Meeting Report
for the First Federal Agencies Ad Hoc Working Group Meeting for the Definition of the Autonomy Levels for Unmanned Systems (ALFUS)

September 11, 2003
POC: Hui Huang at hui-min.huang@nist.gov

Executive Summary

The First workshop accomplished the following:

- Recognized the critical needs to have a set of standard definitions and metrics for specifying and evaluating unmanned systems in terms of their levels of autonomy.
- Recognized the complexity of the unmanned systems autonomy level issues. Identified many factors that needed to be taken into account, including task complexity, human interaction, environmental difficulty, mission and system dependence, and performance and quality factors.
- Extensively exchanged viewpoints and began to grapple with the technical issues.
- Established a forum for discussion and exchange of ideas.

The working group decided to develop the first iteration of the autonomy levels for unmanned systems (ALFUS) model to support the next Operational Requirements Document (ORD) cycle of the Army Future Combat Systems (FCS) program, by September 2003. It was also determined that, to expedite the progress, a smaller team of six representing different application domains should be, and was assembled and charged to:

- define a set of terms,
- define methods for establishing metrics for autonomy, and
- draft an ALFUS model.

The results should provide a focal discussion point for the next workshop, planned to be held at mid September.

The participants were requested to convey their program requirements and expectations toward the working group.

1. Introduction

Unmanned vehicles have been fielded in several domains in the recent past, ranging from battlefields to Mars. Most major efforts have been funded by various U. S. government agencies. As the number of programs for developing unmanned systems (UMS) accelerates within government, there is a growing need for characterizing these systems. Individual Government agencies have begun these efforts. Just to name a few, 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. The Air Force Research Laboratory has established Autonomous Control Levels (ACL). The Army Science Board has described a set of levels of autonomy. It is imperative that these and other agencies leverage each other's efforts and aim at a government wide consistent approach.

All these efforts have been driven by the advancement of mobile robotic technology and the expanded roles that unmanned systems have been playing in military and civilian situations. As Government agencies, private industry as well, are specifying unmanned system capabilities, it is critical to have a set of standard definitions. These definitions can also provide metrics for systems' performance evaluation. These motivate this ad hoc government working group.

2. Overall Objectives

The ultimate objectives for the working group are:

- Determine the needs for metrics for autonomy levels of unmanned systems.
- To devise methods for establishing metrics of autonomy for unmanned systems.
- To develop a set of widely recognized standard definitions for the levels of autonomy for unmanned systems.

A consensus was reached that the autonomy model and definitions developed through this working group will be used in Government contract specifications or program evaluation processes, including the Army FCS program.

3 The First Workshop setting

The first Workshop was held on July 18, 2003 at NIST. Participants included representatives from the Department of Defense Office of the Secretary of Defense (DoD OSD), Defense Advanced Research Projects Agency (DARPA), U.S. Air Force, multiple organizations within the U.S. Army, including ARL, AMRDEC, AATD, CERDEC, DCD MANCEN, TARDEC, and UAMBL, Department of Commerce (DOC), Department of Energy, and Department of Transportation (DOE).

Given the complexity of the problem and the diversity of the application domains, the following near-term objectives were set up for the first meeting:

- To exchange viewpoints and begin to grapple with the technical issues.
- To establish a forum for discussion and exchange of ideas.

The following are the existent autonomy level definitions that were presented and discussed:

- Autonomous Control Levels (ACL) from AFRL
- Levels of Autonomous Behaviors from Army Science Board Ad Hoc Study on Human Robot Interface Issues
- FCS Semi-Autonomous UGV Behavior Levels from Army MANCEN
- FCS UGV Levels of Robotic Behaviors from UGV/S JPO as presented to BG Schenk, February 2003
- Levels of Autonomy from NIST.

4 Motivations for greater autonomy

A brief summary of the motivators for higher autonomy in unmanned system is:

- Autonomy has been motivated by lack of bandwidth. It is not realistic to expect to be able to teleoperate a vehicle remotely due to the large amount of data that needs to be sent back from the vehicle to the human operator. Bandwidth is a limited resource in most circumstances. There are also instances where communications must be curtailed for stealth reasons or where communications are not available (e.g., deep within tunnels).

- Safety for personnel is another major motivator. If an unmanned system requires close attention and monitoring by human personnel (possibly nearby) these humans are potentially in peril due to either lack of focus on their own safety as they tend to the vehicle or because of their physical proximity to a dangerous area.

- Potential system mission effectiveness is limited by cognitive workload. Currently fielded unmanned systems require close control by highly trained human operators. In some cases, multiple operators are required for a single vehicle. The humans are therefore limited in their ability to perform their own tasks within the mission.

5 Requirements expressed by participants

Given that autonomy is desirable in unmanned systems, several of the requirements as expressed by the various participants that drive the working group include:

- Definitions and Framework: A common set of definitions and framework are needed for measuring technology goals and for advancement in terms of system autonomy.

- Metrics and Benchmarks: Conformance metrics or benchmarking are needed for Government to evaluate autonomy that contractors propose.

- Autonomy Level Definitions: The Army Future Combat Systems (FCS) requires autonomy level definitions to be able to specify its unmanned system requirements. While existent references, such as the Joint Robotic Program UGV Master Plan, contain useful information, upgrades are needed.

- Standard Definitions: Definition of success for this group would be the establishment of standard definitions of UGV autonomy that describe UGV mobility, control, and behavior to support combat developments, technology development, and joint communications.

- Quantitative Measures: Participants also welcomed the emphasis on metrics. As technology for unmanned systems matures, the community needs to become more rigorous in its evaluations and definitions. Quantitative measures are necessary.

6 Complexity of ALFUS Definitions

6.1 Definition of autonomy and a set of terms

The following have been proposed as the definition of autonomy:

Autonomy is measuring decisions that vehicle is doing.

Autonomy is an UMS's autonomy is its own ability to achieve its goals.

An UMS's autonomy is its own ability to achieve its goals.

This issue requires further iterations.

6.2 Contributing elements to ALFUS

The participants have converged on the notion that the autonomy levels involve multiple aspects:

- Multiple areas: mobility, control, and tactical behaviors
- Task complexity and adaptability to environment—washing machines should not be considered to have high levels of autonomy.
- Collaboration with humans: levels of involvement and different modes of interaction.
- Quality factors: how do the following affect UMS's autonomy level: mission success rate, response time, precision/resolution/tolerances, and environmental quality.

Vectors, as opposed to a single scale, may be better suited to characterize unmanned system autonomy levels. The following sections elaborate on these elements.

6.3 Human factors

The human and robot interaction (HRI) issues, in terms of how they affect the unmanned systems and how they affect the ALFUS definitions, were discussed in length. The Army states that the control that soldiers have over systems is critical and that it does not foresee a system that does not require HRI.

It was suggested that human and robot involvement should not be complementary fractions that add up to one. Rather, preliminary thinking was that, at higher levels of control, HRI is at higher levels of abstraction and such interactions, when designed properly, might greatly enhance system capabilities. Further exploration along this line is needed.

Additional HRI factors that could contribute to the autonomy level definitions include:

- whether an UMS can initiate and can assume authority,
- what must a human do for a system conducting a certain mission, and
- how should operators be assigned to UMSs depending on operator skill levels and types.
- whether { number of vehicles / number of operators } or { person hours / flight hour } might be sound metrics.

Overall, it was left for further investigation as how human factors affect ALFUS definitions.

6.4 Numbered scales versus named modes

Opposing views were expressed about whether the autonomy levels should be characterized using numbers. It was suggested that modes might be better characterization for UMS autonomous behaviors. Higher autonomy may not be characterized with stepwise capability increase of equal amounts as numbers would indicate. One example given is that the JRP Master Plan describes four modes of operations, which are not expressed in numbers.

There also were counter suggestions that users, meaning the soldiers, relate to numbers better. In this regard, a simple 0 or 1 through 10 scale was the consensus.

6.5 Representation Issues for ALFUS --multiple types of audience

The multi-dimensional, task-specific nature of autonomy measures, coupled with the need to communicate the measures to multiple types of audience poses many challenges in terms of how to represent autonomy levels. The Joint Architecture for Unmanned Systems (JAUS) model is an example effort that includes a Reference Architecture for technical readers, a Domain Model for operational readers, and a Strategic Plan for overall guidance. Another example would be 4D/RCS. 4D/RCS is a reference model architecture and engineering methodology that has been used very successfully in the ARL Demo III program. 4D/RCS is currently being used for development of autonomous driving skills and tactical behaviors on the DARPA Mobile Autonomous Robots (MARS) program, the TACOM VTI program, and the FCS Autonomous Navigation System. The highly modular structure of 4D/RCS is suggestive of how performance of various components, such as planners, perception systems, world modeling algorithms, and cognitive reasoning engines might be evaluated individually as well as part of an integrated system.

It was discussed that the autonomy level specification may contain at least two facets. One would be comprehensive and detailed specifications aiming at technical users such as staff with various Army various Research, Development, and Engineering Centers (RDEC), Government Contracting Technical Specialists and evaluators, and contract concerns. This specification would encompass all the considerations as described in this section.

Another facet would be a set of concise, numbered indices aimed at use by combat leadership, executives, and operational users like program managers (PMs), unit leaders, and soldiers. There needs to be a sound process to translate the technical ALFUS definitions into languages that these types of users speak and into a culture that these types of users live in. An advantage would be simplicity. An important cultural issue is that combat leaders and soldiers are and will remain the centerpiece of our military force.

An important cultural issue is that combat leaders and soldiers are and will remain the centerpiece of our military force. These users are:

- Adaptive and innovative
- Competent with technology and enhanced equipment
- Battle focused leader/soldier training
- Organized to win tactical fight

This working group should interact with users with individual programs so that the particular cultural issues are addressed adequately in considering representations.

6.6 Approach--generic versus specific models

There was consensus that, at the end-user level, the autonomy level definitions should be mission specific to be most useful.

Given the wide differences in unmanned system domains that include ground vehicles, air vehicles, undersea vehicles, surface vessels, and littoral water robots, where autonomy may be defined differently, a great challenge would be whether generic definitions could be obtained.

The notions of generic model and reference model were, however, proposed as worth further investigations. A generic model was presented that attempts to characterize autonomy levels in terms of vehicle groupings, environmental complexity, task complexity, and quality factors. The objective is to explore whether the model can be extended for each individual mission specific ALFUS.

Additional suggestions called for generic term definitions and methods for characterizing system capabilities. It was recommended that the JRP Master Plan, containing relevant term definitions, should be referenced.
It was suggested, and adopted, to develop ALFUS with a spiral approach. The first iteration should respond to the Army FCS needs for its next ORD cycle, by October 2003 and should start with a set of term definitions.

6.7 Missions dependence and task complexity

It was a consensus view that the autonomy levels for particular UMSs are specified and evaluated according to the missions and tasks that the systems are capable of performing.

As a system expands its configuration and includes higher levels in the control hierarchy, the multiple tactical behaviors that lower level subsystems perform may be integrated into single behaviors with a higher level of abstraction (see Reference 8). For example, when the task is for a team of UMSs to conduct security surveillance on the NIST grounds, at the individual vehicle level, we could say that the vehicle #A has ALFUS-5[1] 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 autonomy level should not be characterized as Vehicle #A in section 1 has ALFUS-5 for mobility, etc. Instead, the ALFUS should be specified such as Section Alpha has autonomy ALFUS-3 for the bounding overwatch behavior. Section Bravo has ALFUS-5 for convoying. At an even higher level, joint behaviors including aerial vehicles may be identified.

6.8 System dependence

It was suggested that good characterization of UMS capabilities is critically important for the system autonomy specification. A question was brought up for further investigation: whether small and large robots should be separately evaluated in terms of their autonomy levels.

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.

6.9 Environmental difficulty

It was pointed out that ALFUS should consider the environmental factors. For example, for the task of road following for an UGV, the road could be:

- A road with or without clear markings.
- Road with or without same or opposite direction traffic.
- Light vs. heavy traffic.
- Straight vs. curve roads.
- Urban roads vs. freeways.
- Well paved vs. snow or ice covered roads.

It is possible that multiple ALFUS designations are needed to address all of these road conditions, but this requires further investigation.

6.10 Quality/Performance factors

It was raised that metrics might include:

- precision/error bounds of solutions

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

- solution efficiency and optimality
- mission success rate
- system response time
- system perception capability in handling poor visibility

6.11 Cost and technology readiness

It was pointed out that, cost, affordability, as well as the maturity of the technology enabling particular ALFUS levels, ought to be taken into account when considering autonomy levels. This requires further investigation.

The NASA originated and Army adopted Technology Readiness Level (TRL), both the scale and the entire method behind it, was mentioned as a possible reference.

7 Example functional requirements that affect autonomy definitions

Particular program requirements were presented in the meeting. We described several sets, in the following section as illustrations while additional[2] were also presented, see Appendix C:

7.1 Army/FCS

- Mobility Autonomy
  - Semi Autonomous Navigation
  - Leader Follower
  - Intelligent Driving Decision Aids
- Control Autonomy
  - Operator Control Units
  - Mission Planner
- Behavior Autonomy
  - Intelligent Tactical Behavior
  - Mission “Payload” Behavior

7.2 Unmanned Combat Armed Rotorcraft (UCAR)

The following summarize the autonomy needs from the DARPA/Army UCAR program:

- Technology Challenges
  - Autonomous operation & collaborative execution by teams of heterogeneous systems
  - Low altitude autonomous flight
  - Affordable and robust survivability solutions
  - Substantial improvement in target ID & target recognition ranges
- Top-level mission tasking
- Real-time on-board autonomous mission planning, re-planning and mission execution
- Autonomous operation with collaboration among systems (manned & unmanned, air & ground)
  - Target acquisition hand-off
  - Target ID
  - Weapons tasking
  - BDA
- Command & control from the air or ground

[2] We encourage participants to add particular program requirements in this section.

  - Integration into existing operational architecture

7.3 DOT

DOT has re-emerging interest in autonomy. Major focuses are:

- Bus rapid transit along major travel corridors.
- Community transit services--Driver cost is 70% cost of a transit route.
- Safety poses another constraint to autonomy.

8 The First Workshop Summary

The objectives of the working group were to:

- Determine the needs for autonomy levels metrics for unmanned systems
- Devise methods for establishing metrics of autonomy for unmanned systems
- Develop a set of widely recognized standard definitions for the levels of autonomy for unmanned systems

However, given the complexity of the problem and the diversity of the application domains, the following near-term objectives were set up for the first meeting:

- To exchange viewpoints and begin to grapple with the technical issues.
- To establish a forum for discussion and exchange of ideas.

The morning involved presentations regarding various programs and what the presenters were using/ suggesting for autonomy levels. Several models were provided and none were agreed to. Initial discussions focused on the need to provide two levels of scale, one at a high level similar to the AFRL's ACL scale and another focused on multiple dimensions of autonomy such as level of intelligence, capability, etc. Doug Gage suggested that a vector be utilized as a measure of multiple dimensions. The biggest discussion focused on what dimensions should be measured. One suggestion was made to look at the following three dimensions: Task Complexity, Adaptability to Environment, and Level of Human Interaction. Another suggestion was to include: Mobility, Control, and Behavior Autonomy.

Since the community came from different backgrounds, it was suggested that a set of definitions be created such that a common framework could be established. Primarily, autonomy was suggested that it could be derived from: a) reactive sensor based behavior and b) deliberative knowledge based behavior. This led to even more discussion.

Some metrics were mentioned such as:

- Man hours/ flight hour
- #of vehicles/#of operators
- Quality Factors such as mission performed x% of the time
- Human workload
- Mission planning time

A general consensus was that a simple scale of 1-10 would be desired as a high level scale and another detailed scale would be needed by the technical community to determine where and how a UMS would fit into the 1-10 scale such that Cost as and Independent Variable could be quantified.

It was also suggested that we try to determine the requirements for a solution specification such that we could provide focus for the group. Another suggestion was to develop an initial spiral 1 definition such that we would have an initial starting point on which to build. It was also suggested that the current group size was too large (>20) and that a smaller team needs to be put together to generate a draft consensus of autonomy and a draft model. 6 members were identified to work on this prior to the entire team reconvening in September. Additionally the participants were asked to review the JRP definitions and to provide their expectations for the ALFUS working group.

9 Action Items and Next Workshop

It was requested from the group that a first version of the autonomy level definitions be available for the next edition of the Army FCS ORD by September. This resulted in a group decision to hold the next workshop at mid September. The location would be the Baltimore vicinity.

To accomplish the objective for the next workshop, a small group has been assembled and charged to:

- define a set of terms,
- define methods for establishing metrics for autonomy, and
- draft an ALFUS model.

The group includes representatives from different domains, David Bruemmer of DOE, Robert Ferlis of DoT, Hui Huang of NIST, Brian Novak of TARDEC, Alan Schultz of NRL, and Bob Smith of AFRL.

It has also been resolved for NIST to set up a web site and discussion groups to post information and to facilitate interactions.

Appendix A: List of Participants

Albus, Jim--NIST
Arthur, Keith--Army AATD
Barbera, Tony--NIST
Bruemmer, David--DOE INEEL
Cagle-West, Marsha--Army AMRDEC SED
Cerny, Jeff--Army AMRDEC-ASD
Clough, Bruce--AFRL
Dzugan, Mike--Army CERDEC
English, Woody--AFRL
Ferlis, Robert--DoT FHWA
Gage, Doug--DARPA
Gage, Gerrie LTC--DARPA
Higgins, Ray--Army AATD
Huang, Hui--NIST
Juberts, Maris--NIST
Knichel, David--Army DCD
Kotora, Jeff—OSD Support (Titan)
Messina, Elena--NIST
Novak, Brian--Army TACOM
Overstreet, Dennis--DARPA Support (SRS Tech)
Pavek, Kerry--Army UAMBL (Titan)
Scott, Harry--NIST
Shoemaker, Chuck--ARL
Smith, Bob--AFRL
Wavering, Albert--NIST

Appendix B: References

1) Joint Robotics Program Master Plan 2003, http://www.jointrobotics.com/activities_new/FY2003%20Joint%20Robotics%20Master%20Plan.pdf
2) Army Science Board Ad Hoc Study On Human Robot Interface Issues
3) Care & Feeding Of The ACL
4) Unmanned Systems S & T Roadmap Presentation (Army)
5) Technology Development for Army Unmanned Ground Vehicles – Summary
6) Air Vehicle Mission Behavior, RISTA
7) UGV Mission List (JTA-A WSTAWG UVA IPT)
8) 4D/RCS Reference Model Architecture @ http://www.isd.mel.nist.gov/projects/rcs/
9) Parasuraman, R., Sheridan, T. B., and Wickens, C. D. A Model for Types and Levels of Human Interaction with Automation. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, Vol. 30, No. 3 May 2000.
10) Sheridan, T. B. Telerobotics, Automation, and Human Supervisory Control. The MIT Press. 1992

Appendix C: Workshop I Presentation Slides (Files in CD)

Albus/NIST
Bruemmer/DOE
Clough/AFRL (missing)
Ferlis/DoT-FHWA
LTC Gage/DARPA and Arthur/Army AMRDEC
D. Gage/DARPA
Huang/NIST
Knichel/Army DCD
Kotora/OSD
Novak/Army TACOM
Pavek/Army UAMBL
Shoemaker/ARL
Smith/AFRL (coordinated)