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Autonomy Levels for Unmanned Systems (ALFUS) Framework: An Update

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Abstract

The initial construct of the framework for the Autonomy Levels of Unmanned Systems (ALFUS) was presented in the 2004 SPIE[3] Defense and Security Symposium. This paper describes the continuing development effort and further accomplishments made by the Ad Hoc working group. We focus on two elements of the ALFUS product set, namely, the detailed model that is being implemented as a spreadsheet-based tool and the summary model. We also discuss identified challenges.

Key Words

Autonomy, Environmental Difficulty, Human-Robot Interaction, Metrics, Mission Complexity, Robot, Task, Unmanned Systems

1 Introduction

The Autonomy Levels for Unmanned Systems (ALFUS)[4] Ad Hoc Working Group has formulated, through consensus, a framework within which the levels of autonomy can be described. The initial construct of the framework was presented in the 2004 SPIE Defense and Security Symposium [1]. Significant progress has been made since. However, due to the complexity of the autonomy level issue, the Group has also identified additional technical challenges. Many of the them are open issues in the research communities.

We envision a construct within which a generic framework may be instantiated for program specific ALFUS frameworks. Such a generic framework includes the following components:

1. Terms and Definitions: The first requirement for the Framework that the Ad Hoc working group identified was a set of standard terms and definitions. We have published the results as Volume 1 of the ALFUS Framework [2].
2. Detailed Model for Autonomy Levels: A model that contains three sets of comprehensive and detailed metrics, together with a set of processes for determining the autonomy. The audience is technical users of Unmanned Systems (UMSs). This model is also being implemented as a software tool.
3. Summary Model for Autonomy Levels: Generated from the Detailed Model, the main thrust of this model is a concise scale and a set of corresponding definitions for the autonomy levels. The audience is executives and end users (in the Department of Defense domain, these would include combat leadership, program managers, unit leaders, and soldiers).

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[2] Titan Systems, U.S. Army Unit of Action Mounted Battle Laboratory, Contractor

[3] Society of Photo-Optical Instrumentation Engineers. In 1981 the Society's name was defined as SPIE - The International Society for Optical Engineering

[4] http://www.isd.mel.nist.gov/projects/autonomy_levels/

4. Guidelines, Processes, and Use Cases: A white paper is planned to describe a process to convert the detailed, technical ALFUS model into the summary model. The paper will also include guidelines to apply the generic framework to specific ALFUS applications. A number of use cases may be generated to demonstrate the application process.

Figure 1 illustrates the components and relationships of the Framework. Note the asymmetry between the two types of frameworks. This is because the program specific summary models, generated from the generic summary model, are typically used for specifying requirements at the early stages of the product lifecycles, whereas the detailed models typically are used for evaluating the implementations at late stages of the lifecycles.

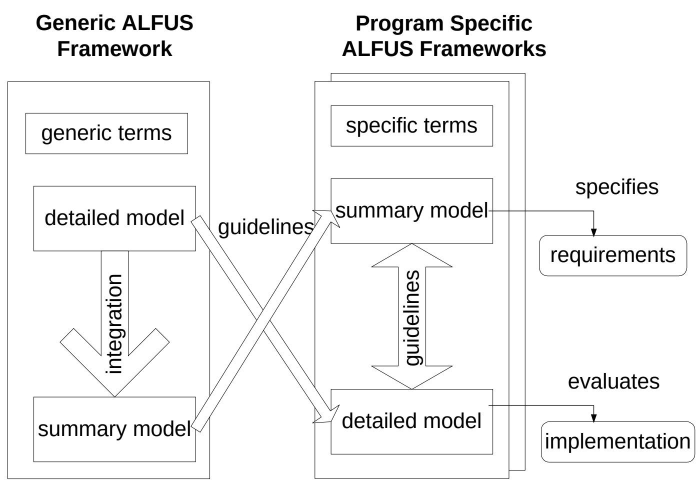


Figure 1: ALFUS Framework

2 User Requirements

The Joint User community has struggled for years to find a common method of articulating its requirements. There are two major parts of the user's needs:

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

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 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 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 domains: aerial (UAV), ground (UGV), underwater (UUV), surface (USV), etc.

3 Detailed Model Autonomy Level Tool and Framework Metrics Issues

The ALFUS Detailed Model is shown in Figure 2. The Group identified that the autonomy levels for unmanned systems must be characterized through the following three perspectives: the missions that the UMS is required to perform or is capable of performing, in the kinds of environments, and with the levels of human interaction. We devised a three-axis representation for the concept. Each axis is elaborated with a set of metrics.

As we attempted to illustrate in the figure, UMS Team Alpha and the UGV#1 have been determined to be at certain levels along the three axes. However, how the three scores for the UMS Team Alpha are computed for the team's resulting autonomy level (and similarly for the scores for UGV#1) is still an open issue in the Group. The possible options include weighted average and weighted minimum/maximum.

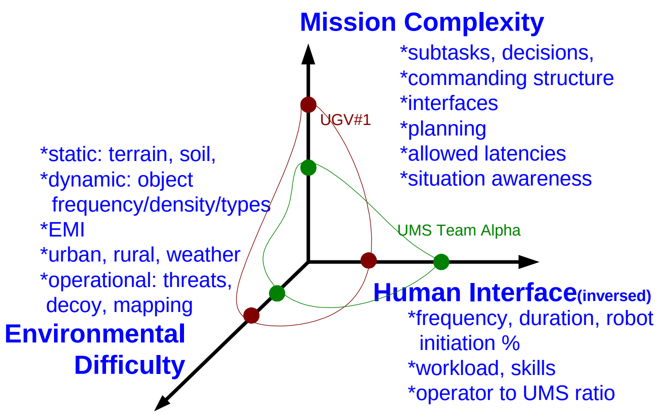


Figure 2: ALFUS Detailed Model

A spreadsheet-based software tool is being developed. The tool automatically computes the autonomy levels based on the weights and the metric scores that users enter. Figure 3 illustrates the tool using a Mission Complexity example. The leftmost section of the spreadsheet contains the hierarchical task decomposition of a mission. In this example, the mission is to Conduct_Route_Reconn. Its main subtasks include Tactically_Follow and Reconn_Avenue_of_Approach. This is only a small part of the complete task structure.

Each of the lowest level subtasks (level 2, in this example) is evaluated against all the three sets of the ALFUS metrics (shown in the middle columns of the figure, only two metrics, selected from the lists illustrated in Figure 2, were shown). These scores are weighted and averaged to form a composite score for the subtasks (shown in the rightmost section of the figure, for example, the score for the Move_to_Standoff_Position subtask is (6 * 1 + 8 * 1.2) / 2 = 7.8).

The subtask scores are further weighted and averaged to provide the composite scores for the next higher level tasks (for Tactically_Follow, in the example). This process continues until the mission gets its composite score.

The main technical issue that the Group is undertaking in this area is to develop guidelines for:

- Decomposing tasks in a commonly agreed, standard way.
- Prioritizing and weighting the metrics.
- Correlating the interdependencies among the metrics.

- Converting the metrics to become measurable and devising the scoring scales for the metrics.
- Integrating metrics for a concise set of indices for the autonomy levels.

mission	subtask_level_1	subtask_level_2	planning metric	metric weight	workload metric	metric weight	subtask score	subtask weight	higher task agg score	higher task weight	▪ ▪ ▪
Route Recon											
	Tactically Follow								5.8	1.4	
		Move To Standoff Position	6	1	8	1.2	7.8	1			
		Turn Onto Road	4	1	3	1.2	3.8	1			
		▪ ▪ ▪									
	Recon Avenue of Approach										
	▪ ▪ ▪										

Figure 3: Conceptual View of the ALFUS Evaluation Tool using a Mission Complexity Example

3.1 Task Decomposition

A benefit of decomposing the UMS tasks is that subtasks are narrower in scope and, hence, easier to analyze. There are plenty of challenges, though, including dealing with different ways to perform the decomposition. Some of the guidelines could be:

- Decompose the tasks according to the performing agents or controller nodes of the unmanned system.
- Decompose and structure the tasks into logical pieces with proper levels of abstraction comparable to how humans would perform them. For example, for the driving tasks, stay in lane and turn right may not be of concern at a high level, but may be essential at a mid level. At a lower level, the proper level of abstraction for the subtasks would include steering angles and gas pedal positions.
- Decompose the tasks along two aspects: spatial and temporal.
- The tasks are executed according to proper logic and the results are tactical behaviors. A task is completed when all its subtasks are executed successfully.
- Human factors and domain cultures affect task decomposition. The following factors may need to be taken into consideration during the process of decomposing the tasks: understandability, manageability, and existent conventions or standard.

Further details of the task decomposition process can be seen in [3, 4, 5].

3.2 Correlations and Interdependency among the Metrics

Some of metrics may be interrelated, some may not be applicable to certain applications. In many situations, using a weighted average method on the metric scores could provide an adequate indication for the autonomy level. However, there may well be cases when weighted minimum or maximum values might be more suitable. For example, the Mission Complexity axis contains metrics for perception and tactical behavior. A low score for the perception capabilities for an unmanned system implies that it may not be able to support a high level tactical behavior requirement because sensing and perception enable complex, autonomous mission behavior. In this situation, the lower score between the perception and tactical behavior should be used as the requirement instead of the average.

Another example is the Group decision to adopt the convention that remote control is the lowest level of autonomy. We effectively weighted out the mission and environmental effects at this level. Note that there were opposing views, though, stating that remote control for a very complex mission in a very difficult environment warrants a somewhat higher level of autonomy.

3.3 Measurability and Measurement Scales

The metrics need to be measurable to be useful. The challenges include determining a proper scale. The following may be used: 0 through 10, low/med/high, minimum/low/med/high/advanced, etc. Proper guidelines are needed.

Some of the measures are open and ongoing research topics in the community. For example, we defined a metric in human-robot interaction (HRI) called " operator mental workload" and assign it a scale of low/med/high. Additional studies are needed to determine what is considered low, med, or high. Could workload be reflected by the frequency of swapping of the operator control unit screens, the number of mouse clicks, or the number of the keystrokes required to complete the task?

3.4 Weights

Similar to metrics, there can be many different weight distribution scales for the metrics, such as binary (applicable vs. non-applicable), 1 through 10, a normal value with a certain percentage of addition or subtraction, etc. Guidelines are to be developed.

3.5 Confidence and Uncertainly

How do we capture uncertainty or perturbation, such as sensitivity of the outcome to small changes in the input data or the environment, and confidence level for the individual scores?

4 Summary Model

The Summary Model (or Executive Model) for ALFUS uses a set of linear scales, 0 through 10 or 1 through 10, together with concise descriptive language, to indicate the level of autonomy of a UMS. This model is envisioned to provide a conceptual level autonomy scale for common reference purposes.

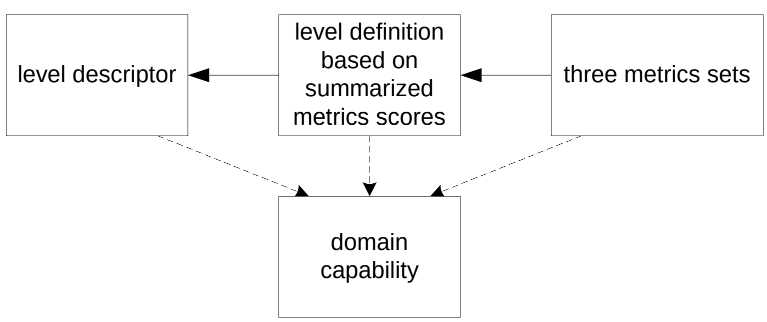


Figure 4: ALFUS Summary Model Overview

This model is derived from the detailed model, as shown in Figure 4. The approach is outlined below:

- Starting from the right hand side, we begin with summarizing the metric values for the particular autonomy levels. This is done at a generic level of abstraction. For example, at the highest level of autonomy, the environmental difficulty should be extremely high and the HRI should be approaching minimum.

- We, then, derive definitions for the levels from the metric summary, as the top-middle box in the figure indicates.
- Third, we create descriptors for the levels. The purpose is to facilitate human communication.
- The generic summary model can be applied to particular domains to identify specific mission and task capabilities as well as particular autonomy level scales, as the bottom box shows.

Figure 5 depicts the general trend in the Summary Model using this approach. The transitions of the levels of mission complexity, environmental difficulty, and human-robot interaction can be seen. Note that while color bands are used to delineate a continuum of different autonomy levels, there is no implication of distinctive switching of autonomy capabilities at the color boundaries.

The general trend is that, the more a robot is able to see, learn, think, plan, and act independently or collaboratively (in this case, the team works independently) to achieve assigned, complex goals in difficult environments, the higher the level of autonomy the robot should have. Whether the robot performs the mission with or without a priori knowledge does not affect its level of autonomy.

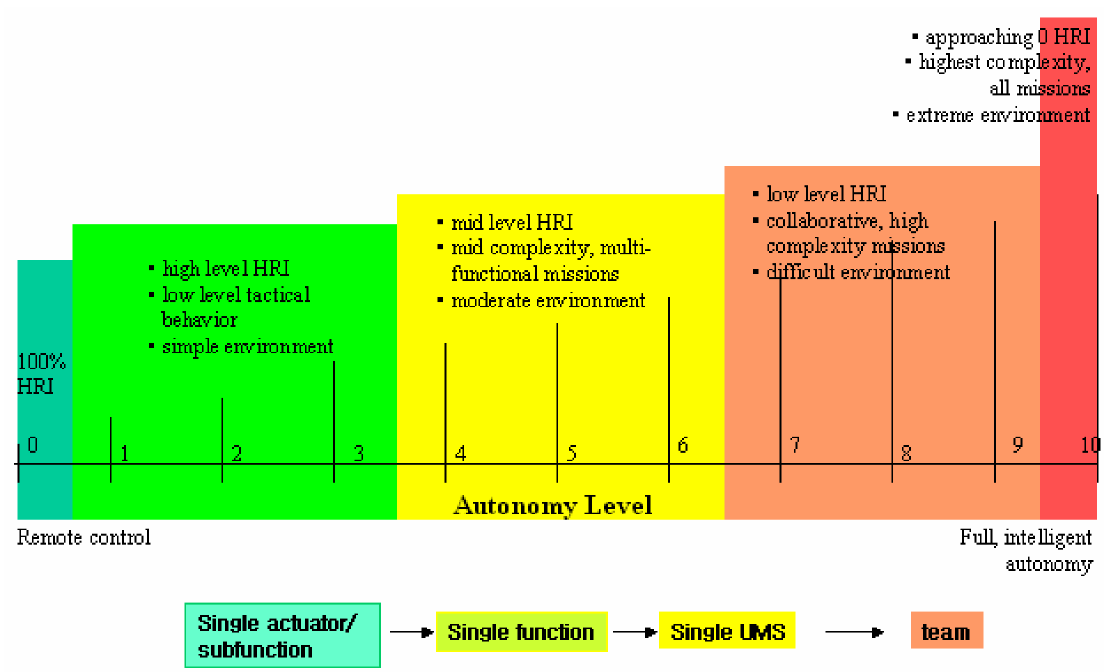
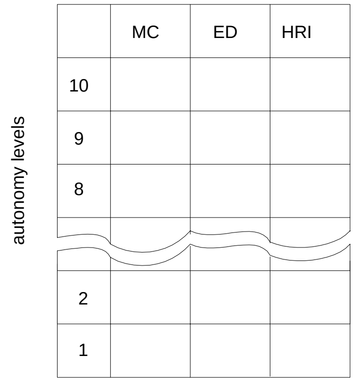


Figure 5: ALFUS Summary Model Overall Concept

4.1 Additional Information in the Summary Model

Using a single number to indicate the autonomy level has the advantage of being simple and providing a high-level, conceptual view. The tradeoff is information loss. Therefore, it looks quite useful to associate the single numbers with the scores on the three axes, as seen in Figure 6.



MC: mission complexity,
ED: environmental difficulty
HRI: human-robot interaction

Figure 6: Three Axis View for the Summary Model

Note that multiple combinations of the scores from MC, ED, and HRI can result in a single autonomy level. The reference definitions for the levels are for the situation when all three axes show the same scores.

In developing the summary model, we seek to determine the upper and lower boundary of the autonomy level spectrum first, as they could dictate the increments in the autonomy capabilities for the intermediate levels.

4.2 The Lower Boundary--Lowest Autonomy Level

1. Defined by Remote Control (RC)

We reviewed the major existent autonomy charts [8, 9, 10, 11] and found that they all define Remote Control (RC) as the lowest level. ALFUS adopts this concept.

However, in the ALFUS framework, remote control is addressed solely in the HRI axis. The issue is, then, whether MC and ED play any role in determining this level of autonomy. In other words, would a robot's ability to perform a very complex mission in a very difficult environment using RC increase the autonomy level of the vehicle? The group concluded that RC solely defines the lowest level of autonomy and the weights for MC and ED are, therefore, zero except for minor consideration as discussed in the section that follows.

2. Level 0 through 1

We decided to use this range to indicate the lowest level to accommodate the variety of RC technology. RC, as strictly defined, calls for direct control of the actuators. However, in more general situations, some of the RC might contain certain low-levels control logic and/or sensing capability. Some of the RC might not directly control the actuators. Deployed RC UMS may also have employed safety features.

Given these variations, we concluded that users should have the subject option. Level 0 would be intended for basic RC and level 1 enhanced RC.

Another reason for us to reach this conclusion would be cultural considerations. Users or developers might feel that RC itself is a significant enough accomplishment toward autonomy (by leaving drivers off the vehicles) and warrants a level number higher than zero.

3. Current draft definition of the lowest level of autonomy:

> *Remote control of UMS wherein the human operator, without benefit of video or other sensory feedback, directly controls the actuators of the UMS on a continuous basis, from a location off the vehicle and via a tethered or radio linked control device using visual line-of-sight cues.*

4.3 Higher Bound—Highest Autonomy Level

The highest level of autonomy is reached when all the three axes reach their full scales. However, an interesting question is: Should the highest level be characterized as achievable or as conceivable but not necessarily achievable capabilities or requirements? We decided not to include achievability as a constraint.

Another point to note is that the highest level of autonomy, requiring no human interaction, may or may not be the most desirable operation method for various robotic programs. The prevailing thinking is that robots serve human needs and the human must be able to control the robotic behaviors. Another reason for humans to prefer some interactions with the robot is the trust issue.

The current working definition for the highest level of autonomy is:

> *Completes all assigned missions with highest complexity; understands, adapts to, and maximizes benefit/value/efficiency while minimizing costs/risks on the broadest scope environmental and operational changes; capable of total independence from operator intervention.*

5 Additional Autonomy Level Framework Issues

There are a number of issues that the Group may consider addressing in the ALFUS framework in the future:

- The ALFUS framework has laid out two layers of abstraction: the Detailed Model and the Summary/Executive model. Additional layers of detail exist for the characterization and specification of autonomy levels, as shown in Figure 7. At the lowest layer of detail, a UMS's autonomy can be characterized in terms of its planning proficiency, taking into account the factors of planning speed, accuracy, resource optimization, update rates, etc.

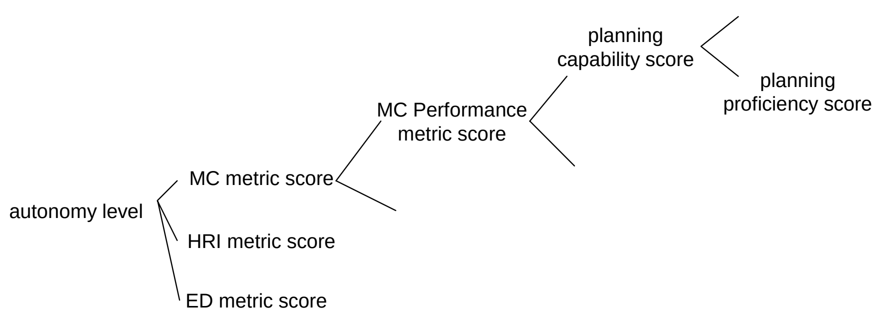


Figure 7: Layers of details for autonomy characterization

- Complexity vs. Intelligence: Should intelligence be a part of the autonomy concern? If we refer to the three-axis framework, a robot should be considered more autonomous when it is able to deal with more complex tasks. At the same time, the robot should be considered more intelligent. The intelligence levels and the autonomy levels appear, then, to some extent, to be parallel. The question is to what extent? The participants' comments were:
  - Intelligence and autonomy are necessarily inextricable, but it may not be crucial to this Group to define the relationship at this point.
  - Intelligence might facilitate or improve autonomy, but the two are not equivalent.
  - Could a difference lie in the independence factor--an intelligent system may know how to acquire information to accomplish the task whereas a high level autonomous system should require minimal external data?

  Further investigation is required.

6 Summary

We have described the Autonomy Levels for Unmanned Systems Ad Hoc Working Group's latest accomplishments in the ALFUS framework. We also listed some of the technical challenges that lie ahead. The Summary/Executive Model aims at defining the upper and lower boundary of the autonomy level spectrum as well as defining the conceptual, intermediate levels. The software tool that we are developing aims at helping the User and Material Developer to articulate system specification and helping development and testing communities to evaluate the autonomy capabilities of their unmanned systems.

Acknowledgement

The ALFUS framework is being contributed by the entire ALFUS Ad Hoc Working Group participants.

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.

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