Ontological Perspectives for Autonomy Performance

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ABSTRACT

Goals must be assigned for any unmanned system's (UMS) operation before the system's autonomous performance can be measured. This paper reports the early results of construction of an ontology for mission goals that could serve as a template for stating the goal. The Autonomy Levels for Unmanned Systems (ALFUS) Framework is a key element in the ontology. In other words, we design the goal ontology in terms of mission, environment, and operator interaction aspects. We also leverage a collection of related efforts to further evolve the goal ontology, including the Urban Search and Rescue (US&R) robots requirements set, the Perception System for Dynamic Manufacturing, and an extension to the NIST-participated Defense Advanced Research Projects Agency (DARPA) Spoken Language Communication and Translation System for Tactical Use (TRANSTAC) project.

Categories and Subject Descriptors

J.2 [physical sciences and engineering] *ontology, unmanned systems performance*

General Terms

Measurement, Performance, Design, Human Factors, Standardization, Verification

Keywords

ALFUS, communication, environment, goal, manufacturing, metrics, mobility, ontology, sensor, terminology, urban search and rescue (US&R)

1. INTRODUCTION

Unmanned systems (UMSs) have been playing increasingly important roles in many aspects of the society. In a broad sense, UMS includes the unmanned vehicles that aid military operations, the robots that aid bomb disposal tasks, the robots that help the search and rescue operations, and the automation machine systems that perform the part manufacturing and assembly tasks. It is vital for practitioners to be able to model the systems and measure their performances.

We propose to develop an ontology for a generic UMS. The ontology should provide a comprehensive and structural organization for the UMS knowledge, including the hardware, software, interfaces, performance, etc. Figure 1 provides an overview. All the aspects must be defined and formally related.

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Typically, a UMS is to perform goals that the operator assigns. Many issues need to be addressed, including how to acquire a UMS that fits the needs, how to state the goals to allow precise execution, how to evaluate the performance, etc. We envision the ontology to be able to provide all these features for practitioners.

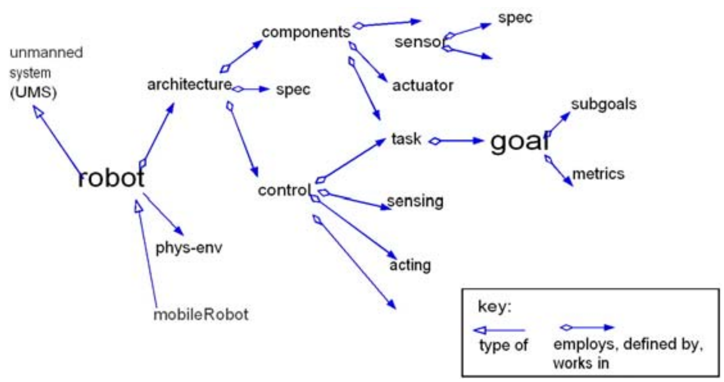

Figure 1: High Level View of the Ontology

The development effort is underway. This paper describes the first increment of results from this effort.

1.1 Scope of the Ontology

This paper describes the development of a particular subset of the ontology, the UMS goal. Given the fact that UMSs may be commanded to perform different types of tasks, it is important to devise a sound approach to knowledge acquisition and organization. Our plan is to develop a structure such that the generic aspects can be instantiated and applied to different applications. We also describe how performance metrics are included in the ontology and are measured by comparing the metrics and the goal.

1.2 Aspects of the Ontology

In the area of information technology, we define ontology as a rigorous or formal model that encompasses a collection of concepts and their relationships for the topic of interest [1, 2, 3, 4, 5, 6, 7]. As such, we propose that ontology should cover the following aspects:

- Terminology and definitions
- Requirements/capability attributes
- Performance metrics

- Engineering specifications
- Standards

In other words, to develop an ontology for a topic, the engineer should:

- identify the key concepts from the terms and definitions used in the domain,
- identify the user, capability, and performance requirements for the program, and
- utilize engineering specifications and applicable standards for the UMS and its subsystems and components.

In this first increment for development of a UMS ontology, we begin with the terminology, metrics, and requirements aspects and leave the others for future development.

1.3 Performance Metrics—ALFUS Framework Overview

The performance of UMS must be measured in terms of the assigned goals. It is desirable to have a generic and standard structure for stating the goal. There are multiple concerns in the goal statement, including operation (or mission), environment, and operator interactions. These lead us to apply the Autonomy Levels for Unmanned Systems (ALFUS) Framework that NIST has been developing [8]. The ALFUS Framework describes that the autonomy of a UMS can be characterized with Contextual Autonomous Capability (CAC). The CAC model is composed of the following three aspects (or axes), Mission Complexity (MC), Environmental Complexity (EC), and Human Independence (HI), as shown in Figure 2. Each axis is further decomposed into a set of performance metrics.

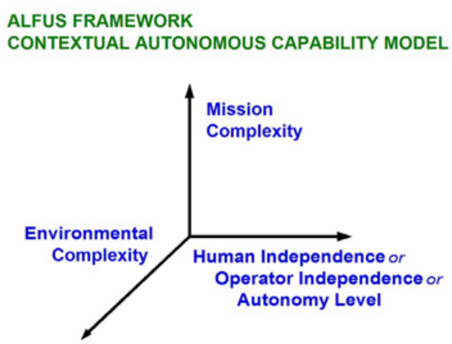

Figure 2: The ALFUS Framework

The ALFUS Framework was developed originally by the ad hoc ALFUS Working Group (WG) that was lead by NIST. The group has later joined the Society for Automotive Engineers (SAE), a standards development organization, as the UMS Performance Measures Subcommittee.

During the first ALFUS workshop, it was determined that the first objective of the group should be terminology [9]. This is because the ALFUS WG decided to take a definition-based approach. The fundamental terms, including autonomy and UMS were defined. The key words and their relationships were further developed into additional terms, sub-relationships, as well as metrics. This fits well with the ontology concept. Figure 3 illustrates this construct.

The MC metrics correspond to, among other aspects, the accuracy and repeatability aspects of a goal. The EC metrics correspond to the spatial and temporal aspects of the goal statement. Human interaction may be critical in assisting the robot to reach a safe state or to reach the goal.

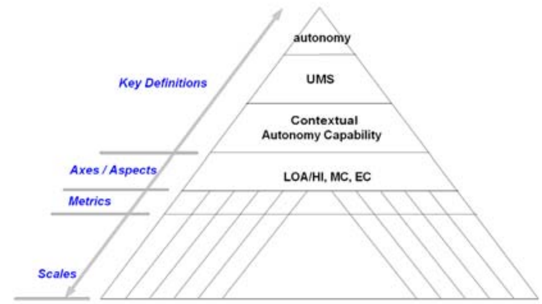

Figure 3: ALFUS Framework Structure

1.4 The Involved Use Cases and Concepts

In the three project activities that we use to further evolve this ontology, the US&R robots project has generated a comprehensive requirements set through intense interactions with the user community. The perception system for dynamic manufacturing project also derived a set of requirements from a workshop attended by the industry. We use these results to iterate the goal ontology. The TRANSTAC project uses a System, Component, and Operationally-Relevant Evaluation (SCORE) approach to evaluate the candidate systems. We began to apply some of the key concepts of SCORE in formulating the ontology [10, 11].

2. PERFORMANCE CHARACTERISTICS AND REQUIREMENTS

The performance characteristics or requirements of various UMS systems were analyzed and pertinent elements were extracted for the development of the ontology, namely, the ontological model of the mission goal for UMS. The following described two use cases.

2.1 Teleoperation Requirements for US&R

Federal Emergency Management Agency (FEMA) US&R Task Force personnel would be among the users who would teleoperate the robots for search and rescue operations. Figure 4 provides an example of the types of terrain which the US&R robots might have to traverse [11, 12].

The users conveyed to the NIST project team how they anticipate the robotic technology could help them. This typifies the interaction between users and technologists who may be implementing the requirements. The entire set of the requirements can be seen in [13]. The existent ontology work in this area includes [14, 15].

Figure 4: Rubble Pile that Robots Might have to Traverse

For this development effort, we examine a subset of the requirements and attempt to restructure them to facilitate the ontology implementation. We also apply engineering disciplines to attempt to explore further details of Requirements. Table 1 illustrates our analysis effort, with the left column stating a subset of the Requirements and the right column listing the robotic functions or subsystems that are involved to fulfill the requirements. The intent is to organize the robotic knowledge through the ontology.

Requirement	**Involved UMS Functions**
To project remote situational awareness (SA), beyond line of sight, into compromised or collapsed structures or to convey other types of information; or be able to operate around corners of buildings; as such, SA for near, far, and field of view are required	Video, command and control signals in tight space
To enable use of video in confined spaces and for short-range object identification, which can wash out from excessive illumination of the scene; therefore, adjustability is required	Variable illumination
To support the SA, the robot should be able to ingress a specified number of meters into the worst case collapse, a reinforced steel structure	Maneuver within tight space
To use this system in sensitive public situations where maintaining control of remote systems is imperative and limiting access to video images and other communications to authorized personnel is prudent; should be shielded from jamming interference and encrypted for security	Security
To project remote situational awareness or to convey other types of information down range within line of sight	Video, command and control over long range

Table 1: Mapping of Requirements to US&R UMS Functions

Beyond this example, we reviewed several other Requirements observing that, overall, the following features are keys to the US&R robotic operations:

- Situation awareness facilitation
- Maneuvering in tight space
- Radio link for video and command and control data
- Usability to the operator
- Minimum training
- System monitoring
- Sufficient power supply
- Compatible with current logistics system

These are to be reflected in the ontology work.

2.2 Requirements for Next Generation Manufacturing

An impediment to advancing manufacturing to its next level is lack of adequate sensors and perception systems, because the involving environments would be dynamic and unstructured. Therefore, dynamic metrology is a key technology. Those perception systems must be comprehensive, pervasive and providing redundancy. In scenarios such as a robot grasping a moving part off an assembly line, a single, narrowly focused sensor will not be sufficient. The sensor may fail, may not be robust enough for the task, may not sense other objects that could become obstacles, or may not be able to adequately sense humans in the workspace to prevent accidents. Perception for such scenarios would require sensor fusion and control logic to facilitate arbitrations among multiple subsystems.

To further discuss the roles and requirements of advanced sensor and perception for the future manufacturing, a workshop was held in October, 2007, which brought together people from Government, industry and academia [16]. A number of the participants indicated that the ability to measure the positions and orientations (6DOF) of components in dynamic environment would result in considerable cost savings in applications such as automobile manufacturing. The installations with more intelligent combinations of sensing and automation will better enable US manufacturers to compete globally. They also called for reference standards, as those would assist the community in establishing clear performance metrics for systems and algorithms.

All these requirements were collected and will be incorporated into a comprehensive robotic ontology. One section of the ontology deals with sensors. A generic sensor includes major attributes of sensing function, sensing target, and sensor specification. Figure 5 provides an illustration of this model using the Protégé tool[1]. Each of the attributes is further elaborated. For example, sensing targets include the properties of spatial-

[1] Disclaimer: Certain trade names and company products are mentioned in the text or identified in certain illustrations to facilitate communication. In no case does such an identification imply recommendation or endorsement by the NIST, nor does it imply that the products are necessarily the best available for the purpose

temporal, chemical, climate, kinematic, etc. This effect is illustrated in Figure 6, using the same tool. Specifications may include speed, drift, resolution, etc. The generic structure, as represented in an ontology, allows the information for specific sensors to be recorded. This ontology will serve as a knowledge base or as a tool for a sensory requirements analysis. It will also be useful in standardizing terminology for robots and sensors and in understanding the application of metrics and standards.

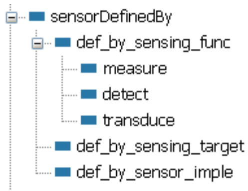

Figure 5: Ontological Model for Sensor Definition

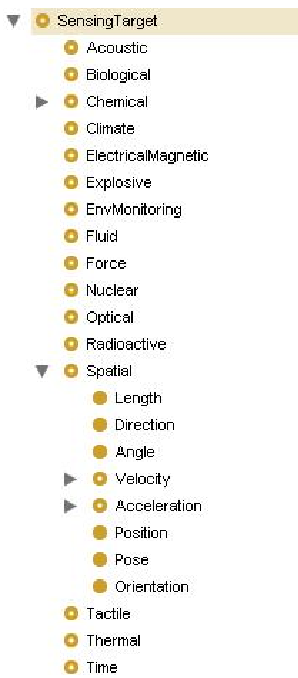

Figure 6: Ontological Model for Sensing Targets

3. ONTOLOGY: ELEMENTARY FEATURES

The previous sections have described the project requirements and the metrics model. Now we will focus on developing the ontology that encompasses those aspects. We first defined sets of fundamental references and relationships that are used to develop the UMS ontology.

3.1 Relationships

Two types of fundamental relationships are defined to associate the ontological entities. These relationships are further subtyped and instantiated to form hierarchical structures.

- Part-whole: *partOf*

  This relationship can be further instantiated to specific needs. The following are two subsets:

  Physical Subtypes: *enclosedBy, boundedBy, composedOf*

  Logical Subtypes: *controlledBy, integratedIn, boundedBy, composedOf*

  These can be further instantiated for particular applications. There are also issues of mapping of numbers (a car is composed of auto parts), complementary active and passive relationships (*composedOf* and *consistOf*).

- Peer: *associatedWith*

  Physical Subtypes: *connectedWith*

  Logical Subtypes: *interfaceWith, integratedWith*

- Generalization/specialization: *typeOf*
- Requirement: *required, optional; and, or*

3.2 Spatial Aspect

3.2.1 References

- *distance, pose, area, tolerance typeOf spatial_feature*
  - *position partOf pose*
  - *orientation partOf pose*
    - *coordinate partOf position*
    - *angle partOf orientation*
  - *coordinate partOf area*
- *range typeOf distance*

3.2.2 Environmental Features

- *object_class typeOf spatial_feature*
  - *ground_ object_class typeOf object_class*
  - *maritime_object_class typeOf object_class*
  - *aerial_ object_class typeOf object_class*

3.3 Temporal Aspect

- *time, tolerance typeOf temporal_feature*
- *duration typeOf temporal_feature*

3.4 Spatial and Temporal

- *speed typeOf temporal_feature and spatial_feature*
- *acceleration typeOf temporal_feature and spatial_feature*

4. GOAL FOR UMS

We began to generate an ontology for the concept of mission goal for the UMS. The identification of the goal attributes is facilitated through the project requirements as described in Section 3. The hierarchical layout of the section headings reflects the structure of the ontology. The mission goal is composed of the subgoals for the subsystems. The subgoals cover operational, environmental, and operator aspects.

Given the fact that UMSs may be commanded to perform vastly different types of tasks, our bottom-up approach is to develop a structure and ontological attributes that might be generic to certain applications. As such, the following subsections describe what is equivalent to an illustrative goal ontology suitable for a particular set of applications. Different types of applications may need separate sets of the ontology.

4.1 Subgoal for Mobility Subsystem

A UMS includes a mobility system. Therefore, the following is modeled:

mobility subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *mobility_goal partOf UMS_goal*
  - *pose partOf mobility_goal*
  - *object_class partOf mobility_goal*
  - *time partOf mobility_goal*
  - *duration partOf mobility_goal*
  - *speed partOf mobility_goal*
  - *acceleration partOf mobility_goal*
  - *mobility_goal boundedBy tolerance*

4.2 Subgoal for Sensor Subsystem

A UMS typically includes a sensor system. Therefore, the following is modeled:

sensor subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *sensory_goal partOf UMS_goal*
  - *range partOf sensory_goal*
  - *frequency partOf sensory_goal*

4.3 Subgoal for Communication Subsystem

A UMS typically includes a communication system. Therefore, the following is modeled:

communication subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *comm_goal partOf UMS_goal*
  - *cover_range partOf comm_goal*
  - *set_bandwidth partOf comm_goal*
  - *receive_send_line_of_sight partOf comm_goal*

4.4 Subgoal for Power Subsystem

A UMS typically includes a power system. Therefore, the following is modeled:

power subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *power_subgoal partOf UMS_goal*
  - *set_peak_power_output partOf power_subgoal*
  - *save_min_power partOf power_subgoal*

4.5 Subgoal for Mission Package Subsystem

A robot typically carries additional subsystems beyond the platform. They may be manipulators, tools, special sensors, weapon, etc. Subgoals must be developed for them.

mission package integratedWith UMS

The subsystem's goal can be modeled as:

- *mission_subgoal partOf UMS_goal*
  - *identify_victim partOf mission_subgoal*
  - *assemble_door partOf mission_subgoal*
  - *establish_observation_post partOf mission_subgoal*
  - *translate_text partOf mission_subgoal*

4.6 Subgoal for Chassis Subsystem

A UMS includes a chassis system. Therefore, the following is modeled:

chassis subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *chassis_goal partOf UMS_goal*
  - *set_illumination_intensity partOf chassis_goal*

4.7 Subgoal for Human-Robot Interaction (HRI) Subsystem

A UMS includes a HRI system. Therefore, the following is modeled:

HRI subsystem integratedWith UMS

The subsystem's goal can be modeled as:

- *HRI_goal partOf UMS_goal*
  - *sound_alarm partOf HRI_goal*
  - *display_health_status partOf HRI_goal*

4.8 Collaboration

A UMS goal may be to collaborate with other systems. The subsystems of a UMS may need to collaborate among themselves.

- *collaboration_subgoal partOf UMS_goal*

The subsystem's goal can be modeled as:

  - *wait_until partOf collaboration_subgoal*
  - *synchronize_with partOf collaboration_subgoal*

Note that the performance metrics for the collaboration will be described later in this paper.

4.9 Prioritization and Management

The UMS entities may be given multiple goals. The entities may receive multiple goals from their collaborators.

- *manage_goals partOf UMS_goal*
  - *multi-tasking partOf manage_goals*
  - *prioritize_goals partOf manage_goals*

- *value partOf prioritize_goals*
  - *costs partOf prioritize_goals*

Note that being able to prioritize the goals would enhance the autonomous performance of the UMS.

4.10 Additional Subgoals

Additional subsystems may be employed and the subgoals should be identified.

5. ALFUS METRICS

As described earlier, the definition of performance metrics is an important aspect of the UMS knowledge and, therefore, it is a part of the ontology. We have developed the autonomous performance of UMS using the ALFUS metrics.

- *Autonomy_performance partOf UMS_performance*
  - *MC partOf Autonomy_performance*
    - *{ subtasks_structure, precision, repeatability, uncertainty, safety_level, risk_level } partOf MC*
    - *{ control_echelon, interoperability, knowledge_shared } partOf MC*
    - *{ situation_analysis, replans } partOf MC*
    - *{ perception } partOf MC*
  - *EC partOf Autonomy_performance*
    - *solution ratios partOf EC*
    - Scale: No impediment, one impediment out of N *possibilities*, (N-1) out of N, n out of N, N out of N
    - *solution_difficulty_levels partOf EC*
    - *{ energy consumption levels, computation load levels, look-ahead ability } partOf solution_difficulty_levels*
  - *HI partOf autonomy_performance*
    - *{ % of plan generated by UMS, % of plan pre-generated, % of plan execution that operator is involved, % of robot vs. operator initiated interactions, required training, workload } partOf HI*

6. GOAL STATE-METRICS ASSOCIATIONS

Various aspects of the ontology should be related. In this section, we illustrate how the requirements, goal, and autonomous performance aspects fit together, focusing on the US&R application example.

- The goal model *is* driven by the Requirements, which state that the robot "should be able to ingress a specified number of meters into the worst case collapse" and "project remote situational awareness or to convey other types of information down range." These are reflected in the mobility and communication subgoals in the ontology.

- The US&R Requirements call for the operator control unit (OCU) displays to be clear and legible in outdoor situations and under *ambient* light conditions. This is to facilitate UMS control and to reduce the stress level of the user, one of the autonomous performance metrics in the ALFUS Framework.

- The US&R Requirements further call for "enable use of video in confined spaces and for short-range *object* identification." This corresponds to the *solution_difficulty* and *situation_analysis* metrics in ALFUS.

7. SUMMARY

An ontological approach is used to model certain aspects of UMS. The objective is to facilitate the investigation of the performance of UMSs. In particular, we represented the goal of a UMS in the ontology, followed by representing the autonomous performance. We further identified several cases illustrating that the two are integrated. Our ultimate goal is to expand on this work for a broad scope ontology that can be helpful to a large audience in the community.

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