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AUTONOMY MEASURES FOR ROBOTS

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ABSTRACT

Robots are becoming increasingly autonomous. Yet, there are no commonly accepted terms and measures of how "autonomous" a robot is. An ad hoc working group has been formed to address these deficiencies, focusing on the unmanned vehicles domain. This group is defining terminology relevant to unmanned systems and is devising metrics for autonomy levels of these systems. Autonomy definitions and measures must encompass many dimensions and serve many audiences. An Army general making decisions about deployment of unmanned scout vehicles may want to only know a value on a scale from 1 to 10, whereas test engineers need to know specifics about the types of environments and missions that the vehicles are expected to deal with. Any system will have to communicate with humans, hence this is an important dimension in evaluating autonomy. The autonomy levels for unmanned systems (ALFUS) group is therefore developing metrics based on three principal dimensions: task complexity, environmental difficulty, and human interaction. This paper reports on the current state of the ALFUS metric for evaluating robots.
Keywords: robots, autonomy levels

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 terrorist attacks.

Organizations planning to fund development of new mobile robots 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 mobile robots. The Department of Defense Joint Program Office (JPO), the U.S. Army Maneuver Support Center, and 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

Autonomous Control Levels (ACL) [4]. The Army Science Board has described a set of levels of autonomy [5]. It is imperative that these and other agencies leverage each other's efforts and aim at a government wide consistent approach. This is why ALFUS was formed by government practitioners. We envision that participation in group will be open to industry in the future.

ALFUS strives to address many aspects pertaining to UMS definition, including providing reference standards for system specification and performance measurement purposes.

1. 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. [14] 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 three level categorization [15]:

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 [4] describes an 11 level ACL chart that ranges from 0 for remotely piloted vehicles to 10 for Human-Like, fully autonomous vehicles. 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 chart is specific to air vehicles.

Within the ALFUS work group, we define an UMS's autonomy as its own ability to achieve its goals. Therefore, the more complex the goals are, the higher the level of autonomy the UMS has achieved. The ALFUS working group defines autonomy as [7]:

(A) The condition or quality of being self-governing [8].

(B) A 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 human-robot interaction (HRI). Autonomy is characterized into levels by factors including mission complexity, environmental difficulty, and level of HRI to accomplish the mission.

2. THE ALFUS FRAMEWORK

Thus far, the ALFUS Working Group has formulated, through consensus, a framework within which the levels of autonomy can be described. Not just operational or technical aspects are covered. The framework is intended to support financial and lifecycle issues. Thus, the Autonomy Levels for Unmanned Systems (ALFUS) framework includes the following elements:

1. Terms and Definitions: A set of standard terms and definitions that support the autonomy level metrics.
2. Detailed Model for Autonomy Levels: A comprehensive and detailed specification for determining the autonomy. The audience is technical users of UMSs.
3. Summary Model for Autonomy Levels: A concise, scalar presentation of the autonomy levels. The audience is executives and end users (in the DoD domain, these would include combat leadership, program managers, unit leaders, and soldiers).
4. Guidelines, Processes, and Use Cases: A process to translate the detailed, technical ALFUS model into the summary model as well as guidelines to apply the generic framework to specific ALFUS models. A number of use cases may be generated to demonstrate the application processes.

At the end-user level, mission-specific autonomy level definitions will be most useful. At the other extreme of the spectrum, it will be very beneficial to have a generic framework that applies to unmanned system domains that include ground vehicles, air vehicles, undersea vehicles, surface vessels, and littoral water robots. Figure 1 demonstrates these Framework concepts. To address the challenge of developing a truly generic model spans various application domains, the working group will develop ALFUS using a spiral software development approach. The first iteration will address the Army Future Combat Systems (FCS) needs.

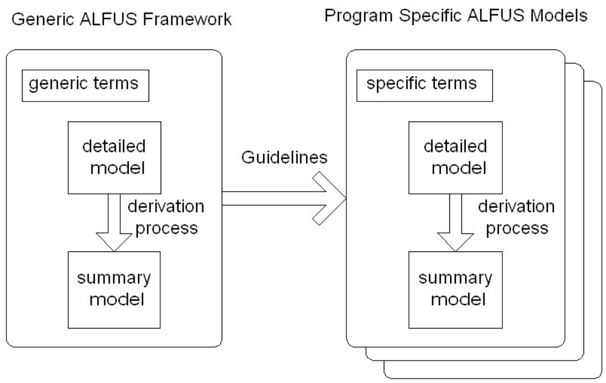

Figure 1: The construct of the ALFUS framework

2.1 Terms and Definitions

Terms and definitions provide a core vocabulary necessary in the discourse pertaining to unmanned systems. They are key to establishing a common description of Autonomy Levels for Unmanned Systems. These terms will provide a basis for metrics for system performance evaluation on which the Autonomy Level for a UMS will be determined. The terminology definition process strives to leverage existing work as much as possible by adopting existent, relevant definitions. Certain existing terms may be adopted and modified to fit the objectives of the ALFUS group. The terminology definitions must also take into consideration cultural factors, such as how terms are currently used in a particular domain. Generic terms as well as domain-specific terms will be defined and identified as such.

The main generic terms that we have defined or adopted to support the ALFUS framework include: autonomy, environment, fusion, human robot interface (HRI), mission planning, mode of operation, perception, robotic follower, situation awareness, task decomposition, and unmanned system (UMS). The main domain specific terms include: cooperative engagement, sensor to shooter, and unattended ground sensors. Version 1.0 of the terminology has been published [7]. The detailed and summary model for autonomy levels are described in the following two sections.

2.2 Detailed Model

The detailed model is defined as comprehensive set of metrics that represent multiple aspects of concerns, including mission complexity, environmental difficulty, and level of HRI that, in combination, indicate a UMS's level of autonomy.

Autonomy levels are driven by multiple factors, which have been identified as:

- Task complexity and adaptability to environment
- Nature of collaboration with humans, including levels of operator or other human involvement and different types of interaction
- Qualitative Factors: e.g. whether and how do the following affect a UMS's autonomy levels: mission success rate, response time, and precision/ resolution/ allowed latencies [9]

Figure 2 illustrates the ALFUS detailed model. This model's three axes are difficulty of the environment, complexity of the mission, and operator interaction (inversely proportional – less interaction is more autonomous). The autonomy level of a particular UMS can be represented with a triangular surface fitted through the values on the three axes. This model suggests vectors, as opposed to a single scale, to characterize unmanned system autonomy levels.

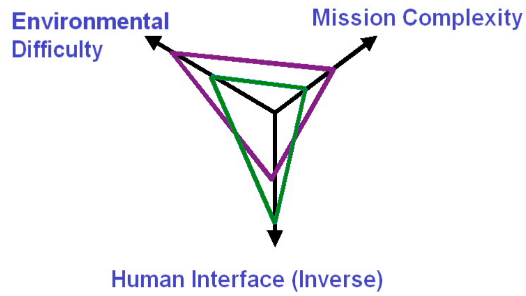

Figure 2: Three dimensions determining the autonomy level for unmanned systems, detailed model

2.3 Summary Model and Its Derivation Process

The summary model is defined as a set of linear scales, 0 or 1 through 10, used to indicate the level of autonomy of a UMS[1]. This model is derived from the UMS's Detailed Model for Autonomy Levels [9].

Ultimately, the intent for ALFUS is to convey high-level characteristics of unmanned systems to engineering managers, procurement officers, government officials, corporate leadership, and other non-technical parties. In the DoD domain, these would include combat leadership, program managers, unit leaders, and soldiers. The metrics that are developed should use the languages that these types of users speak and be consistent with a culture that these types of users live in.

Basing the Summary Model on the Detailed Model provides the target audience a certainty in the foundation and formulation of the level of autonomy assigned. An issue addressed was whether the autonomy levels should be characterized using numbers versus labels such as modes. Higher autonomy may not be characterized with stepwise capability increase of equal amounts, as numbers would indicate. A counter argument is that, users, meaning the soldiers and combat leaders in the DoD domain, relate to numbers better. In this regard, a simple 0 (or 1) through 10 scale was selected.

In terms of converting the detailed model to the summary model, a simple way is to weigh and add up all the metric measurements in the detailed model. Sophisticated algorithms involving statistics or mathematical functions could also be used.

[1] Some of the existent charts use 0 while others use 1 as the lowest level. This remains an open issue in the Group as we strive to be compatible with existent work.

3. METRICS FOR DETAILED MODEL

Having established the general approach for the definition of the Autonomy Levels for Unmanned Systems, the next challenge is establishing the comprehensive set of metrics to support the Detailed Model for Autonomy Levels. At this time the Detailed Model is composed of three primary groupings: Mission Complexity, Environmental Difficulty, and the Level of HRI. Each group will be populated with an exhaustive set of measurable factors. These factors, in addition to a formalized approach for their analysis (*statistical analysis, "weighted average", distribution*), will aid in the formulation of a consistent and repeatable measure(s) of "autonomy" for communicating functionality within the unmanned systems framework. The following sections describe the metrics and the detailed model. Additional, detailed descriptions can be found in [16].

3.1 Mission Complexity

Autonomy levels for particular UMSs are specified and evaluated according to the missions and tasks that the systems are capable of performing. An unmanned system that is capable of performing a security surveillance task is regarded as having a higher level of autonomy than a system that is only able to perform a point-to-point driving task.

There are four major categories of metrics for measuring the complexity of missions. They are:

1) Tactical Behavior: The composition and structure of the involved tasks provide an essential measure for the complexity of a mission. The particular metrics include:
    - Number of different types of major subtasks
    - Numbers of supervisor-subordinate levels within the UMS
    - Number of decision points

    Note that, for UMSs that employ solution paradigms other than hierarchical task decomposition, these metrics can be given zero or low weights, depending on the metrics' relevance to the UMS architecture.

    A mission may be typically decomposed into levels of subtasks until reaching the actuator level task commands. This concept is described extensively in the NIST 4D/RCS architecture [10]. The combination of the number of subtasks after the first-level decomposition and the number of levels of decomposition should provide system technical staff a good measure of the complexity of the mission without requiring exhaustive details of a complete task decomposition structure. In experimental systems, there may well be multiple ways to perform task decomposition, whereas in an established domain such as DoD, standard task lists may exist that may provide helpful constraints for task decomposition.

    Number of decision points indicates how the subtasks are used in the mission execution. In simple cases, the subtasks may be executed only once to accomplish the mission goals, whereas complex situations may require the execution of multiple instances of some of the subtasks, possibly concurrently.

2) Coordination and Collaboration: A mission with a higher level of complexity typically requires a higher level of coordination and collaboration among the components or subsystems. From a system perspective, a UMS that is able to perform a high level of coordination and collaboration should be regarded as having a high level of autonomy.

    The metrics in this category include:
    - Number of participating entities
    - Enabling interfaces: types of data, frequency, number of channels, idling time due to data dependency.

3) Performance: A UMS's ability to achieve mission goals with high efficiency and accuracy through its planning and execution components indicates the UMS's autonomous capability. The specific measure of performance include:
    - Mission planning and analysis capability at pre-mission, during mission, and post mission stages
    - Allowed latencies and errors

    Mission planning capability is the UMS's capability to generate plans to achieve the desirable states for the three stages, namely, Ready, Goal, and Standby, respectively. Allowed latencies and errors mean the UMS's capability to execute the plans to achieve and maintain at the Goal state. The allowed errors contain spatial and temporal aspects. Note that effectiveness and efficiency of the generated plans should be a part of the measure.

4) Sensory Processing/World Modeling: The perception requirements for particular missions and the dependency on external information indicate levels of complexity of the missions. The metrics include:
    - Situation awareness required
    - Information independence

    Task planning and performance require corresponding perception capabilities, ranging from sensing, information modeling, knowledge updating through event detection. Information independence means the extent to which the required information is generated and maintained onboard the UMS and, therefore, indicates the capability requirement.

As the number of control levels in a system increases, the multiple tactical behaviors that the lower level subsystems perform may be integrated into single behaviors with a higher level of abstraction [10]. For example, when the task is for a team of UMSs to conduct security surveillance at a certain area, at the individual vehicle level, we could say that the vehicle A has ALFUS-5[2] for mobility, ALFUS-3 for the Reconnaissance, Surveillance, and Target Acquisition (RSTA) function, and ALFUS-4 for communication. Vehicle B may have different ALFUS capabilities. However, at the higher, Section level, the ALFUS should be specified such as Section Alpha has autonomy ALFUS-3 for the bounding over-watch behavior. Section Bravo has ALFUS-5 for convoying. At an even higher level, joint behaviors including aerial vehicles may be identified.

3.2 Environmental Difficulty

The measure of Environmental Difficulty is complex and closely intertwined with the other measures. This measure is decomposed into categories including Static Environment, Dynamic Environment, Electronic/Electromagnetic Environment, Mobility, Mapping and Navigation, Urban Environment, Rural Environment, and the Operational Environment. Each category is further described with a draft set of specific measurable factors. The granularity of the factors within each category must still be determined. For example, although a UMS can maneuver through smoke, the level of visibility must remain greater than 5 meters and the obscurant limits the safe speed of the vehicle. Many such inter-dependencies and issues with the detail of the measure arise.

At this time, the working group is not directly addressing specific inter-dependencies between the various measures. The granularity of the measure, however, will be proposed and used for development of the model for the Autonomy Levels. As the model matures, many changes in both the categories and factors of the data set and the granularity of measures will occur.

The type of soil, for instance, does not fully quantify its impact on the vehicle system. Clay might be easily traversable until a hard rain makes it all but impossible for a light skid-steer UMS to perform simple maneuvers. The classification of elevation data, presented as an average for an area, would not, at first glance, appear to have an impact on the Autonomy Level of Unmanned System. However, combined with minimum and maximum factors, the measure provides a basis for determining the fit of a robot to a particular terrain. Further, these factors do not provide any quantities to process within a mathematical model.

3.3 Level of HRI

The relationship between the Level of Human Robot Interaction (HRI) and the Autonomy Level for the Unmanned System is fairly linear for simple systems. The inclusion of planning and coordination capabilities by the robots forces the introduction of complexity into the measure of HRI. Rather than collecting factors based on intervals between instructions or on bandwidth for command and control, the measures must now account for the time before and after a mission the HRI is required for mission completion: duration (seconds) and frequency (Hz) of HRI pre-mission, during mission, and post-mission. For highly experimental robots, the time of the scientists and engineers must be added to that of the operators. For example, for five minutes of unsupervised operation, the machine might require five days of direct human interaction. As this will not be the case for most unmanned systems utilizing the ALFUS framework, the model must allow for the omission of such attributes.

The following categories were created for capturing metrics to account for the impact of HRI on autonomy:

Human Intervention: This metric captures the frequency, duration, and number of unplanned robot initiated interactions. Intervention is "an unanticipated action or input by the user to help complete a task" (as defined by ALFUS WG). Normal interaction is measured by Operator Workload.

Operator Workload: Operator workload: Measures the workload associated with normal (i.e. planned) operation of the UMS. This measure is captured for Pre/Post Mission workload and Mission workload. The NASA TLX [13] is a common measurement tool for operator workload that includes six categories (Physical Effort, Mental Effort, Temporal, Performance, Frustration, and Overall Mental and Physical Effort).

Operator Skill Level: Both the UMS Operator and Support Personnel are included in this category. This measure captures the training and education level. The higher the autonomy level of the robot, the less skill is required of the operator.

Operator to UMS Ratio: This measure captures the ratio of operators to unmanned systems. The larger number of robots one operator controls, the higher the level of autonomy is assumed for the robots.

Two other metrics identified by the HRI subgroup are Logistics and Ease of Use. Currently these metrics are not included in the HRI ALFUS matrix. The logistics measures deal with system-specific aspects of the unmanned system such as effort to launch and retrieve, control station attributes and communications. Ease of use measures that are not subjective will be captured in the other categories.

Relevant HRI studies, such as [11][12], must be investigated to find out their potential impact on the ALFUS HRI metrics.

3.4 Additional Concerns

We have determined that our first model should focus on the aforementioned three axes. Additional axes, however, may be required for the future versions. The concerns may include:

System Dependence

It was suggested that good characterization of UMS capabilities could be important for the system autonomy

[2] We use the hypothetical indices, without elaboration, only as an illustration and do not imply establishing any ALFUS metrics at this point.

specification. A question was brought up for further investigation: whether small and large robots should be separately evaluated in terms of their autonomy levels.

Implementation also may affect the ultimate autonomy ratings or evaluation frameworks. It was pointed out that different system control approaches, e.g., reactive sensor-based behavior and deliberative knowledge-based behavior might lead to different autonomy frameworks.

Cost and Technology Readiness

An open question is whether cost, affordability, as well as the maturity of the technology enabling particular ALFUS levels should be taken into account when considering autonomy levels. This requires further investigation.

3.5 Perceived Application Models and Benefits for Autonomy Level Framework

Various types of users may employ the autonomy level framework at various levels of detail. As mentioned, a corporate executive or battlefield commander may only need to know a concise index showing the UMSs' autonomy level. Engineering staff may need the full detail of the presented detailed model to test and evaluate a UMS. Project management personnel might need a representation that is between the two extremes. Discussions have begun on how to summarize and present the metrics in such a format.

We envision that each of the detailed metrics axes, as described in the earlier sections, can be summarized into a one to ten scale, indicating the autonomy level from the particular perspective. In addition to the level numbers, three sets of descriptors can be developed to capture the functional characteristics that the particular levels entail. Figure 3 demonstrates the effect.

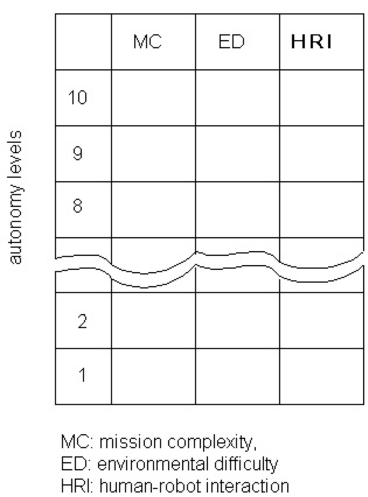

Figure 3: Autonomy levels matrix

Since these descriptors aim to be commonly accepted within the community, this framework provides a common reference for communication. Executive or end users can use either the level numbers or the descriptors to communicate about the requirements for their planned new UMS systems. For example, it should help facilitating unambiguous system specification. This would be potentially significant benefit, as some of the users have conveyed to us, since lengthy text is currently being used to capture the requirements which often causes confusion due to the ambiguity.

We further envision applying this matrix to each of a UMS's major functions. Figure 4 demonstrates a particular vehicle being specified or evaluated with the matrix.

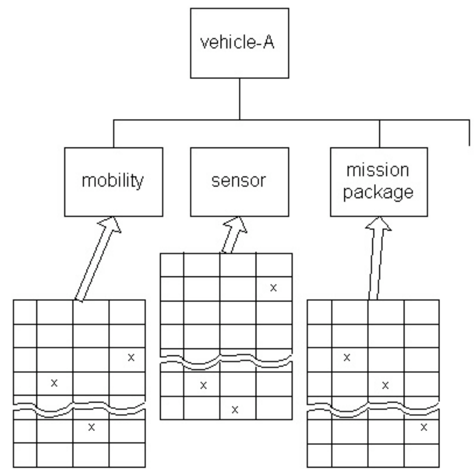

Figure 4: Applying the autonomy level matrix to a UMS

4. SUMMARY AND PLANS

It is recognized that the issue of autonomy levels for unmanned systems is extremely complex. The Autonomy Levels for Unmanned Systems working group has established a structure for the autonomy level framework and has accomplished an initial set of metrics for the framework. A significant amount of work remains to be accomplished, including:

- refine the metrics along the three axes,
- resolve potential overlaps and conflicts among the metrics,
- develop guidelines for integrating the metrics, including the relative weights, interdependency, and various algorithms,
- devise a method of transforming the three-axis detailed model to the concise, summary model for autonomy levels,
- develop methods to apply the ALFUS framework,
- develop testing evaluation procedures for the ALFUS framework,
- develop documentation, use cases and examples to help disseminating the framework, and
- seek to apply the framework to the Army Future Combat Systems and other unmanned system programs.

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