A Framework For Autonomy Levels For Unmanned Systems (ALFUS)

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1 Introduction

Rapid evolution of mobile robotic technology is witnessed by the fact that unmanned vehicles have begun to be fielded in many problem areas ranging from homeland security and battlefield support to Mars exploration. Military and civilian agencies continue to expand the roles that unmanned systems (UMS) may serve. As government agencies continue to specify UMS capabilities for future applications, there are increasing demands for a facilitating common framework. The demands include a common terminology for characterizing the UMS requirements and standard metrics for evaluating the autonomous capability of the UMS. Individual government agencies have begun the efforts toward building facilitating frameworks. The Department of Defense Joint Program Office (JPO), the U.S. Army Maneuver Support Center, and the National Institute of Standards and Technology (NIST) have, in separate but related efforts, described levels of robotic behaviors for the Army Future Combat Systems (FCS) program [1, 2, 3]. The Air Force Research Laboratory (AFRL) has established an Autonomous Control Levels (ACL) [4] scale. The Army Science Board has described a set of levels of autonomous behavior [5]. Central to these efforts is the concept of autonomy levels for the UMS. It is extremely beneficial that these and other agencies leverage each other's efforts and aim at a government and industry-wide consistent and standard approach.

Recognizing the benefits and the needs, in July 2003 an initiative was launched to assemble key representative practitioners from U.S. Departments of Commerce (DoC), Defense (DoD), Energy (DoE), and Transportation (DoT) (and their supporting contractors). This group assembled at NIST and formed the Autonomy Levels For Unmanned Systems (ALFUS) Ad Hoc Work Group to address the autonomy issue.

2 Requirement Analysis

As the technological frontier for unmanned systems has expanded, the potential applications for their use have also expanded. These technological and application expansions have complicated the users'[iv] problem in articulating both the potential for, and requirements associated with, the use of UMS. A common means by which to articulate both capabilities and requirements is essential to the ability of the user

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[iv] The term user is used in a broad sense, covering operators, their supervisors, the UMS acquirers, etc.

community to adequately express its needs, and allows for the establishment of a "language" that is understood by all facets of the acquisition community.

The expansion in capabilities (and therefore potential operational application) from simple tele-operated systems that perform a specific task within a well defined environment to more complex, autonomous or semi-autonomous systems that perform multiple tasks in complex environments has evolved several means by which disparate "User communities" articulate their needs. The DoD "Joint User" community has struggled for years to find a common method of articulating its requirements given the wide range of operational and organizational contexts across the services. The disparate missions and use of UMS within other government agencies (DoT, DoE, DoC, NASA, etc.) have also complicated intelligent comparison of and dialog about UMS capabilities. To best capitalize on limited funding, cross-fertilization of ideas, experiences and technology among cross-agency efforts is seen as essential and would be enhanced by a common baseline for discussion.

The User community, therefore, has articulated two major thrusts/needs:

- A common vernacular that could be used to articulate capabilities (common set of definitions). This facilitates comparisons between systems/capabilities, and allows for disparate organizations to intelligently discuss issues surrounding the use of Unmanned Systems capabilities within their operational constructs.
- A means by which to articulate the amount of autonomy required/expected from an Unmanned System. This would facilitate interactions between the Users, Research and Development agencies, and Materiel Developers.

The variety of autonomous systems currently envisioned for use by government and non-government entities makes a common set of terminology and definitions paramount. It also provides a challenge to the determination of the proper metrics to apply so that these definitions and metrics can be universally utilized in all the UMS vehicle domains: aerial (UAV), ground (UGV), underwater (UUV), surface (USV), etc. The end result of the creation of a common vernacular would be to enhance the common understanding of terms which would, in turn, be a key enabler for intelligent dialog and collaboration amongst disparate organizations.

In terms of defining autonomy, the User community sees two levels of need. At an executive level, there is a need to provide a means by which to easily articulate requirements. This would provide a means of common communication between the User and Material Developer in expressing requirements, but would also provide an easy to understand method of explaining autonomy requirements to decision makers. At a more technical level, the User community sees a need for a tool by which interactions between the User, Material Developer, Industry, and the Test Community can be made easier. This tool could then be used to articulate system-specific, specification-level detail and provide a framework for the testing/verification of autonomy.

The combination of common terms and definitions and a means to define autonomy are seen as key enablers for the interaction and cooperation amongst Users and Developers of UMS. This has the potential of increasing the ability of disparate organizations (across the government and industry) to interact and collaborate in the development of UMS technologies facilitating cost savings and knowledge sharing.

3 Work Group Objectives, Plan, and Approach

The overall objectives for the work group are to produce:

- Standard terms and definitions to facilitate characterizing the levels of autonomy for unmanned systems.
- Metrics, methods, and processes for evaluating and measuring the autonomy of unmanned systems.

The development plan for the Group contains the following phases:

- Phase 1, Development of Framework Content
  Develop the core technical content of the ALFUS framework. This effort will be an iterative process between a top-down approach for constructing the generic framework and a bottom-up approach for evaluating the framework concepts through use-case experiments with selected application programs.
- Phase 2, Enhancement and Evolution of the Framework
  - Investigate and develop testing and validation plans and methods. Generalize the framework further by experiments in additional domains.
  - Revise and upgrade the framework based on user feedback. Expand metrics as testing and measurement technologies advance. For example, continued research efforts may produce measurement methods for certain metrics that are currently hard to measure, such as workload for a robotic operator.
- Phase 3, Expansion. Investigate expansion of the ALFUS framework to a generic performance metrics framework for unmanned systems (“PerMFUS”).

The planned migration path of the work group effort is:

- Start as a government only user effort.
- Include the contractors for the selected use case programs once the critical elements of the Framework have been established, during Phase 1.
- Open to industry, during Phase 2.
- Migrate to a U.S. or international standards development organization (SDO), during Phase 2.

4 Participation

The government organizations and programs that are represented in the ALFUS work group include:

DoD:

- Aviation Applied Technology Directorate (AATD)* [v]
- Air Force Research Laboratory (AFRL)

[v] Asterisks denote U.S. Army.

- Aviation and Missile Research, Development and Engineering Center (AMRDEC)*
- Army Research Laboratory (ARL)*
- Communication-Electronics Research Development & Engineering Center (CERDEC)*
- Defense Advanced Research Projects Agency (DARPA)
- Maneuver Support Center (MANCEN)*
- Naval Air System Command Naval Air System Command (NAVAIR)
- Naval Sea System Command (NAVSEA)
- Naval Research Laboratory (NRL)
- The Office of the Secretary of Defense/ Joint Project Office (OSD/JPO)
- Tank-Automotive Research, Development & Engineering Center (TARDEC)*
- Training and Doctrine Command (TRADOC) Systems Manager Future Combat System (TSM FCS)*
- TRADOC Unit of Action Maneuver Battlelab (UAMBL)*

DoC – National Institute of Standards and Technology (NIST)
DoE – Headquarter (HQ), Idaho National Engineering and Environmental Lab (INEEL)
DoT – Federal Highway Administration (FHWA)

The work group has identified FCS as its first use case. Therefore, the FCS Lead System Integrator (LSI), namely, the Boeing and SAIC companies and their subcontractors are also represented in the work group.
Each of these entities has identified a need for autonomy level definitions.

5 ALFUS Framework

Nine workshops have been conducted, so far, in an effort to develop the ALFUS framework. The accomplishments include:

5.1 Formulated the ALFUS Framework

We envision that a generic autonomy level framework should include:

- A set of terms and definitions for UMS that facilitates communications on the UMS autonomy requirements and capabilities.
- A Detailed Model for the autonomy levels that includes sets of identified metrics used for evaluating the autonomy levels for UMSs.
- A Summary (or Executive) Model that defines an autonomy scale from zero or one through ten. This scale can be used for describing the UMS autonomy levels at a high level of abstraction.

We further envision that this generic framework is to be instantiated for various UMS programs specific ALFUS models. The resulting ALFUS framework [6] is illustrated in Figure 1.

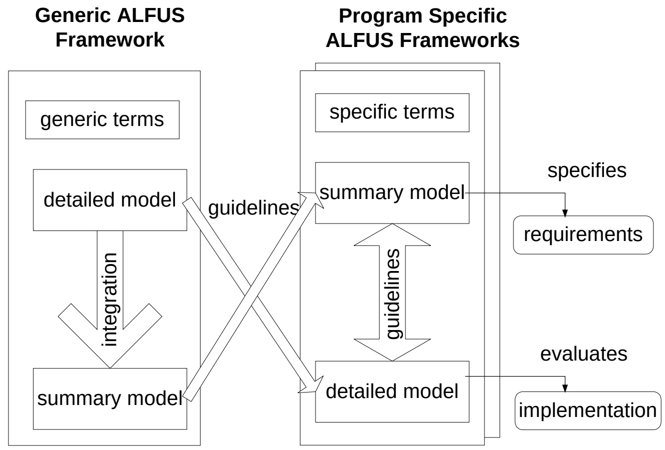

Figure 1: ALFUS Framework

5.2 Established the metrics sets for the Detailed Model

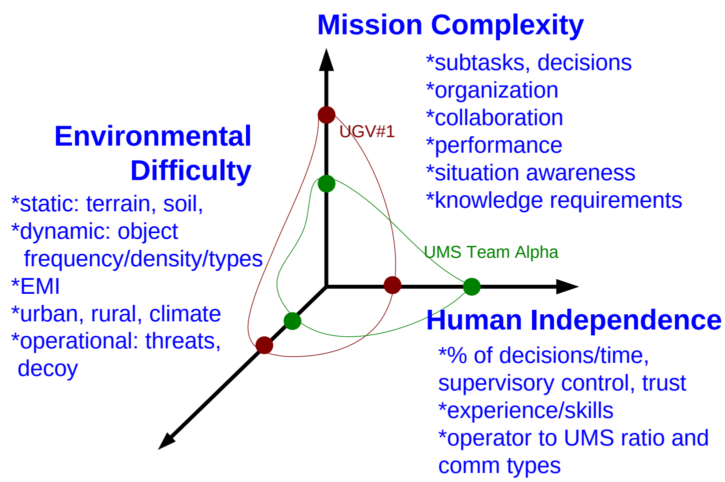

Figure 2: ALFUS Detailed Model

The ALFUS framework Detailed Model contains the following defining concepts:

- UMS autonomy concerns multiple technical areas. Task complexity and adaptability to environment are among the key aspects.
- The nature of UMSs' collaboration with human operators, such as the levels of involvement and types of interaction is important to the autonomy capability.
- Performance factors, such as mission success rate, response time, precision, resolution, and allowed latencies affect a UMS's autonomy levels [7].

The ALFUS Detailed Model is shown in Figure 2. In this three-axis model, the autonomy level is determined by the complexity of the missions that a UMS is able to perform, the degrees of difficulty of the environments within which the UMS can perform the missions, and the levels of operator interaction that are required to perform the missions. Note that we used curved lines to connect the three scores for

each of the illustrated vehicles to indicate that users might use some complex algorithms, as opposed straightforward, weighted-average ones, to determine the vehicles' resulting autonomy levels. The curve lines also imply that they may be used to define maximum capabilities, i.e., the UMSs can perform at any combination of complexity/difficulty/independence that lies on or below the surfaces.
Mission complexity could be measured with the metrics of: levels of subtasking, decision making, and collaboration, knowledge and perception requirements, planning and execution performance, etc. Human independence level (HI) can be measured with the metrics of: interaction time and frequencies, operator workload, skill levels, robotic initiation, etc. Environmental difficulty can be measured through obstacle size, density, and motion, terrain types, urban traffic characteristics, ability to recognize friends/foe/bystanders, etc. Work is underway to define measuring scales for the metrics. Priorities will be set to include the metrics in various versions of the framework.

5.3 Established a process model for ALFUS

Figure 3 depicts how the autonomy levels for a UMS can be evaluated in the ALFUS framework. We outline the process as the following:

- An identified mission is decomposed, via an adopted method, to generate a task structure covering from the mission to the lowest level skills. This is shown on the top of Figure 3, from left to right. An earlier paper describes some of the current concepts [8]. The NIST 4D/RCS [9] architecture may provide a viable method. However, modifications might be needed to suit the purposes of autonomy level analysis.
- The decomposed subtasks or skills should be assigned relative weights (labeled as "task weight" in the Figure) in terms of their criticality to the performance of the parent tasks or missions.
- The metrics should be reviewed and relative weights (labeled as "metric weight" in the Figure) should be assigned based on the particular focuses or requirements that the applying program has established. Non-applicable metrics are weighted zero.
- As shown in the MC row in the Figure, tasks and skills are evaluated and scored against each of the metrics. A composite score for each task is obtained through a weighted average (or a different integration method if the user prefers) of all the individual metric scores. The "task/skill complexity" box depicts the result. Note that "additional constraints," such as inter-metric dependence, could conceivably affect the metric scores. This issue will be further developed in the future.
- Composite scores for the higher-level tasks or missions can be obtained similarly through the weighted averages of the subtask scores, as the corresponding boxes in the Figure depict.
- The UMS autonomy levels can be determined by the vehicle's overall mission scores.

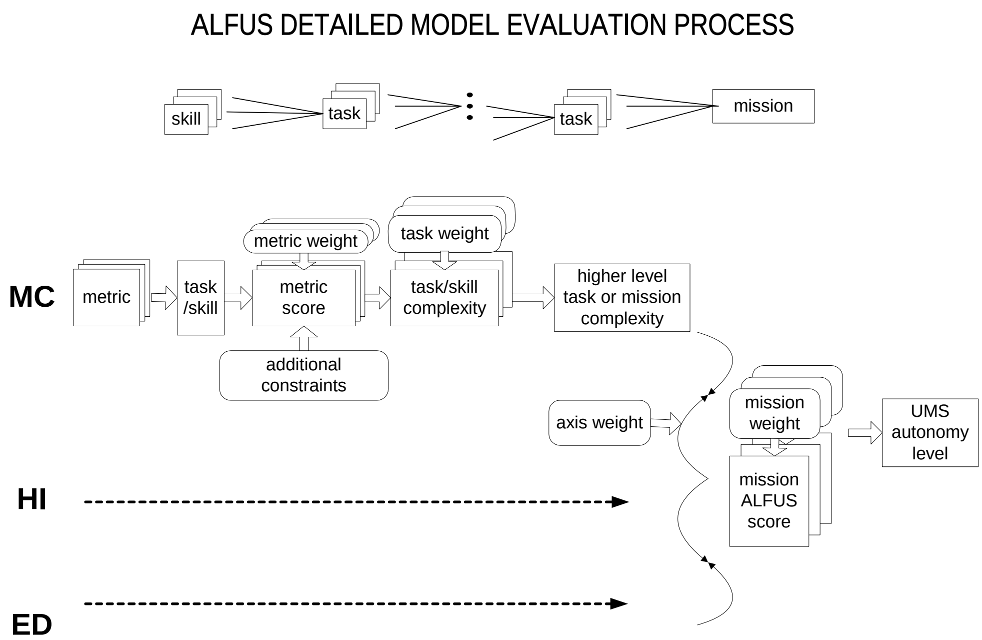

Figure 3: ALFUS evaluation process

5.4 Published the terminology

This report [10], as shown in Figure 4, includes such terms as UMS, autonomy, levels of fusion, levels of perception, etc., which are needed to address the UMS capability and requirement issues. We adopted and modified existent definitions when feasible.

Autonomy Levels for Unmanned Systems (ALFUS) Framework

Volume I: Terminology
NIST Special Publication 1011
Version 1.1

Figure 4: ALFUS Terminology Publication

5.5 Began prototyping a tool for evaluating the autonomy levels for UMS

An autonomy level evaluation software tool is being implemented based on the ALFUS process model and Detailed Model. An earlier paper [8] described the concept in detail.

5.6 Began defining the Summary/Executive Model

The Summary Model (or Executive Model) for ALFUS devises a linear scale, zero through ten or one through ten, together with definitions and concise descriptors, to be used to represent the level of autonomy of a UMS. This model is envisioned to serve the conceptual, common reference purposes.

Figure 5 depicts the general trend of the metric scores, in terms of mission complexity, environmental difficulty, and human-robot interaction, along the Summary/Executive

Model scale. In general, the more a robot is able to see, learn, think, plan, and act independently or collaboratively (in this case, the team operates independently) to achieve assigned, complex goals in difficult environments, the higher the level of autonomy score.

5.7 Established a web site.

http://www.isd.mel.nist.gov/projects/autonomy_levels/ was established to facilitate interaction and information sharing within the UMS community.

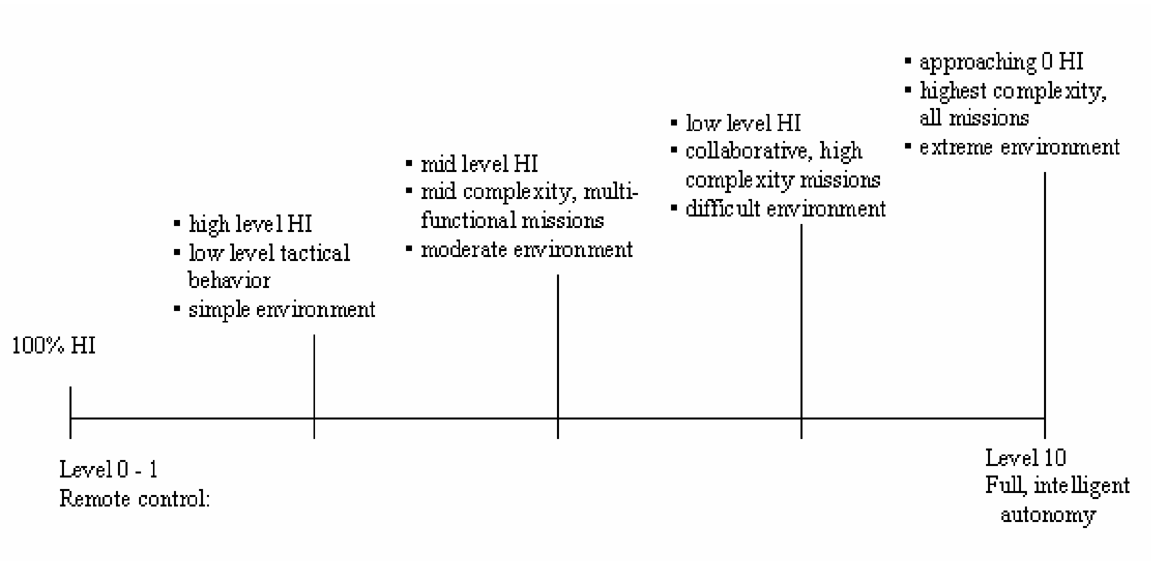

Figure 5: ALFUS Summary Model Overall Concept

6 Summary

We have reported the latest concepts for the Autonomy Levels for Unmanned Systems (ALFUS) framework. It is recognized that autonomy level is an extremely complex issue. Therefore, the work group still faces major technical challenges that lie ahead, including:

1. Refine and prioritize the metrics. Identify overlaps and conflicts among them along the three axes and provide resolutions.
2. Provide standard measuring scales for the metrics.
3. Generate high-level definitions for the autonomy levels for the Summary or Executive Model.
4. Devise methods and plans for testing and validating UMSs' autonomy levels.
5. Establish domain-specific autonomy level models for selected programs.

We anticipate holding frequent workshops to address these issues to complete, apply, and expand the ALFUS framework.

Acknowledgement

The entire ALFUS ad hoc work group participants contribute to the ALFUS framework. Charles Bishop, Technical Fellow, Boeing Company proposed and conceptualized the autonomy level evaluation software tool, a critical ALFUS product, and currently leads

the development effort. Woody English, Systems Engineer, SAIC, leads the Environmental Difficulty metrics group.

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