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# Toward a Generic Model for Autonomy Levels for Unmanned Systems (ALFUS)

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## Abstract

Unmanned systems (UMSs) have been deployed to military and civilian operations. UMSs vary widely in their capabilities and purposes. It would be beneficial to have a set of widely recognized standard definitions on the capabilities of the UMSs. Efforts have begun in various organizations in defining autonomy levels for unmanned systems.

As part of this ongoing research, we are attempting to define a generic model for the autonomy levels for unmanned systems (ALFUS). Our intention is for this model to be used to derive mission-specific ALFUS. In this paper, we describe autonomy levels in three tiers, subsystem, system, and system of systems (SoS). Within each tier, the levels of autonomy are further divided with the factors of task complexity, environmental complexity, human involvement, and a set of quality factors. The work presented is a snapshot of an ongoing process.

## 1. Introduction

The technological advances in mobile robotics have been significant enough to warrant the deployment of unmanned systems (UMSs) in military and civilian operations. Aerial and undersea UMSs have been performing missions for a number of years. Ground UMSs have been introduced in recent wars. UMSs have also participated in the search and rescue missions after natural disasters and terrorist attacks.

UMSs vary widely in their capabilities and purposes. They may be developed either with particular requirements or for general purpose. Some operating environments are known and structured, allowing UMSs to perform repetitive but unsupervised tasks. Other environments are much more unpredictable, requiring unmanned systems to make decisions according to the current environmental conditions obtained through onboard sensing and processing capabilities. There is no guidance available to match situations with required system capabilities. Organizations planning to fund development of new autonomous systems currently lack means of specifying the level of autonomy required – and of validating that the delivered systems meet those specifications.

It would, therefore, be beneficial to have a set of widely recognized standard definitions on the capabilities of the UMSs. ALFUS may address many aspects of the UMSs problem area, including as references for the system specification and performance measurement purposes. A particular procurement program may specify ALFUS-5. A particular area in a map may be certified for ALFUS-3 operations. Similar practices are seen in other fields, such as the five-level Capability Maturity Model (CMM) in Software Engineering (although that applies to the organization that develops the software) [4] and the nine-level NASA/Army Technology Readiness Level (TRL) structure [5].

In this research, we attempt to develop a generic framework for the autonomy level specification for unmanned systems. Our objective is for particular system users to be able to generate their specific ALFUS model from this generic model.

## 2. Related Work

There have been other discussions on autonomy levels published, but to our knowledge, there has been no other concerted effort to bring together communities of users to define a set of autonomy measures that are common to the UMS constituency.

A definition of autonomy proposed by Antsaklis et al. [6] states

> Autonomous control systems must perform well under significant uncertainties in the plant and the environment for extended periods of time and they must be able to compensate for system failures without external intervention.

Ziegler describes conceptual views of autonomy from the perspective of several fields (artificial intelligence, intelligent control, simulation, robotics, etc.) and proposes a summary 3 level categorization [7]:

1. ability to achieve prescribed objectives, all knowledge being in the form of models, as in the model-based architecture.
2. ability to adapt to major environmental changes. This requires knowledge enabling the system to perform structure reconfiguration, i.e., it needs knowledge of structural and behavioral alternatives as can be represented in the system entity structure.
3. ability to develop its own objectives. This requires knowledge to create new models to support the new objectives, that is a modeling methodology.

Whereas this broad classification is useful as a high-level abstraction of the categorization of capabilities, it would not provide much guidance to an Army procurement specification.

A more fully developed framework for defining Autonomous Control Levels (ACL) for air vehicles has been developed by the Air Force Research Laboratory. Clough [1] describes an 11 level ACL chart that ranges from 0 autonomy for remotely piloted vehicles to 10 for Human-Like. The highest level attainable by aerial vehicles is 9 for Multi-Vehicle Tactical Performance Optimization. There are various dimensions considered in determining the autonomy level: Perception/Situation Awareness, Analysis/Decision Making, and Communication/Cooperation. The model is specific to air vehicles.

The Army Science Board has conducted a study on Human Robot Interface (HRI) [8]. This study includes an autonomy level chart covering a lowest level as remote control to a highest level as autonomous conglomerate. While this chart provides a good reference for generic levels, it lacks rationale and in-depth description guiding specific system users. This has a potential of resulting in mis-identification of levels within particular programs.

The U.S. Army Maneuver Support Center and the National Institute of Standards and Technology (NIST) have earlier efforts of autonomy level charts [2, 3] that were developed for the Army Future Combat System (FCS) program. These charts provided references as how an end product of the autonomy level model may look like as we start our research effort from a generic point of view.

## 3. Defining Autonomy

The term autonomy must be defined before the autonomy level definitions. Section 2 described related definitions for certain contexts. Our definition for autonomy would be specific for unmanned systems.

### 3.1 A proposed definition

We propose to define a UMS's autonomy as its own capability to achieve its mission goals. The more complex the goals are, the higher the level of autonomy the UMS has achieved.

### 3.2 UMS capability

We propose to define that levels of autonomy for a UMS are proportional to the system's capability to perceive, plan, decide, and act to achieve the goals. Humans can play different types of roles [9, 10], which should affect the system autonomy in different ways. This issue will be investigated, in detail, in the next version of this model. In this version, we simplify the human interaction issue by stating that the amount and the criticality of human interactions would be inversely proportional to the levels of autonomy for a UMS. In other words, systems with high levels of autonomy, in general, require less human interactions. Further, the required human interactions should be non-critical and less in amount. The system with high levels of autonomy should not only be able to perform routine missions independently, but also gracefully handle unexpected situations.

We make a distinction between the terms of "degrees of autonomy" and "levels of autonomy." Total autonomy in low-level creatures does not correspond to high levels of autonomy. Examples include the movements of earthworms and bacteria that are 100% autonomous but considered low levels of autonomy.

### 3.3 Goals and goal representations

Humans evaluate a system's autonomy. Therefore, UMS stakeholders specify the system mission or task goals, which, in turn, dictate the system's autonomy level. For a military Unmanned Ground Vehicle (UGV), the main areas of concern include mobility and mission behaviors. The mobility goals could be any tactical movement. Mission behaviors could include countermining. A UMS could have a high level of autonomy in mobility but a rudimentary level in any mission behaviors.

Within the context of mobility autonomy level, fuel sufficiency should be assumed. At a higher level of SoS autonomy, there should be a task of fuel management as a part of the mission activities.

The system's goals, state, and status must be described and presented in reference frames that are easily understandable to humans. In an electro-mechanical system, the low-level actuator motions typically reference local coordinate frames. Once the components are assembled into a subsystem, the subsystem-centric reference is typically used. The same principle applies when subsystems are assembled into a system and when a group of systems is assembled into a SoS.

### 3.4 Complexity

We propose to characterize the complexity of a UMS's actions with the following attributes:

- Degrees of dynamics of the system actions. When a UMS has to navigate through complex trajectories with accelerations, decelerations, turns, and stops, the actions are considered more complex than navigating through a smooth and straight path without encountering any objects.
- Degrees of environmental uncertainly—frequencies of changes, visibility of objects.
- Number of steps toward the solutions.
- Relative amount of efforts for the UMS to decide and act—when a UMS is able to respond to situation A quickly but to situation B slowly, situation B might be more complex with respect to the UMS's capability.
- Number of components involved in coordination.
- Levels of coordination—frequency of interactions.

## 4. Defining ALFUS

### 4.1 Structure

We propose a multiple-layer generalization-specification structure for ALFUS. The objective would be the ability to instantiate the generic model for any mission or goals specific ALFUS as particular programs require.

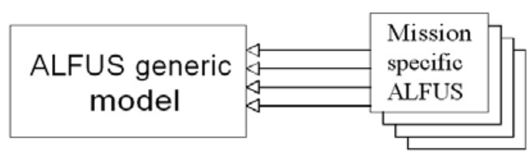


**Figure 1: Autonomy level model relationships**

Quite a few of the current solutions use a ten level structure; we prefer to relax this constraint to give us more freedom.

### 4.2 Performance and quality factors

In trying to define various levels of autonomy, there are associated variables of:

- **Mission behavior resolutions**—for example, contrast a "road march from city to city" vs. "go 50 meters on the road (with traffic)"
- **Perception capability**—what level of perception capability do we assume for the UMS to be able to perform specified behaviors? For example, if we specify that a UGV is to perform road following at ALFUS-n, what kind of road conditions do

we imply? Is it sufficient to quantify the conditions as excellent, fair, and poor? Users can further define the set of quantification indices.

- **Spatial and temporal resolutions**—the example of pure road following may be easy, i.e., all legal speeds, adding traffic negotiation will be hard to specify. If we define what constitutes an obstacle for an ALFUS level, how far ahead is the obstacle before the system detects it? How fast is the UMS moving?
- **Tolerance on the specified behavior**—in performing a countermine operation, is a UMS categorized for a specified level if it clears 85% of the field on average?
- **Mission success rate**—if a UMS accomplishes its missions 50% of the time, how do we specify its autonomy level?
- **Action quality and value judgment**—does a UMS that performs missions with optimal solutions have a higher level of autonomy than a UMS that completes missions with only adequate solutions? Can the system generate actions based on risk and benefit factors?

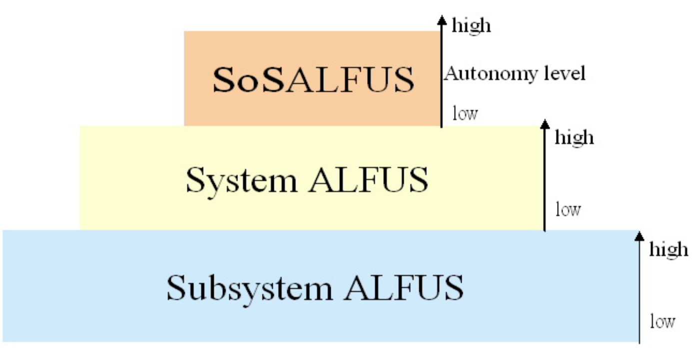


**Figure 2: ALFUS Classification**

### 4.3 Proposed generic ALFUS

We describe our proposed model for specifying UMS autonomy levels:

A. We propose that system autonomy should be specified in four tiers: actuator, subsystem, system, and System of Systems (SoS). The actuator tier represents remote control, the lowest level of autonomy. At the subsystem tier, autonomy levels are defined in terms of subsystem functions, such as mobility and functions performed by onboard mission packages. The vehicle can be a part of an SoS and the SoS, itself, can have its own level of autonomy. SoS can be further subdivided to align with operational units. **Error! Reference source not found.** depicts the structure with the actuator tier omitted for simplicity.

B. Within each tier, autonomy levels are divided, from low to high, according to following types of actions:
   - Simple goal attainment—when the UMS can only perform feedback actions with respect to the UMS state (position in the situation of mobility) to reach the given goal and is unable to respond to any environmental conditions[1].
   - When an individual UMS is able to achieve goals in a static environment. Examples in the UGV domain would include road following and obstacle avoidance. The UMS possesses required perception capability to perform these behaviors.
   - When a group of UMSs is able to achieve goals in a static environment.
   - When an individual UMS is able to achieve goal in a dynamic environment. An example in the UGV domain would be on-road driving in traffic.
   - When a group of UMSs is able to achieve goal while in a dynamic environment. An example would be when a military unit of UMS is fighting with an enemy unit, both in motion.

Each higher level assumes all the capabilities stated for the low levels. Figure 3 illustrates the structure.

C. Each level, as specified in paragraph B, can be further subdivided according to the performance and quality factors as stated in section 4.2.

[1] For SoS, this would be to move a SoS to location without concerning group level obstacles such as enemy units.

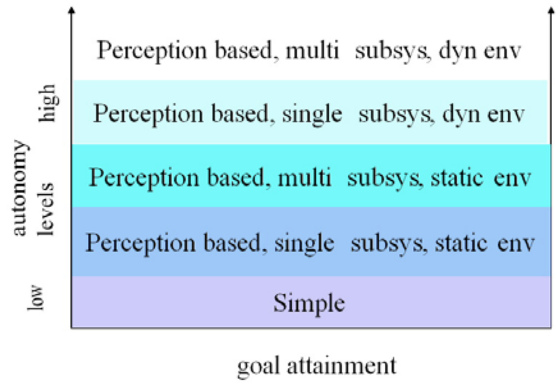


**Figure 3: Dividing ALFUS per environmental difficulties**

There could be multiple ways of characterizing these factors. For example, mission success rate can be represented in terms of either percentage, a high-resolution way, or from one to ten, a low resolution way. Since the purpose of this research is to quantify system autonomy in a low-resolution scale, typically from one to ten, all the performance and quality factors should be characterized in low-resolution indices. The values for each factor can be either individually kept or lumped into a single index, depending on users requirements. Figure 4 illustrates that these factors are combined to divide system autonomy levels.

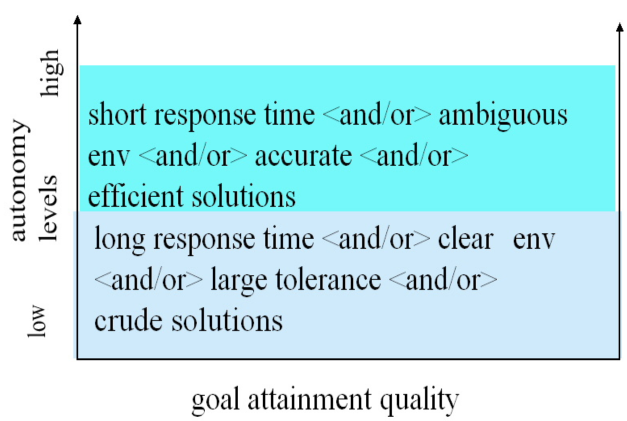


**Figure 4: Further dividing subsystem ALFUS per quality factors**

Human factors can divide the autonomy levels similarly. Further elaborations will be conducted in the next version.

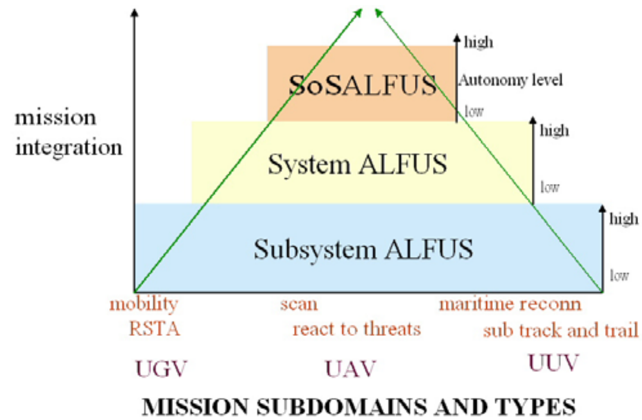


**Figure 5: ALFUS to be mission specific**

D. Our proposed ALFUS model is based on missions and tasks. Users specify mission requirements, which should be analyzed and form task structures according to complexity. In military domains, the task structures should be parallel to or consistent with commanding structures and are used as a basis for specifying system autonomy levels. Figure 5 shows that, low level missions are specified for subsystems. They are integrated into high-level missions as the system scope expands.

### 4.4 Example

Figure 6 shows a simplified view of possible autonomy levels based on task complexity. The mission is to make sure that the NIST campus is secure. At each level, a possible task is shown for that level, along with a descriptive list of the attributes for the capabilities, knowledge levels, uncertainty assumptions, and spatial and temporal scopes. The attributes illustrate the complexity of the tasks. The type of interaction (level of discourse) becomes more dependent on human decision-making and intelligence in the lower levels of the hierarchy.

## 5. Summary

We define a preliminary model for specifying levels of autonomy for unmanned systems. The model contains a definition of autonomy, a set of tiers for autonomy per system configuration, and a set of variables for dividing autonomy levels. An example is used to illustrate some aspects of this model. We plan to further develop this model and verify the model against particular applications.

| System Scope | Mission Scope | Mission Complexity |
|---|---|---|
| System of Systems | Make sure that the NIST campus is secure | Multiple vehicle cooperation, high level of task knowledge, high uncertainty, large spatial and temporal scope |
| Single Vehicle | Go behind building 202 and keep a lookout for intruders coming through fence | Single vehicle, multiple subsystems, medium level of task knowledge, high uncertainty, medium spatial and temporal scope |
| Subsystem | Goto_waypoints (UTM1, UTM2, …UTMn) Scan_direction(UTMa, UTMb, dwell) | Single subsystem, low level of task knowledge, medium-low uncertainty, medium-small spatial and temporal scope |
| Actuator | Remote control | Single subsystem, no task knowledge, very low uncertainty, small spatial and temporal scope |

Note that all the high, medium, low, large, and small designations are relative.

**Figure 6: Example of levels of autonomy characteristics for an unmanned system**

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