The Autonomy Levels For Unmanned Systems (ALFUS) Framework

Interim Results

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Abstract

Unmanned systems have become more and more widely used. Yet, various practitioners have different perceptions and different expectations of the systems. They also have different definitions for the term autonomy and different concepts about how it should be measured. We have been developing a framework called Autonomy Levels for Unmanned Systems (ALFUS) that aims at providing a common reference for the communication and the evaluation of the autonomy capabilities of unmanned systems. The framework is under development. This paper is a work-in-progress report on some key areas.

Keywords

autonomy, robot, environment, human independence, mission, task, unmanned system

I. INTRODUCTION

A wide range of applications has been either exploring the feasibility of, or actually employing, unmanned systems (UMS). Examples include aerial reconnaissance, bomb detection and disposal, combat support, urban search and rescue, physical security, and intelligent transportation systems [1, 2, 3, 4, 5, 6, 7, 8]. Figure 1 shows a robot searching for victims through a collapse scene. Practitioners across those application domains have different perceptions and different expectations of the systems. In addition, the term autonomy has been interpreted differently in different areas. The methods with which autonomy is measured lack consistency. For example, Air Force Research Laboratory (AFRL) has established Autonomous Control Levels (ACL) [9]. The Army Science Board has described a set of levels of autonomy [10]. Many programs need only remotely controlled UMSs. For other programs, fully autonomous operations were required. Traditionally, autonomy has been perceived as the amount of the human interaction required. However, when analyzing the requirements for UMS, one must consider what kinds of tasks or missions are planned for the UMS and in what kinds of environments the UMS will operate. We have been coordinating a cross Government and industry, ad hoc working group on developing a comprehensive framework for autonomy. The framework is called Autonomy Levels for Unmanned Systems (ALFUS) [11]. ALFUS aims at defining key autonomy issues, providing a commonly understood framework for communicating UMS autonomy issues, and evaluating UMS autonomy capabilities. Some early concepts have been reported since 2003 [12, 13]. This paper is a work-in-progress report stressing some key areas.

Figure 1: Robot searching through a wood pile for victims

II. ALFUS FRAMEWORK

The ALFUS Framework has been under development since 2003. The ALFUS framework:

- includes a generic model that can be instantiated for program specific models
- contains a metrics based model for autonomy levels that is flexible, quantified, and with smooth transitions
- employs multiple layers of abstraction in expressing autonomy requirements and capabilities
- is applicable to UMSs with various kinds of configurations
- is extendable as a general performance metrics model for unmanned systems.

Thus, the model is designed to apply to single UMS low-level operational behavior as well as multiple-UMS, high-level missions.

The first effort for this group was to define a set of terms. The group has reached consensus on defining UMS as: "An electro-mechanical system, with no human operator aboard, that is able to exert its power to perform designed missions. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned surface vehicles (USV), unattended munitions (UM), and unattended ground sensors (UGS). Missiles, rockets, and their submunitions, and artillery are not considered unmanned systems [1, 14]."

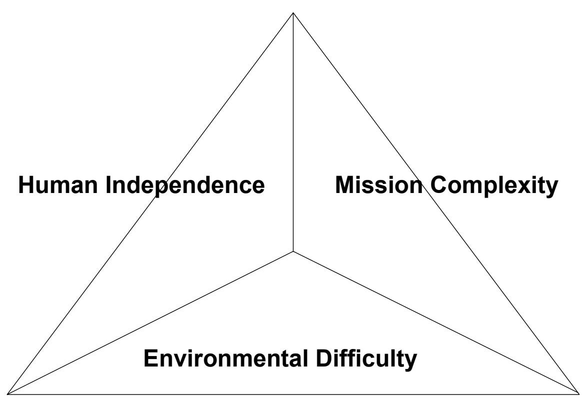

Figure 2: ALFUS Metric Overview

The group defined autonomy as "UMS's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as assigned by its human operator(s) through designed HRI [14]." This emphasizes that, in the ALFUS model, the more the robots are able to serve human purposes, the higher the autonomy level would be. It is also proposed by the group that this model is to be called intelligent autonomy.

A fundamental concept for the ALFUS framework is that human interactions, types of tasks, teaming of UMSs and humans, and operating environment are the essential issues that need to be accounted for when characterizing UMS. This understanding leads to the three-aspect view in ALFUS for characterizing the autonomy of unmanned systems. The three aspects are:

- mission complexity
- human independence
- environmental difficulty

as shown in **Error! Reference source not found.**. Each of the aspects contains a set of metrics, which will be described later in this paper.

The ALFUS Framework also emphasizes a generic model that can be instantiated for a program specific autonomy model. Figure 3 depicts the framework, which includes the following items:

- Terms and their definitions. Standard terms are defined to facilitate communicating UMS autonomy and ALFUS framework description.
- Detailed model. The aforementioned metrics form the detailed model of ALFUS. The metrics are applied to the UMS and scores are accumulated as the autonomy level of the UMS. This application process will be described, in detail in a later section.
- Executive model. Metrics descriptions are summarized to form this conceptual, high level autonomy model. While the detailed model facilitates technical development and evaluation of UMSs, the executive model facilitates communications among users and program managers.

While the generic model covers many types of UMS, individual programs would derive specific ALFUS models according to the programs' emphases and particular needs. This paper focuses on the detailed model and how it may be applied.

III. ALFUS DETAILED MODEL METRICS

Efforts have been dedicated to the foundation of the ALFUS framework, the metrics. There have been many iterations due to the following challenges:

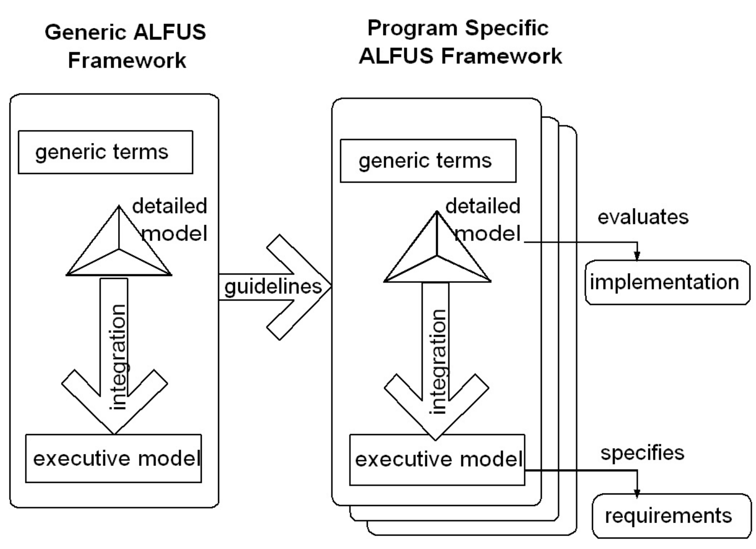

Figure 3: The ALFUS Framework

- Some of the metrics seem to be subjective in nature.
- Some of the other metrics are still being actively studied by the corresponding research communities and the measures/scales are not well defined yet.
- Participants might have been familiar with different analysis methods which might have resulted in overlapping, gaps, varied emphases, or different understanding on the contributed metrics.

The following sections describe the latest metrics.

A Human Independence

Following the model shown in **Error! Reference source not found.**, we propose that the following metrics facilitate in-depth analyses of the human independence (HI) requirements for UMSs:

1. Operator interaction time. How much time does an operator have to interact with the UMS, relative to the whole mission execution and completion time?
2. Mission Planning ratio. What percentage of a mission is to be planned by an operator and by the UMS?
3. Level of interaction. Does the operator only have to assign a mission? Does he have to also assign strategic goals and/or tactical goals of the mission? Does she/he have to provide detailed plans? Auto-piloting?

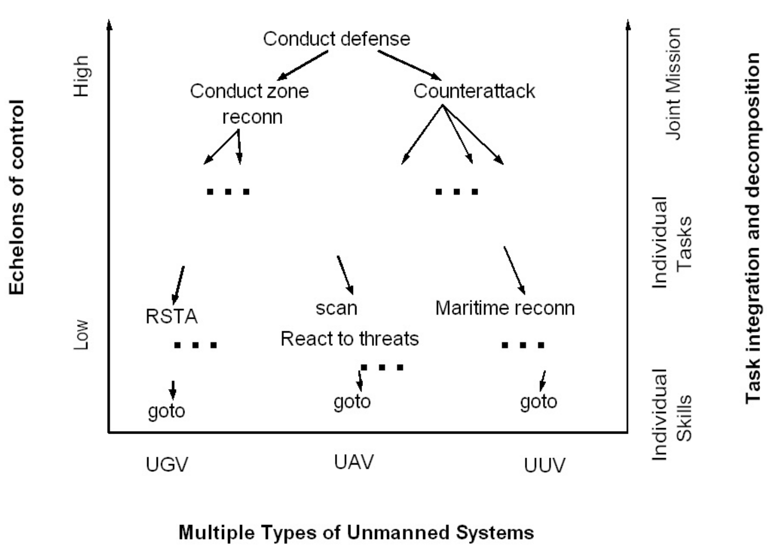

Figure 4: Task decomposition and integration

4. UMS initiation. How well is the UMS able to communicate to the operator? Is the UMS able to identify and communicate to the appropriate operator with proper information, such as a problem report and at the proper time? Does the UMS only respond to operator's requests? Does the UMS wait for proper input before it can proceed with its mission execution?
5. Operator workload. What is the workload for the operator during the UMS performance of missions? Is the operator highly stressed? Is the operator fully occupied but handling the tasks comfortably?
6. Training. What levels of training are required to operate the UMS? Does it take a highly skilled operator? Would a novice be able to operate the UMS?

B Mission Complexity

In analyzing the complexity of UMS missions, the following metrics should be included:

1. Task decomposition, or task integration in the reversed direction. What is the width and depth of task decomposition for a mission? A full-scale decomposition of a military mission could include the following levels: battalion, company, platoon, vehicle, skills, primitive, and actuator. There could even be levels higher than battalion. Multiple types of vehicles could be involved to conduct joint missions at these high levels. Figure 4 illustrates the point.

   A simplified task decomposition model considers only three levels, namely, group tasks, vehicle tasks, and skills. In this model, the tasks that are at levels lower than skills implicitly affect the degrees of complexity of the corresponding skills. The similar argument can also be made for the high-level tasks.

2. Type of tasks. Would the task be mission level, groupings of high risk, highly complex tasks, single subsystem tasks, or actuator tasks? How many vehicle functions are involved-- Mobility, System C4 (Command, Control, Communications, Computers), Lethality, Survivability, Tactical C4, ISR (Intelligence, Surveillance, and Reconnaissance), and Support? How many vehicles are involved? How many subtasks or skills are needed?
3. Complexity of tasks. Is the mission coupled with other missions? What is the level of uncertainty of the mission? ? What is the required level of precision? What are the rules of engagement (in military situations)? The following factors facilitate the evaluation of the complexity: (i) numbers of transitions and state and

their ratios, depth/breath of search tree (ii) numbers of concurrent tasks.

4. Decision space structure. What are the knowledge requirements--number of knowledge types and associated confidence levels, such as signals, entities, events, images, maps, laws of physics, and cultural values? What are the temporal and spatial resolutions for task execution? What are the required safety and risk levels? What are the rates of changes of tasks?
5. Collaboration level. The highest level of collaboration for a UMS team would be mission level collaboration and parenthetical understanding of mission intent. Detailed factors include number of communication channels, types of data exchanged, frequency of the data exchange, and synchronized vs. asynchronized operations.
6. Dynamic planning. The UMS's capability to perform planning onboard and in real-time indicates how it might be able to handle dynamic and changing environments and missions.
7. Analysis. Capability of values/cost and benefit/risk analysis.
8. Situation Awareness (SA): The highest level SA is omniscience. Below, the SA metric scale goes, from high to low: at the strategic level, at the tactical level, and at the internal level. At each level, the SA metric is further divided into, from high to low: projection, comprehension, and perception.

C *Environmental Difficulty*

UMS autonomy includes finding task solutions, navigation and others, for every environmental situation. The solutions should be characterized with respect to their difficulty levels. For example, if a UMS needs to cross a bridge, a solution may or may not exist depending on the width of the bridge. Even if the bridge is crossable, execution difficulty varies widely in different situations. Therefore, the task solution should be indexed with the difficulty level. The level of difficulty could be measured as:

- beyond the UMS's physical capability: for example, when the bridge is narrower than the width of the UMS. In other words, the identified, "apparent solution" is actually not a solution.
- restrictive: when there is clearance but requires high level perception, planning, and execution capabilities of the UMS.
- unrestrictive: open space and does not require advanced capabilities.

Environmental difficulty is evaluated with the concept of solution ratio, which is the ratio of the number of total possible choices a UMS can make and the number of solutions that meet the mission/task objectives. Individual programs can set their own thresholds on the difficulty, based on cost/benefit/risk factors, and determine whether to accept or reject a "solution."

IV. APPLICABILITY ISSUES

The application of the metrics to the targeted UMS is illustrated in Figure 5. Individual metrics are applied to mission tasks and scores are averaged. One of the challenges during the development effort is to generate quantifiable scales for all the metrics, including those metrics that are rather subjective in nature.

Metric weight is another important factor. Since the metrics are developed for general purposes, weights should be used to ensure that the metrics are applied appropriately. Individual, weighted scores are added and averaged to derive a final score, which will be the autonomy level for the UMS.

The ALFUS framework is scalable. It can be applied to vehicle subsystems as well as large teams of vehicles. Figure 6 illustrates that a metric scoring form can be applied to UMSs with various configurations.

The ALFUS framework is extensible. The metrics can be used to measure not only for autonomy measures but also for general performance measure, once the metric scales are modified to reflect the performance requirements.

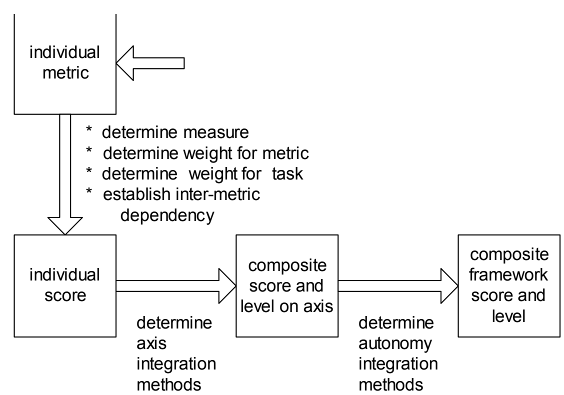

Figure 5: ALFUS Application Process

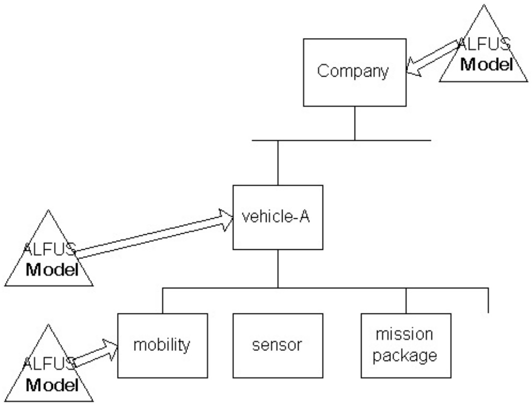

Figure 6: Applying a metric scoring form to different UMS Configurations

V. SUMMARY

The key concepts and critical elements of the ALFUS model are presented. The ALFUS framework applies metrics to unmanned systems for characterizing their autonomy capabilities. The framework is intended to be both scalable and extensible. It intends to provide detailed measures as well as high-level definitions for the UMS autonomy. ALFUS is an ongoing project with some interim results published

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