasis), object identification (hence the color emphasis), and detailed inspection (hence the emphasis on short-range system acuity).
- **Color Video System Acuity (Far)** - expectation to use video for key tasks such as maneuvering (hence the real-time emphasis), object identification (hence the color emphasis), and path planning (hence the emphasis on long-range system acuity).
- **Color Video Field of View** - expectation to use real-time video for a variety of tasks.

With these requirements in hand, the next step was to model these requirements in 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
- Available 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 addition information.

The benefits of having a robot ontology are numerous. In addition to providing the data structures to representation 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 current status of the robot ontology, including information about the technologies it is built off of and the way that it is structured.

4. BACKGROUND

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 following technologies:

4.1 OWL/OWL-S

We decided to use the OWL-S upper ontology [10] 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 DARPA Agent Markup Language (DAML) program, is based on OWL [7]. 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:

- 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.

4.2 Protégé

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 [9]. 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 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 tools.

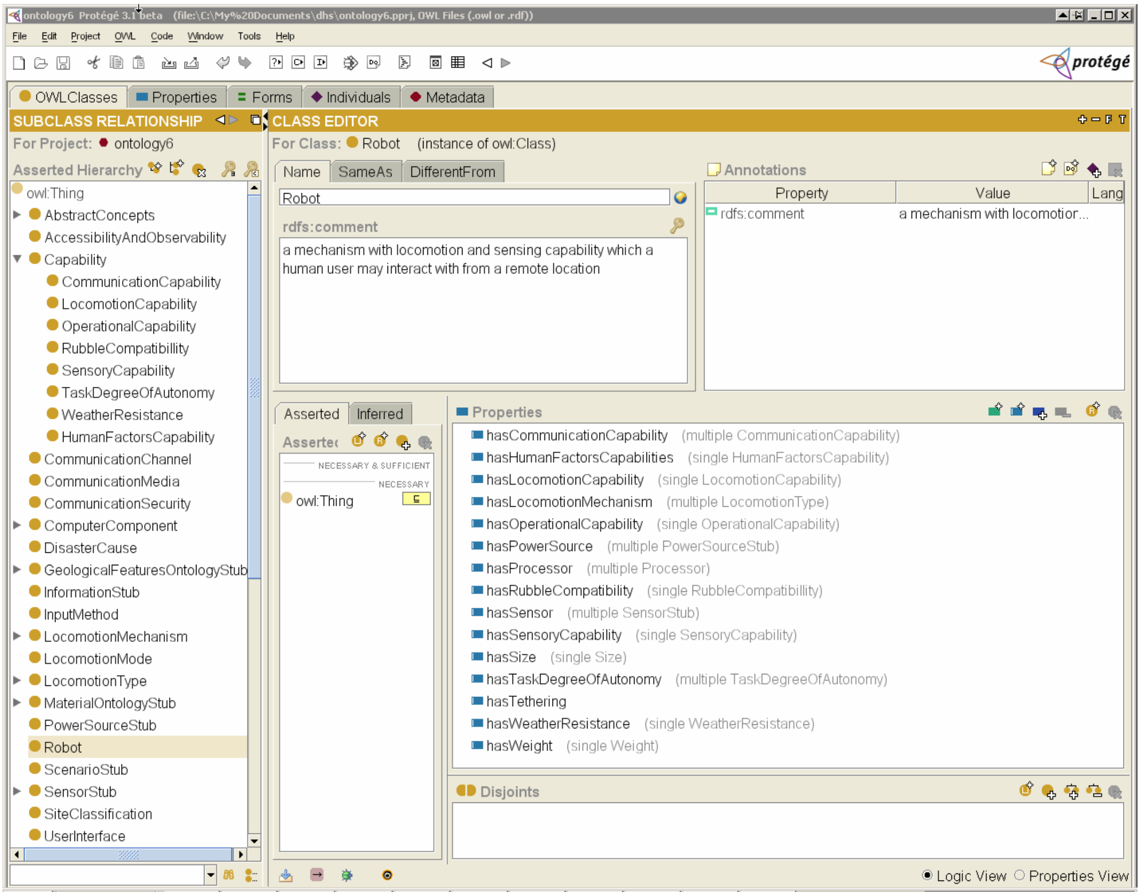

Figure 1: The Robot Ontology

5. ONTOLOGY STRUCTURE

To capture the requirements discussed in Section 3, an initial structure for the Robot Ontology has been developed. As mentioned earlier, the Robot Ontology has been captured in the Protégé tool. A screenshot of Protégé is shown in Figure 1. 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 (with the blue boxes on left) show the attributes that are associated with the highlighted class (Robot). Robots have attributes such as hasCommunication Capability, hasHumanFactorsCapabilities, hasLocomotionCapabilities, etc. Each one of these attributes may point to 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

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
- Weight
- Tethering
- Power Source
- Locomotion Mechanism (wheeled, walking, crawling, jumping, flying, etc.)
- Sensors (e.g., camera, FLIR, LADAR, SONAR, GPS, Audio, Temperature Sensor)
- Processors

Many of the above are direct attributes of the robot class. The robot class and its attributes are shown in Figure 1. Another

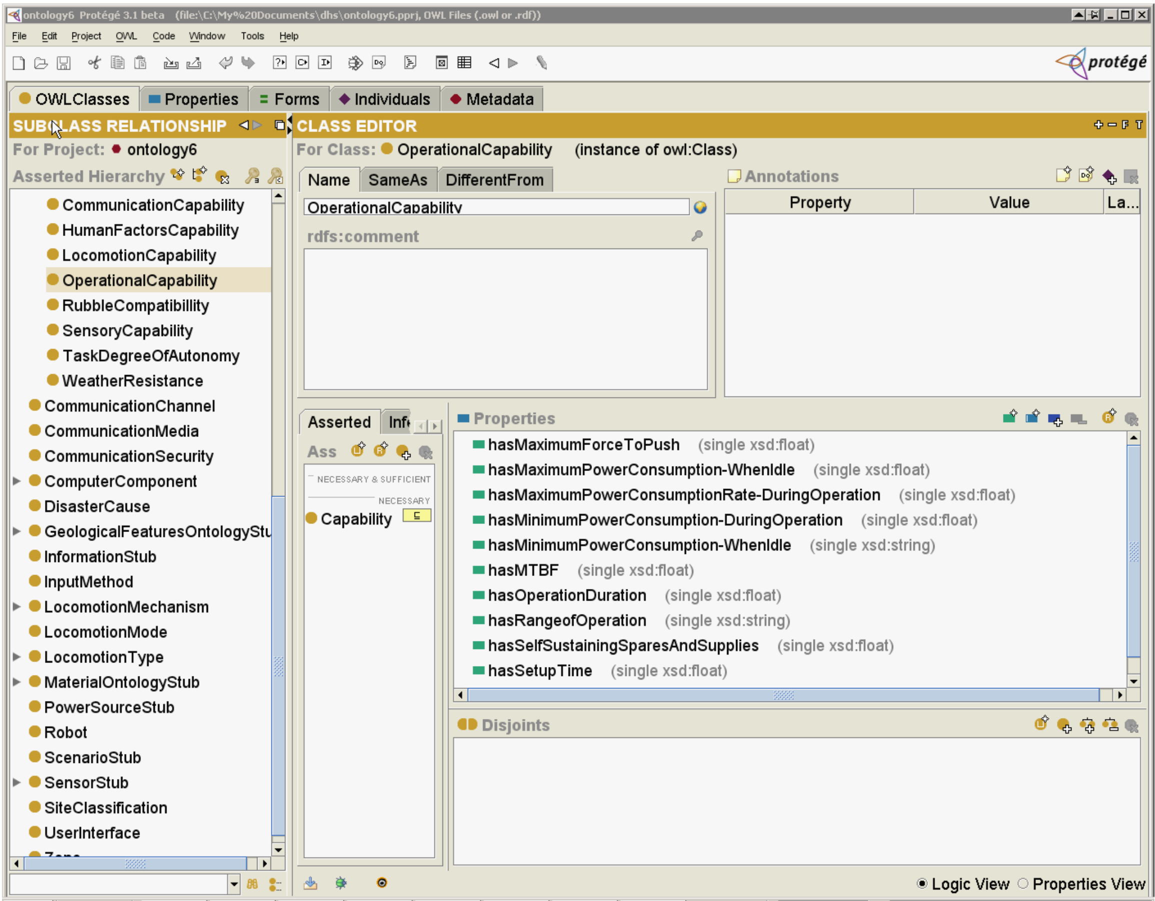

Figure 2: Operational Capability Attributes

important thing to notice in Figure 1 are the classes that end in the word "stub". These are meant to be placeholders to integrate in more establish (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)

Figure 2 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. 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 (e.g., float, string, Boolean).

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 size)
- Intra-Group Interaction (i.e., interaction with other similar robots)
- Inter-Group Interaction (i.e., interaction with other 3rd party robots or computers)

Figure 3 shows an example of the human factors attributes that may be associated with a robot.

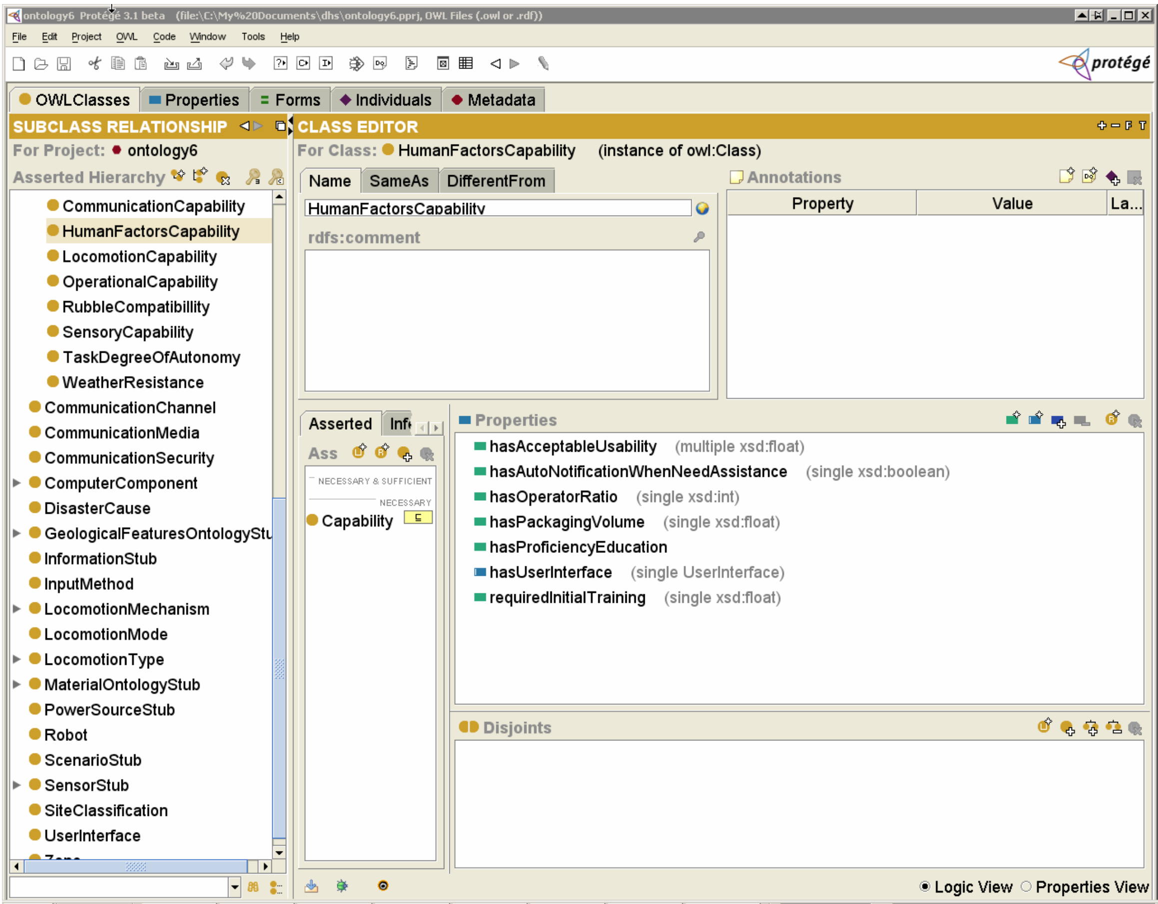

Figure 3: Human Factors Attributes

6. STATUS AND CONCLUSION

The paper describes our progress in developing a robot ontology for US&R. 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 Source
    - Materials
    - Environment
- Continue to incorporate the requirements from the requirements workshops into the robot ontology structure
- Explore the use of reasoning engines to suggest robots as well as configurations (e.g., sensors to be mounted) for different situations

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