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# Characterizing Unmanned System Autonomy:
## Contextual Autonomous Capability and Level of Autonomy Analyses

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**Abstract:**
The Autonomy Levels for Unmanned Systems (ALFUS) workshop series was convened to address the autonomous nature of unmanned, robotic systems, or unmanned systems (UMS). Practitioners have different perceptions or different expectations for these systems. The requirements on human interactions, the types of tasks, the teaming of the UMSs and the humans, and the operating environment are just a few of the issues that need to be clarified. Also needed is a set of definitions and a model with which the autonomous capability of the UMS can be described. This paper reports the current results and status of the ALFUS framework, which practitioners can apply to analyze the autonomy requirements and to evaluate the performance of their robotic programs.

Key words: autonomous system, autonomy, environment, human independence (HI), human robot interaction (HRI), metrics, mission, task, unmanned system (UMS)

## 1 Introduction

Since its inception in 2003, the ad hoc ALFUS Working Group has been devoted to the development of a framework to facilitate the articulation of autonomy requirements and the evaluation of autonomous capabilities of military and civilian unmanned systems. The need for such a framework has been reinforced through the ALFUS workshop series and was reported in earlier publications [1-3]. Representatives from a variety of Federal agencies and organizations, including the Departments of Commerce, Defense, Energy, and Transportation and NASA participated in the ALFUS effort. As a result, the work to date has provided some keen insights into the complexities of a common definition set that would be applicable across UMS domains, missions and environments.

Across the technical community, autonomy is being perceived in different contexts. In the literature, Bruemmer [4] uses the term dynamic autonomy, while Barynov and Hexmoor, in [5], define the terms including preference autonomy, choice autonomy, and decision autonomy. The authors attempt to describe, in this paper, that these concepts are all consistent with and can be facilitated by the ALFUS framework. Expanding from the conventional perception that autonomy levels are inversely proportional to the degrees of human interactions, ALFUS's premise is that the autonomous capability for UMS is characterized with two additional, significant factors: the complexity of the missions that the UMS is capable of performing and the difficulty of the environments in which the missions are performed.

There is now a consensus at the ALFUS workshop level that a contextual basis needs to be used when defining autonomy for UMS. Autonomy, by itself cannot be separated from its context of mission and environmental complexity. However, for like missions and environments, autonomous capability for UMS is really a measure of the amount of human interaction required by the UMS. To that end, the ALFUS effort has modified its approach to accommodate this consensus. This paper will address an update to the ALFUS framework. The three-axis approach outlined previously [2,3], is still relevant to the community at large as a tool set to help form and articulate requirements, engineering development, and testing. This update refines that approach using Human Independence as the measure of autonomy, while the

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Environmental Difficulty (ED) and Mission Complexity (MC) axes provide context to the measure of autonomy enabling useful comparisons to be made between UMSs.

For comparing UMS, fixing two of the axes would provide a comparison along the third axis. For example, two UMSs with similar missions and environmental requirements could be compared in terms of their autonomy, in other words, their abilities to perform with the maximal degrees of Human Independence (HI) or the minimal degrees of Human-Robot Interaction (HRI). Two UMSs of like HRI could be compared by measuring the mission and environmental situations within which they could maintain that autonomy.

## 2 Autonomy and Contextual Autonomous Capability

The *American Heritage Dictionary* [6] defines autonomy as "The condition or quality of being self-governing." To apply to the domain of unmanned systems, the ALFUS group defines autonomy as "A UMS's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing to achieve its goals as assigned by its human operator(s) through designed HRI or assigned through another system that the UMS interacts with."

Autonomy levels have been used to characterize the autonomous capability of UMSs. The ALFUS group believes that, in a general case, the aforementioned three aspects, namely, MC, ED, and HI should all be considered for such purposes. In the revised ALFUS framework, the three-axis model is called Contextual Autonomous Capability, whereas autonomy level is deemed as, virtually synonymous with Human Independence. This restructuring of the ALFUS framework better reflects the ALFUS objectives and is more consistent with the conventional view of the autonomy levels. The following sections describe the refined ALFUS framework.

## 3 The Framework

### 3.1 Contextual Autonomous Capability for Unmanned Systems Model

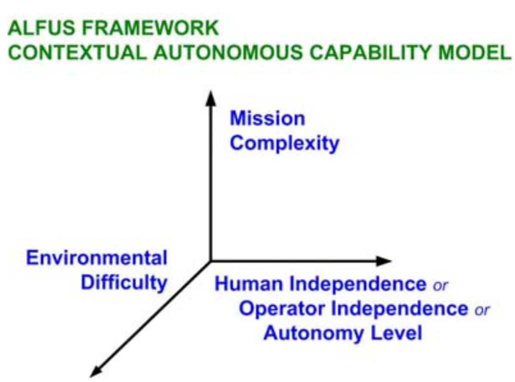


Figure 1: Contextual Autonomous Capability Model

An unmanned system's autonomous capability is characterized by the missions that the system is capable of performing, the environments within which the missions are performed, and human independence that is allowed or required in the performance of such missions. Figure 1 illustrates the concept. The HI level is the inverse of the level of HRI.

Each of the aspects, or axes is further attributed with a set of metrics to facilitate the specification, analysis, evaluation, and measurement of the Contextual Autonomous Capability of particular UMSs.

This model, the metrics along the axes/aspects, provides ways to characterize the Contextual Autonomous Capability in terms of UMSs' levels of requirements, capability, difficulty, complexity, and sophistication. The model also provides ways to characterize UMSs in terms of their autonomous operating modes [1].

The Contextual Autonomous Capability model encompasses multiple layers of details for the autonomy information:

- At the detailed layer, a UMS is characterized with metric scores, for such quantities as the percentage of a mission that is planned and executed by the UMS onboard processors, the levels of task decomposition, the solution ratio in the physical environment, etc. This layer is also called the ALFUS Detailed Model.
- At the intermediate layer, a UMS is characterized with the three aspects or axes scores (autonomy), namely, MC, ED, and HI. These axis scores are weighted averages of the individual metric scores of the detailed layer.
- At the highest layer, the Contextual Autonomous Capability for a UMS is a weighted average of the three axis scores of the intermediate layer.

Figure 2 provides an illustration of multiple layers of information detail and how different combinations of detailed information can be averaged for the same levels at higher levels of abstraction. The Contextual Autonomous Capability can be represented as a linear scale, shown as the line at the bottom. At the lowest degree of the Capability, all the three axis scores are lowest. At the next higher degree of Contextual Autonomous Capability, tele-operation, one or multiple of the three scores could be a little higher, as long as the summation remains the same. At an even higher degree of Contextual Autonomous Capability, the variations among the axis scores could be even higher, as long as the summation remains the same. At the highest degree, fully autonomous, all the three scores are at their highest level.

Note that the ALFUS framework allows for additional layers of details from the aforementioned detailed layer. For example, the human interaction time metric along the HI axis might be further decomposed to actuation time, monitoring time, sensory data acquisition time, etc. This is an issue requiring further investigation.

At different stages of the UMS lifecycle, different layers of detail may be needed. The highest layer, single value may facilitate communication purposes among battlefield users, whereas the detailed layer may facilitate implementation, testing, and evaluation. All of these types of information may be used in a nominal sense, while the specific scores are dynamic along the courses of mission execution when the environmental and operating conditions are anticipated to continuously change.

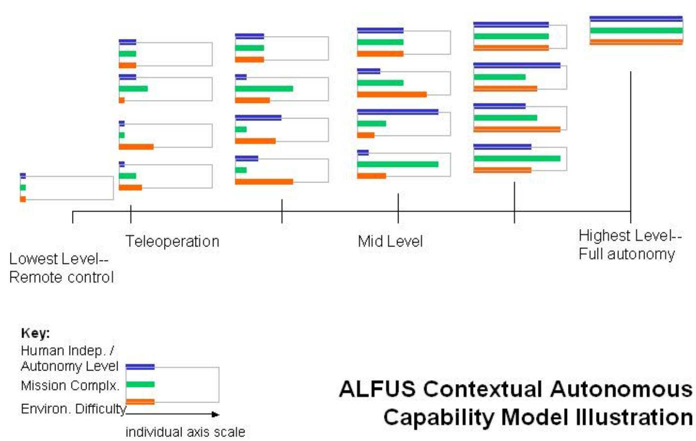


Figure 2: Illustrative UMS Contextual Autonomous Capability

### 3.2 Metrics

Mission complexity is measured by examining the following factors, the levels of task decomposition, type of tasks, complexity of tasks, decision space structure, collaboration, dynamic planning and analysis, and situation awareness.

Human independence can be measured by examining the following factors: unmanned system to operator communications, ratio of human intervention time / mission time, ratio of human planning time / mission time, and level of human interaction.

Environmental difficulty is measured with a generic, system independent approach, which is essentially the ratio of the number of total possible choices a robot can make to the number of correct choices that meet the mission/task objectives. For example, when a robot can move freely, ED = 1. Conversely, if a robot can find no correct solution, the ED is infinitely complex.

Further details can be found in our previous publications [2,3].

### 3.3 Task Decomposition Process

A task decomposition process is used to decompose a high level mission to low level tasks. The autonomy capabilities are analyzed for the individual low-level tasks. The following is a set of guidelines for performing the task decomposition (TD), as described by Albus [7]:

- Tasks are decomposed with two aspects: spatial and temporal.
- Spatial Perspective
    - Tasks are to be decomposed from the performer perspective. In UMS, performers are the hardware components and their layouts to form subsystems and systems.
    - Spatial TD leads to hierarchical task structures. Each layer in the task structures represents a different level of abstraction of the tasks.
- Temporal Perspective: Temporal TD involves the logical breakdown of a large task into manageable sizes.
- Computing efficiency: load distribution, efficient interfacing, and conforming to standards.
- Task decomposition is further guided by a set of human factors: understandability, manageability, and standard tasks.

### 3.4 Contextual Autonomous Capability Application Process

When specifying the requirements of a UMS, one can utilize the three aspects of the Contextual Autonomous Capability model, i.e., the levels of complexity of the missions, the levels of difficulty of the operating environments, and the levels of HI that is required. Alternatively, one can also use a composite index of CAC, i.e., a weighted average of the three axes.

When the task is to evaluate the autonomous capability of a UMS, the three sets of metrics should be used. The process is illustrated in Figure 3 and is described below:

- Determine which metrics are applicable and their relative weights.
- Determine which levels of details for the tasks that need to be evaluated.
- Decompose the missions to the levels of tasks.
- Apply the metrics to the lowest-level tasks.
- The metric evaluations for the higher-level tasks may be obtained by either weighted averages of the lower-level task evaluations or by applying the metrics to the high-level tasks directly. Further investigation is needed in this area.

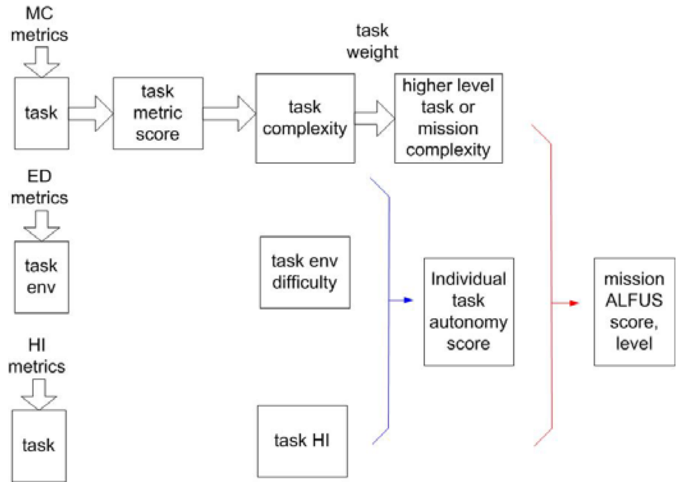


Figure 3: Contextual Autonomous Capability Evaluation Process

## 4 Autonomy Level Analysis in Future Combat System (FCS) Program

The ALFUS definition for autonomy, as explained in Section 2, was used as a basis to form the definitions for the autonomy levels. The U.S. Army Future Combat System (FCS) program Lead System Integrator (LSI) performed an in-depth analysis of the program's autonomy requirements and presented/proposed the results in the ALFUS workshop.

As previously defined, in [1], remote control is an operational mode with which the operator controls the UMS the whole time during missions. However, in practices, such as in FCS, it has been discovered that there are a small amount of functions that may always be performed by the UMS. As can bee seen in Figure 4, at the lowest level, almost all the autonomy functions are performed by the operator remotely. Therefore, it remains a to-be-resolved issue on whether to give the situations a modified name, such as enhanced remote control or modified remote control or to recognize the fact that there will be machine performed functions in remote control. Furthermore, in the latter case, it must be determined on what kinds of functions are to be allowed to be machine performed under remote control.

Also, as previously defined, in [1], at the highest level of autonomy, fully autonomous, the autonomy functions should be all UMS performed. A legitimate question to ask would be whether this might ever be achieved. In many implemented systems and operational principles, humans should always be ready to intervene when situations warrant. This raises the question as to how best to define the upper bound of the autonomy level spectrum.

Figure 4 is used to assess the general migration of functional performance from human to machine. This chart updates definitions and validates the differences between levels. Figure 4 documents the functional migration of the five levels of autonomy across various functional classes. The color scale indicates the degree of functional shift (red: all man; green: all UMS). The numbers (e.g., +1) indicate the degree of functional shift between two levels; each level shows the total functional shifts between two levels. This method of counting functional shifts as opposed to counting individual functions makes the definitions more focused on tendency and less dependent on the details.

The autonomy level definitions resulting from the analysis conducted by FCS LSI are the following:

Increasing Autonomy →

| | Sensing Level 0 Fusion | Perception Levels 1&2 Fusion | Analyzing Level 3 Fusion | Planning | Decision-making | Acting | Commu-nicating |
|---|---|---|---|---|---|---|---|
| Level 5 (Autonomous) The operational case with an unmanned system afforded the maximum degree of independence and self-determination within the context of the system's capabilities and limitations; the case of minimum human influence over unmanned performance; an unmanned system performing out of the direct observation of the human controller; requiring the unmanned system to sense its environment and report its state to the human; all perceiving and acting are done by the machine, most analyzing, planning and decision-making are conducted by the unmanned system; negotiation and collaboration may be performed by the human. | All UMS | All UMS | Most UMS | Most UMS | Most UMS | All UMS | Most UMS |
| +5 | | +1 | +1 | +1 | +1 | +1 | |
| Level 4 (Human Aided) The operational case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense its environment and report its state to the human; analyzing, planning, and decision-making are shared between the human and the machine; most perceiving and acting are done by the unmanned system. | All UMS | Most UMS | Shared | Shared | Shared | Most UMS | Most UMS |
| +6 | +1 | +1 | +1 | +1 | +1 | +1 | |
| Level 3 (Human Directed) The operational case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense its environment and report its state to the human; most analyzing, planning, and decision-making are done by the human; perceiving and acting are shared between the human and the unmanned system. | Most UMS | Shared | Most Man | Most Man | Most Man | Shared | Most UMS |
| +6 | +1 | +1 | +1 | +1 | +1 | +1 | |
| Level 2 (Tele-operation) The operational case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense its environment and report its state to the human; all analyzing, planning and decision-making are done by the human; most perceiving is done by the human; human directs all unmanned system actions from the machine's frame of reference. | Shared | Most Man | All Man | All Man | All Man | Most Man | Most UMS |
| +5 | +2 | +1 | | | | | +2 |
| Level 1 (Remote Control) The operational case with an unmanned system afforded neither self determination nor independence. All sensing, perceiving, analyzing, planning, and decision-making are done by a human; human directs all unmanned system actions from the human's frame of reference; the case of maximum human influence over unmanned performance. | All Man | All Man | All Man | All Man | All Man | Most Man | Most Man |

Figure 4: Proposed Levels of Autonomy Definitions

Level 5 (Autonomous): The operational case with an unmanned system afforded the maximum degree of independence and self-determination within the context of the system's capabilities and limitations; the case of minimum human influence over unmanned performance; an unmanned system performing out of the direct observation of the human controller, requiring the unmanned system to sense its environment and report its state to the human; all perceiving and acting are conducted by the machine; most planning and decision-making are conducted by the unmanned system; negotiation and cooperation must be performed by the human.

Level 4 (Human Aided): The operational case with an unmanned system performing out of the direct observation of the human controller, requiring the unmanned system to sense its environment and report its state to the human; analyzing, planning, and decision-making are shared between the human and the machine; most perceiving and acting are done by the unmanned system.

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Level 2 (Tele-operation): The operational case with an unmanned system performing out of the direct observation of the human controller, requiring the unmanned system to sense its environment and report its state to the human; all analyzing, planning, and decision-making are done by the human; most perceiving is done by the human; the human directs all unmanned system actions from the machine's frame of reference.

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## 5 Issues

As the group has been tackling the autonomy issues, a list of issues has been identified for continuing investigation. They are listed as the following:

5.1 Should higher fidelity be considered in the resulting LSI levels?

- Section 4 concluded that more than 5 levels might not provide sufficient separations between the levels. However, it remains to be resolved as whether the context factor would warrant further subdivisions of the levels. For example, might it be beneficial for the "human directed" level be divided into "simple, human directed" sublevel for simple missions and/or environments and "complex, human directed" sublevel for otherwise?
- Alternatively, the proposed autonomy level model assigned to a given system might need to be specified with a caveat, i.e., only valid in conjunction with explicitly defined missions and environments. For instance, a washing machine might be classified at the highest level within its very limited context. However, the level is not comparable to that of a UMS executing an extremely complex mission.

5.2 How would Figure 4 be implemented, namely, how does one distinguish the relative degrees of performance attributable to "Most Man" or "Most UMS", versus "Shared"?

- Could the metrics be a percentage of human intervention time? A percentage of human planning time? Commanding levels at which intervention occurs? Robotic initiation level? Robotic independence level (i.e., Sheridan model)? All of these are ALFUS metrics, which might be applicable to the situation.

5.3 Is autonomy level applied to the agents performing the tasks or to the tasks/functions, themselves, to be performed? Could both be applicable? How might they be related?

- Would it be specified that "a UMS is to operate at a certain level" or "a mission or task is to be performed at a certain level?"
- Would the UMS autonomy overall level be calculated, and thus quantified, as a weighted average of the levels for all missions?

5.4 Would the proposed approach require exhaustive decomposition of all the missions operating in all required environmental conditions? If so, this would require an enormous amount of effort.

5.5 How would the low-level functional autonomy levels be reflected at higher functional levels?

## 6 Summary

ALFUS's premise is that the autonomous capability for unmanned systems (UMS) is characterized with three significant factors: to what degree can the system perform without or with minimal human intervention, how complex are the missions that the UMS is capable of performing, and how difficult are the mission environments. Thus, the Contextual Autonomous Capability model is perceived as a three-axis vector. Detailed metrics are being developed to characterize each of the three factors. Summaries for the detailed metrics are also being generated to provide a high-level, executive view for unmanned system autonomy.

The goal of the ALFUS work group remains to provide a useful set of tools that enable requirements writers, materiel developers, and testers flexibility in the articulation and measurement of Autonomy. To that end, the methodology is outlined and the FCS LSI's resultant definition of "levels of Autonomy" is proposed. Furthermore, issues/questions for the community are provided as a means by which to stir dialog and encourage participation in the ALFUS Workshop process. The ALFUS work group sees this dialog as essential to garnering a broad consensus on the ALFUS approach and help refine its end product.

## 7 Acknowledgement

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