NIST Special Publication 1011

Autonomy Levels for Unmanned Systems (ALFUS) Framework

Volume I: Terminology

Version 1.1

Contributed by the Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems Working Group Participants[1]

Edited by: Hui-Min Huang
National Institute of Standards and Technology

September 2004

[1] See list for Contributors.

EXECUTIVE SUMMARY

This document, produced by the Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems (ALFUS) Working Group (WG), defines and collects the terminology to support the Group's main objective, the definitions of the unmanned system autonomy levels and the metrics for measuring the autonomy levels.

The WG consists of, and was founded by, unmanned systems professionals from government agencies and their supporting contractors[2] on a voluntary basis. The WG output is based on Group consensus. In its first workshop, held on July 18, 2003, the Group has decided to launch an effort to produce a framework for autonomy level definitions and metrics. A committee, composed of six participants and representing different application domains, was formed and charged to draft the framework. Also decided was that the first version of the framework should focus on supporting the first client of this working group effort, the Army Future Combat Systems (FCS) program.

The WG determined, at the second workshop, held on September 11, 2003, that terminology should be the first part of the to-be-developed initial framework. The terms should be defined in a generic way to support unmanned vehicles of various domains, including aerial, ground, and water. In this version of the document, we attempt to maintain the generic nature of the terms as well as to support the specific program, FCS.

The approaches in this terminology effort are:

- Leverage existent work and adopt existent definitions given in relevant references. This would expedite the Group's effort in proceeding with its core objective, the autonomy level model. The references are listed at the end of this document. Modifications to the existent definitions may be necessary[3] to fit the objectives of this working group.
- Consider the cultural factor, for example, how people are using the terms, to ensure a seamless transition of the outcome to the users.
- Consolidate similar terms and resolve conflicting ones.
- Some terms may have generic and widely applicable definitions but are further defined for specific domains. We may provide both their generic definitions, in the GENERIC TERMS AND DEFINITIONS section, and their extensions in the DOMAIN SPECIFIC TERMS OR EXTENSIONS section. There are also terms that are only applicable to specific domains. They are defined in the DOMAIN SPECIFIC TERMS OR EXTENSIONS section, as well. Further efforts are needed to enhance this categorization.
- Derived terms are not redefined but are cross-referenced to the definition for the root term.

Version 0 of the document, from NIST and the working committee, was presented and discussed in the second workshop. Additional terms were identified, which were assigned to the

[2] The WG will be open to all the interested professionals at a later stage.
[3] There are several cases when the definitions contributed by our WG members are similar to those given in the existent references. The descriptions from the existent references were typically adopted as the basis but enhanced by Members' contributions.

participants for definitions. Numerous further iterations have been conducted with the working group participants and user communities thereafter. This draft has all the contributions incorporated. The plan is to finalize Version 1 of this document by January 2004 for the FCS. Since the working group has adopted a spiral development approach, this document is fully anticipated to evolve alongside the autonomy level framework itself. Readers and user communities have been, and are continuously encouraged to provide feedback.

Please address feedback to:

Hui-Min Huang
National Institute of Standards & Technology
Bldg. 220 Rm. B124
100 Bureau Drive, Stop 8230
Gaithersburg, MD 20899-8230
Tel: 301 975-3427
Fax: 301 990-9688
Email: hui-min.huang@nist.gov

TABLE OF CONTENTS

AUTHORING COMMITTEE

Bruemmer, David—DOE INEEL[4]
Ferlis, Robert—DoT FHWA
Huang, Hui-Min—NIST
Novak, Brian—U.S. Army TACOM
Schultz, Alan C.—U.S. Navy NRL
Smith, Robert—U.S. Air Force AFRL

CONTRIBUTORS

Adams, Curt—U.S. Army TACOM
Albus, James—NIST
Antonishek, Brian—NIST
Arthur, Keith—U.S. Army AATD
Barbera, Anthony—NIST
Barnhill, Robert MAJ—U.S. Army
Brendle, Bruce—U.S. Army TACOM
Bruemmer, David—DOE INEEL
Cagle-West, Marsha—U.S. Army AMRDEC SED
Cerny, Jeffrey—U.S. Army AMRDEC-ASD
Clough, Bruce—U.S. Air Force AFRL
Dzugan, Mike—U.S. Army CERDEC
English, Woody—U.S. Air Force AFRL Support
Ferlis, Robert—DoT FHWA
Gage, Doug—DARPA
Gage, Gerrie LTC—DARPA
Higgins, Ray—U.S. Army AATD
Hirtz, Julie—U.S. Army DCD
Hodge, Kelley A. MAJ—U.S. Army
Huang, Hui-Min—NIST
Juberts, Maris—NIST
Knichel, David— U.S. Army DCD
Kotora, Jeffrey—OSD Support (Titan)
Mamplata, Caesar G.—U.S. Navy NAVAIR
Messina, Elena—NIST
Novak, Brian—U.S. Army TACOM
Overstreet, Dennis—DARPA Support (SRS Tech)
Rovegno, John COL—U.S. Army
Pavek, Kerry— U.S. Army UAMBL (Titan)
Scholtz, Jean—NIST
Schultz, Alan C.—U.S. Navy NRL
Scott, Harry—NIST
Shoemaker, Charles— U.S. Army ARL
Smith, Robert— U.S. Air Force AFRL
Swan, Stephen—U.S. Army Support (Titan)
Wavering, Albert—NIST
Wit, Jeffrey— U.S. Air Force AFRL Support

[4] See APPENDIX B: ACRONYMS.

VERSION HISTORY

- Version 1.1—Document title changed from “Terminology for Specifying the Autonomy Levels for Unmanned Systems” to “Autonomy Levels for Unmanned Systems (ALFUS) Framework, Volume I: Terminology,” September 2004.
- Version 1.0—Published in January 2004.
- Draft Version 1.0—Accommodated comments raised in the Workshop #3, distributed on December 11, 2003.
- Draft Version 0.9—Distributed to members and user community on October 25, 2003, redistributed on November 10, 2003.
- Draft Version 0.7—Distributed to members and user community for feedback at the end of September 2003.
- Draft Version 0—Presented and discussed in Workshop #2, September 11, 2003.

INTRODUCTION

Unmanned systems have been fielded in several domains in the recent past, ranging from battlefields to Mars and mostly sponsored by the Government. As the number of programs for developing unmanned systems accelerates, there is a growing need for characterizing these systems. Individual government agencies have begun these efforts. The Department of Defense Joint Program Office, the Air Force Research Laboratory, the U.S. Army Science Board, the Army Maneuver Support Center, and National Institute of Standards and Technology have described levels of autonomy for various programs [2, 28, 29, 30, 31]. NASA has embarked upon a project on defining levels of autonomy for a human space flight vehicle [32]. It is beneficial that these and other agencies leverage each other's efforts and aim at a consistent approach.

This incentive gives rise to the Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems (ALFUS) Working Group. The Group's objectives are to define methods for establishing metrics for autonomy and to draft a framework for autonomy levels for unmanned systems (ALFUS). The Group determined that a beginning step would be to identify and define a set of terms that may be needed to support the framework development effort. The terms should include a set that is generic and applicable to unmanned vehicles of various domains and another set that is domain specific, including extensions to the generic terms.

The workshop participants identified the terms based on such premises. However, it is possible that, after further investigation, some of the terms currently identified as generic might be reassigned to the domain specific section. Some other terms might even be considered beyond the scope of the autonomy level definition. It is also understood that additional terms may be included as the working group efforts proceed further. We plan to continue updating this document and addressing these issues in the future versions.

Several format and structural notes:

1. Terms are listed in alphabetical order. Terms that have the same roots are grouped together and defined to facilitate consistent definitions. These terms also appear according to their original alphabetical order without being redefined.

2. Boldface is used to indicate the terms defined in this document. When used in defining other terms, a term is hyperlinked to its original definition in the electronic version of the document.

3. On the different types of references, we use:

    - braces, { }, to indicate that the definition is adopted, i.e., a direct cut-and-paste or close to it, from the cited reference,
    - brackets, [ ], to relate the stated definitions to the cited reference(s), and
    - angular brackets, < >, to point to ongoing discussions, potential future expansions, unresolved issues, etc., as described in APPENDIX A. TO-DO LIST.

    Note that footnotes are indicated with numbers in superscript.

4. Multiple definitions, obtained either from multiple references or through members consensus, may be given to a term when necessary. They are indicated with (A), (B), (C) ... .

5. APPENDIX B: ACRONYMS facilitates both the definition of the Terms and the autonomy level framework itself.

GENERIC TERMS AND DEFINITIONS

Adapt to Failures and Operational Conditions.

An unmanned system experiencing either system failures or operational conditions that prevent it from continuing its optimal mission profile will react within the confines of its capabilities. Adaptation with respect to capabilities includes hover, orbit, stop, and station keeping. This adaptation is performed by the system until the condition is cleared or by the operator. System requirements may mandate that the unmanned system continue to perform the mission in a degraded mode.

Autonomous.

Operations of an **unmanned system** (**UMS**) wherein the **UMS** receives its **mission** from the human <1> and accomplishes that **mission** with or without further **human-robot interaction (HRI**). The level of **HRI**, along with other factors such as mission complexity**,** and environmental difficulty, determine the **level of autonomy** for the **UMS** [2]. Finer-grained autonomy level designations can also be applied to the **tasks**, lower in scope than **mission**.

Associated terms:

Fully autonomous. See under **Mode of Operation**.

Semi-autonomous. See under **Mode of Operation**.

Autonomous Collaboration.

The ability of a **UMS** to **collaborate** with one or more manned vehicles or **UMS** without the need for an external controlling element**.**

Autonomy.

(A) The condition or quality of being self-governing {1}.

(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 **HRI**. Autonomy is characterized into levels by factors including **mission** complexity, environmental difficulty, and level of **HRI** to accomplish the **missions**.

Associated terms:

Autonomy Level or Level of Autonomy.

Set(s) of progressive indices, typically given in numbers, identifying a **UMS**'s capability for performing **autonomous** missions. Two types of metrics are used, **Detailed Model for Autonomy Levels** and **Summary Model for Autonomy Levels**.

Autonomy Levels for Unmanned Systems (ALFUS).

A general term referring to the autonomy level framework, models, and the level numbers.

Detailed Model for Autonomy Levels.

A 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**. This model corresponds to the **Summary Model for Autonomy Levels.**

Summary Model for Autonomy Levels.

A set of linear scales, 0 through 10 or 1 through 10, indicating the **level of autonomy** of a **UMS**. This model is derived from the **UMS**'s **Detailed Model for Autonomy Levels.**

Built-in Test.

Equipment or software embedded in operational components or systems, as opposed to external support units, which perform a test or sequence of tests to verify mechanical or electrical continuity of hardware, or the proper automatic sequencing, data processing, and readout of hardware or software systems.

Classes of UGVs. The JRP postulates several classes of **UGV**s, based on weight {2}, <3>:

- Micro: < 8 pounds[5]
- Miniature: 8-30 pounds
- Small (light): 31-400 pounds
- Small (medium): 401-2,500 pounds
- Small (heavy): 2,501-20,000 pounds
- Medium: 20,001-30,000 pounds
- Large: >30,000 pounds.

Cognizance Levels or Levels of Cognizance.

The levels of what a **UMS** can know or understand based on its **sensory processing** capability:

- Level 1 – data, or observed data. In initially processed forms after measured by sensors.
- Level 2 – information. Further processed, refined and structured data that is human understandable.
- Level 3 – intelligence, knowledge, combat and actionable information. Further processed for particular mission needs. Directly linked to tactical behaviors.

Collaboration or Cooperation.

The process by which multiple manned or **unmanned systems** jointly work together by sharing data, such as coordinates of their maneuver(s) and local Common Relative Operational Picture (CROP), or by acquiring intelligence to perform a **mission** synergistically, i.e., perform better than each could have alone <2>.

Associated term:

---

[5] NIST endorses SI units. However, since the definition is adopted, in its entirety, from the cited reference, the usage of British units is retained.

Coordination.

The ability for **UMS**'s or manned systems to work together harmoniously through common data such as mission or task plans, coordinates of maneuver(s), local CROP, etc. A common way is for a superior to **coordinate** the task execution of the subordinates to accomplish the missions [1, 3].

Control Level or **Level of Control.** <10>

Controlling Element.

The part of a **UMS** that provides a method for a human to control it remotely.

Cooperation. See **Collaboration.**

Coordination. See under **Collaboration.**

Data Fusion. See **Fusion.**

Detailed Model for Autonomy Levels. See under **Autonomy.**

Dynamic mission planning. See **mission planning.**

Environment.

Used as a general reference, environment includes the generic, natural conditions; e.g., weather, climate, ocean conditions, terrain, vegetation, etc. Modified environment can refer to specific induced environments; e.g., dirty battlefield environment, nuclear-chemical-biological environment, etc. Environment includes those conditions observed by the system during operational use, standby, maintenance, transportation, and storage. Mission environment includes threat situation or Electronic Order of Battle (EOB), Rules of Engagement (ROE), Emission Condition (EmCon), etc.

Fault Tolerance.

The ability of a system or component to continue normal operation despite the presence of hardware or software faults {14}.

Fully autonomous. See under **Mode of Operation**.

Fusion. Also referred to as **Information Fusion** or **Data Fusion.**

(A) The combining or blending of relevant data and information from single or multiple sources (sensors, logistics, etc.) into representational formats that are appropriate to support the interpretation of the data and information and to support system goals like recognition, tracking, situation assessment, sensor management, or system control. Involves the process of acquisition, filtering, correlation, integration, comparison, evaluation and related activities to ensure proper correlations of data or information exist and draws out the significance of those correlations [6, 7]. The processes can be performed with a combination of human analysis/judgment and system processing.

(B) Information processing that deals with the association, correlation, and combination of data and information from single and multiple sources to achieve refined position and identity estimation, complete and timely assessments of situations and threats, and their significance in the context of mission operation. The process is characterized by continuous refinement of its estimates and assessments, and by evaluation of the need for additional sources, or modification of the process itself, to achieve improved results [8].

Fusion Levels or **Levels of Fusion.**

Each of the six levels of fusion adds progressively greater meaning and involves more analysis {9} [5]:

- Level 0 - organize. This is the initial processing accomplished at or near the sensor that organizes the collected data into a usable form for the system or person who will receive it.
- Level 1 - identify/correlate. This level takes new input and normalizes its data; correlates it into an existing entity database, and updates that database. Level 1 Fusion tells you what is there and can result in actionable information.
- Level 2 - aggregate/resolve. This level aggregates the individual entities or elements, analyzes those aggregations, and resolves conflicts. This level captures or derives events or actions from the information and interprets them in context with other information. Level 2 Fusion tells you how they are working together and what they are doing.
- Level 3 - interpret/determine/predict. Interprets enemy events and actions, determines enemy objectives and how enemy elements operate, and predicts enemy future actions and their effects on friendly forces. This is a threat refinement process that projects current situation (friendly and enemy) into the future. Level 3 Fusion tells you what it means and how it affects your plans.
- Level 4 - assess. This level consists of assessing the entire process and related activities to improve the timeliness, relevance and accuracy of information and/or intelligence. It reviews the performance of sensors and collectors, as well as analysts, information management systems, and staffs involved in the fusion process. This process tells you what you need to do to improve the products from fusion level 0-3.
- Level 5 - visualize. This process connects the user to the rest of the fusion process so that the user can visualize the fusion products and generate feedback/control to enhance/improve these products.

Goal.

A result (or state) to be achieved or maintained [3].

Hazard Avoidance.

Similar to **obstacle avoidance** except that the subjects are not limited to physical objects but also include adversarial situations, as either assessed by the **UMS**’s perception functions or provided through the **HRI**, that are to be avoided.

Human/Operator Intervention.

The need for **HRI** in a normally **fully autonomous** behavior due to some extenuating circumstances. An unanticipated action or input by the user to help complete a task.

Human robot coordination. See **coordination.**

Human Robot Interaction/Interface (HRI). Also referred to as **human interaction** or **operator interaction.**

(A) The activity by which human operators engage with **UMS**s to achieve the **mission goals**.

(B) The architecture for interaction between the robot and the human. It includes the specification of the interaction language: what tasks the user can ask of the robot and the corresponding actions, what tasks the robot can ask of the user and the corresponding actions. It is independent of a particular display or interaction modality. It is the planned and anticipated interactions between the robot and the user.

(C) **Human Robot Interface** is further used to reference the physical realization of the method of **Human Robot Interaction** or **Intervention**.

The following are the different roles of interaction possible for the human in **HRI** <4>. Note that one person could possibly assume a number of roles or numerous people could take individual roles or even share roles. The user interface should be based on the types of roles the user will assume. In addition to specific information needed for each role, the user will need some awareness of other roles simultaneously interacting with the robot.

Supervisor – the supervisor monitors one or more robots with respect to progress on the mission, can task the robot(s) at the mission level, monitors mission progress, provides mission level directions, coordinates missions, and can assign an operator to assist a robot if needed.

A commander would be an example of a person who performs the supervisor-only role.

Teammate/Wingman – this is considered to be a human team member. **UMS** and its **teammate** each performs part of the overall mission and they coordinate when needed. The teammate may command the **UMS** at the levels of detail of **tasks** or **task** plans.

Operator – the role assumed by the person performing **remote control** or **teleoperation, semi-autonomous** operations, or other man-in-the-loop types of operations. The operator input is expected at certain states during normal operations. During error conditions, the operator determines the problem that a robot is experiencing in interacting with the physical world, interacts with the robot to solve this if possible and returns control to the supervisor with an outcome, successful or not. If the operator cannot overcome the problem it may be necessary to pass the robot control to the mechanic.

Mechanic or **Developer –** determines the problem with the hardware or software that the robot is having, solves this if possible, may interact with the robot to test out the proposed solution, and returns control of the robot to the supervisor with a determination.

Bystander – coexists in the same environment as the **UMS** but with an unknown role. The bystander role could be neutral, friendly, or adversarial, or include various combinations. The bystander and the **UMS** need to build up some expectation of what the counterpart will do in order to react accordingly. For example, the driver, a **bystander**, of a car may have to interact at a four way stop with a UMS. They both need some indication as to whether the other vehicle knows the rules of the road.

Pedestrians and traffic police would be examples of bystanders who would have limited interaction with autonomous driving vehicles. **UMS** needs to be able to protect itself from possible harm from adversarial **bystander**.

Human Operated.

The type of **HRI** that refers to **remote control** or **teleoperation**.

Human Assisted.

The type of **HRI** that that refers to situations during which human interactions are needed at the level of detail of **task** plans, i.e., during the execution of a task.

Human Delegated.

The type of **HRI** that refers to situations during which human interactions are mainly at the **task** level.

Human Supervised.

The type of **HRI** that refers to situations during which humans play the monitoring role and human interactions are mainly at the mission level.

Information Fusion. See **Fusion.**

Leader Follower. See **Robotic Follower.**

Markers (physical or electronic).

A visual or electronic aid used to mark a designated point for such tactical purposes as route following, determination of bearings, courses, or location, and key items or points of interest, including landmine markers, minefields markers, and area NBC decontamination markers. Traffic signs and signals are additional examples of **Markers**.

Methods of Control.

The interface, either software or hardware, such as a joystick, waypoint selection via a map interface, natural language, hand signals, etc., that operators use to control a **UMS**.

Mission.

The highest-level **task** assigned to the **UMS** {3}.

Mission Module.

A self-contained subsystem installed on a **UMS** that enables the **UMS** to perform designed **missions**. It can be easily installed and replaced by another type of mission module [2].

Mission Planning.

The process to generate tactical goals, a route (general or specific), commanding structure, coordination, and timing for one or teams of **UMS**s. The mission plans can be generated either in advance by operators on an **OCU** or in real-time by the onboard, distributed software systems. The latter case is also referred to as **dynamic mission planning** [2**,** 3].

Mobility.

The capability of a **UMS** to move from place to place, with its own power and while under any mode or method of control. Characteristics: the **UMS**'s speed, location, and fuel availability [2]. Refueling could be performed either as a part of the **HRI** or autonomously by a fuel management autonomy task at a higher level.

Mode of Operation or Operational Mode.

Human operator's ability to interact with a **UMS** to perform the operator assigned **missions**. The following are the defined **modes of operation**: **fully autonomous, semi-autonomous, teleoperation,** and **remote control.**

Associated terms:

Fully autonomous.

A **mode of operation** of an **UMS** wherein the **UMS** is expected to accomplish its **mission**, within a defined scope, without human intervention. Note that a team of **UMS**s may be **fully autonomous** while the individual team members may not be due to the needs to coordinate during the execution of team missions.

Semi-autonomous.

A **mode of operation** of a **UMS** wherein the human operator and/or the **UMS** plan(s) and conduct(s) a **mission** and requires various levels of **HRI** [2] <6>.

Teleoperation.

A **mode of operation** of a **UMS** wherein the human operator, using video feedback and/or other sensory feedback, either directly controls the actuators or assigns incremental goals, **waypoints** in mobility situations, on a continuous basis, from off the vehicle and via a tethered or radio linked control device [2]. In this mode, the **UMS** may take limited initiative in reaching the assigned incremental goals.

Remote control.

A **mode of operation** of a **UMS** wherein the human operator, without benefit of video or other sensory feedback, directly controls the actuators of the **UMS** on a continuous basis, from off the vehicle and via a tethered or radio linked control device using visual line-of-sight cues {2}. In this mode, the UMS takes no initiative and relies on continuous or nearly continuous input from the user.

Observation.

(A) The information collection stage of the "OODA Loop" (Observation, Orientation, Decision, Action)[6]

(B) Measurement of the environment by sensors that produce signals that can be analyzed.

Obstacle.

(A) Any physical entity that opposes or deters passage or progress, or impedes mobility in any other way [12].

(B) Any obstruction designed or employed to disrupt, fix, turn, or block the movement of an opposing force, and to impose additional losses in personnel, time, and equipment on the opposing force. Obstacles can be natural, manmade, or a combination of both. [13] They can be positive, negative (e.g., ditches), or groupings (e.g., areas with high security alert) and can be moving or still <5>.

Operational Mode. See **Mode of Operation.**

Operator Control Unit (OCU).

Also referred to as **operator control interface (OCI)** or **human interaction control unit**. The computer(s), accessories, and data link equipment that an operator uses to control, communicate with, receive data and information from, and plan **missions** for one or more **UMS**s {2}.

Orientation.

(A) The stage in the OODA loop (Observation, Orientation, Decision, Action) that involves analysis and prediction and generates information to support decision making stage

(B) Rotational displacement between two coordinate frames of reference.

Perception.

A **UMS**'s capability of sensing and building an internal model of the environment within which it is operating, and assigning entities, events, and situations perceived in the environment to classes. The classification (or recognition) process involves comparing what it observed with the system's a priori knowledge[7] [3].

Associated term:

Local perception.

When the perception process has occurred locally onboard the **UMS** and is regarding the **UMS's** local environment and within the **UMS**'s mission context.

Perception Levels or Levels of Perception [3].

The progressive results of sensory information after the data have gone through multiple levels of **sensory processing**:

---

[6] Conceived by Col. John R. Boyd in the 1970s as an air-to-air combat strategy for military fighter pilots.
[7] Similar to the combination of Observation and Orientation as used in ACL.

- Level 1 – point or pixel. A point of concern has physical properties that, quantitatively, can be either measured with the systems' sensor(s) in a one-to-one correspondence or computed over time and space.
- Level 2 – line or list. Groupings of sets of points according to certain criteria, such as continuity in position and direction, over space and/or time.
- Level 3 – surface or boundary. Groupings of sets of contiguous lines or lists according to certain criteria, such as continuity in orientation or curvature, over space and/or time.
- Level 4 – object. Groupings of sets of contiguous surfaces and boundaries according to certain criteria, such as rigid body mechanics, over space and/or time.
- Level 5 – unit of objects. Groupings of sets of objects according to certain criteria, such as density, distribution, and relative positions, motions, and interactions, over space and/or time.

Point Man or **Unmanned Point Man, Robotic Point Man.**

(A) A human (soldier in the military domain) assigned some distance ahead of a patrol as a lookout.

(B) The capability of an unmanned system to perform tasks analogous to a soldier **point man** [12].

Prognostic Health Management.

System using artificial intelligence or other intelligent algorithms and a combination of sensors and models of systems to autonomously react to environmental changes and monitor the operational and maintenance characteristics of the system or systems under consideration [16].

Rear Guard, Unmanned Rear Guard or **Robotic Rear Guard.**

(A) The rearmost elements of an advancing or a withdrawing force. It has the following functions: to protect the rear of a column from hostile forces; during the withdrawal, to delay the enemy; during the advance, to keep supply routes open.

(B) Security detachment that a moving ground force details to the rear to keep it informed and covered. {13}

(C) The capability of a **UMS** to perform tasks within a detachment normally assigned to a human **rear guard**.

Remote Control. See under **Mode of Operation**.

Remotely Guided.

An unmanned system requiring continuous input for mission performance is considered remotely guided. The control input may originate from any source outside of the unmanned system itself. This mode includes remote control and teleoperation.

Robot/Robotic.

An electro-mechanical system that can react to sensory input and carry out predetermined missions. A robot is typically equipped with one or more tools or certain capabilities, including knowledge so that it can perform desired functions and/or react to different situations that it may encounter [4].

Robotic Follower or **Leader Follower.**

The capability of a UGV to traverse a safe and tactically relevant route previously traversed <7>. The follower vehicle traverses the route automatically (i.e., under computer control using onboard sensors) potentially with significant physical or temporal separation from the leader. This capability takes advantage of human sensing and reasoning in the lead vehicle to reduce the perception and intelligence requirements for the follower vehicle. The follower vehicle may incorporate some limited perceptual capabilities to detect and avoid new obstacles that appear after the lead vehicle has passed {10}.

Self-Healing.

Automated or semi-automated capability of system repair, covering the infrastructure, hardware, and software aspects [17].

Self-Diagnosis.

Ability to adequately take measurement information from sensors, validate the data, and communicate the processes and results to other intelligent devices {18}.

Scout.

Also referred to as **unmanned scout** or **robotic scout**:

1. A person, aircraft, or ship sent out to obtain information, esp. in preparation for military action {13}.
2. The capability of an unmanned system to perform tasks analogous to a human scout.

Semi-Autonomous. See under **Mode of Operation.**

Sensor.

Equipment that detects, measures, and/or records physical phenomena, and indicates objects and activities by means of energy or particles emitted, reflected, or modified by the objects and activities. [19, 20]

Sensor Fusion:

(A) same as **fusion** except limiting data source to sensors.

(B) A process in which data, generated by multiple sensory sources, is correlated to create information and knowledge. Sensor information, when fused, may yield immediately actionable combat information and/or intelligence. The capabilities are of four essential types: Detection, Classification, Recognition, and Identification [9].

Sensory Processing.

Computing processes that operate on either direct sensor signals or on low level sensory signatures to detect, measure, and classify entities and events and derive useful information, at proper resolutions and at levels of abstractions, about the world. **Sensory processes** can be organized hierarchically with proper relative spatial and temporal resolutions and organized horizontally with assigned but coordinated focuses [3].

There are several ways to organize the progressive sensory processes, to perceive the resulting information, and to structure the knowledge and intelligence:

- **Levels of Fusion.** See **Fusion Levels.**
- **Levels of Perception.** See **Perception Levels.**
- **Levels of Cognizance.** See **Cognizance Levels.**

Situational Awareness.

The perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the future. In generic terms the three levels of **situational awareness** are level 1, perception, level 2, comprehension, and level 3, projection. There is both individual and group or team **situational awareness** [25].

Summary Model for Autonomy Levels. See under **Autonomy.**

Tactical Behavior.

A behavior that has some high level tactical significance.

Task.

A named activity performed to achieve or maintain a goal. **Mission** plans are typically represented with tasks. Task performance may, further, result in subtasking. Tasks may be assigned to operational units via task commands [3].

Task Decomposition.

A method for analyzing **missions** and **tasks** and decomposing them into hierarchical subtask structures according to the criteria of command/authority chain, control stability, computational efficiency, and management effectiveness [3].

Teaming.

(A) The linking together of platforms, forces, or systems to complete a **mission** or **task** collectively that would be more difficult to do if the units acted separately. The process is characterized by distributed operations and high tempo maneuvers, which demands rapid synchronization, swift adaptation of plans and control measures, flexible groupings of distributed staff elements, and direct exchanges between commanders across hierarchies. For example, manned and unmanned platforms can be teamed to emphasize their complementary strengths. The unmanned systems have the further requirements of being able to easily and quickly communicate their intentions, goals, present state in the accomplishment of these goals, intended next action, and current problem areas. Additionally, they have to be able to be re-tasked easily to participate in the current overall goal and to fit into their new position in the organizational structure. The above is critical if they are to perform effectively in team activities [22].

(B) A method of operation where a system uses the combined sensing, information exchange, decision-making, and acting capabilities of humans and robots function together to carry out missions within the planned scope.

In the situations of manned – unmanned **Teaming,** air-to-ground teaming means that the manned system is in the air with **UMS** on the ground. Similarly, there could be air-to-air, ground-to-ground, and ground-to-air types of teaming.

Teleoperation. See under **Mode of Operation.**

Telepresence.

The capability of a **UMS** to provide the human operator with some amount of sensory feedback similar to that which the operator would receive if he were in the vehicle {2}.

Team of Teams or **System of Systems.**

Grouping(s) of vehicle teams (unmanned and/or manned) for a particular mission where a team is a collection of vehicles for a particular **task** or subtask.

Terrain.

The physical features of the ground surface, to include the subsurface. These physical features include both natural (e.g., hills) and manmade (e.g., pipelines) features. Major terrain types are delineated based upon local relief, or changes in elevation, and include: flat to rolling, hilly and mountainous. Other important characteristics used to describe the terrain include: hydrologic features (e.g., swamps), vegetation characteristics (e.g., forests) and cultural features (e.g., cities). Complex terrain includes any characteristics or combination of characteristics that make military action difficult. Mobility classes are also used to describe the trafficability of the terrain. The terrain should also be rated as to its trafficability by class of vehicle, this is especially relevant to the use of different classes of UGVs. The three mobility classes are: unrestricted, restricted, and severely restricted. Derived from [26]

Terrain Visualization.

A component of battlefield visualization that provides a detailed understanding of the background upon which enemy and friendly forces and actions are displayed. Terrain visualization provides common terrain background for all users and all applications. Additionally, terrain visualization allows interactive planning and mission rehearsal. Terrain visualization includes both natural and man-made features to include impacts of terrain on vehicle speed, maintenance, river-crossing operations, cross-country trafficability, and maneuverability. Terrain visualization includes the subordinate elements of data acquisition, analysis, database management, display and dissemination. Derived from [27]

Tether.

A physical communications cable or medium that provides connectivity between an **unmanned system** and its **controlling element** that restricts the range of operation to the length of the physical medium [2].

Threat Avoidance.

Ability to detect/degrade/defeat threats. The continual process of compiling and examining all available information concerning threats in order to avoid encounter <5>.

Threat Levels.

The relative ability of an enemy, or potential enemy, to limit, neutralize, or destroy the effectiveness of the current or projected **mission**, organization, or equipment.

Unattended System.

Any manned/unmanned, mobile/stationary, or active/passive system, with or without power that is designed to not be watched, or lacks accompaniment by a guard, escort, or caretaker.

Unmanned System (UMS).

A electro-mechanical system, with no human operator aboard, that is able to exert its power to perform designed **missions**. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned surface vehicles (USV), unattended munitions (UM), and unattended ground sensors (UGS). Missiles, rockets, and their submunitions, and artillery are not considered unmanned systems {2}. See the DOMAIN SPECIFIC TERMS OR EXTENSIONS section for extensions.

Waypoint.

An intermediate location through which a **UMS** must pass, within a given tolerance, en route to a given goal location {2}.

Wingman, or **Unmanned Wingman, Robotic Wingman.**

(A) An aviator subordinate to and in support of the designated section leader; also, the aircraft flown in this role {13}.

(B) The wingman concept assists the leader in the command and control of the system. During operations, the wingman orients his **UMS** on the section leader and, in the absence of orders, moves, stops, and shoots when his leader does. Anytime the wingman of a section is engaged or begins an engagement, the section leader supports the wingman's effort {23}.

(C) The capability of an **unmanned system** to perform tasks analogous to the wingman tasks performed by a serviceman operating a military aircraft or ground vehicle as part of a team or unit {24}.

World Model.

A **UMS'**s internal representation of the world. The world model may include models of portions of the environment, as well as models of objects and agents, and a system model that includes the intelligent **unmanned system** itself. {3}.

Associated term:

World Modeling. The process of constructing and maintaining a **world model**.

DOMAIN SPECIFIC TERMS OR EXTENSIONS

Avenge Kill.

A lethal retaliatory response to the enemy platform that has targeted or engaged friendly forces. This ensures destruction of the enemy that targeted our forces and discourages other enemy forces from sighting, targeting, or designating our forces. When a friendly soldier/platform is designated, the targeted platform immediately alerts supporting forces via the COP. The platform also deploys survivability means like obscuration/screening smoke and fires back to disrupt the enemy designation and engage enemy munitions fired at him. The targeted friendly platform fires back at the enemy as do supporting weapons systems to ensure the enemy is destroyed. This has the potential to psychologically affect other enemy attacks as they realize even by designating a UA element, they may be destroyed. The retaliatory fires can be executed by the targeted/engaged platform, or a supporting platform. {25}.

Cooperative Engagement.

A method of engagement for destroying enemy forces, employing sensors and shooters not resident on the same platform [25].

Point and Shoot.

A subset of **cooperative engagement** that allows a soldier or platform to designate a target for lethal engagement by another platform. The information is immediately displayed on the COP. Point and Shoot implies the immediacy of effects and generally occurs within the same echelon.

Sensor to Shooter.

(A) The information link from a target acquisition capability to the weapons platform(s) that engage(s) the target [19].

(B) Movement of appropriately formatted information from the reconnaissance platform to the attacking weapon system [21].

Standoff.

Detection or lethality efforts intended to suppress an enemy threat from a position outside the range of the enemy threat.

Unattended ground sensors (UGS).

Small, low cost, robust sensors, capable of operating in the field for extended periods of time (30 days or more). They will consist of modular groups of sensors utilizing tailorable ground sensing technologies, such as seismic, magnetic, infrared, acoustic, radio frequency, and CBRN detection, and other advanced sensing capabilities. UGSs self-organize into a networked sensor array (sensor web) by locating the most efficient gateways for transmission of information. They are also self-healing, able to quickly bypass a neutralized gateway and locate a functional one within the sensor web. [Derived from conceptual work in TRADOC Pam 525-3-90, Maneuver O&O]

APPENDIX A. TO-DO LIST

1. It should be considered whether external intervention other than **HRI** should be included in the definition of **autonomous**. If so, then, in the case of an unmanned commanding structure, the commander and subordinates are constantly interacting via commands and status, i.e., they are **cooperating** or **collaborating**. Are we saying that the entire system is fully autonomous, but the individual vehicles are not, and, that **cooperating** or **collaborating** are considered **non-autonomous**?

   HRI has been identified as one of the axes contributing to levels of autonomy. Does this imply an expansion and call "Intervention" as an axis, or do we add another axis and keep HRI as one on its own, due to the vast amount of research results in the subject?

   Further thoughts are needed in the next version.

2. Another school of thoughts argues that, relatively, **coordination** indicates a low level of interaction--inform and don't conflict. **Cooperation** requires, in addition, for the **UMS**s to work toward a common goal. **Collaboration** requires the most, implying some high level, intellectual effort in interactions. In other words, **Cooperation** may occur at **task** level and **Collaboration** at the **mission** level. However, the majority of the comments within the group favor not distinguishing **Cooperation** and **Collaboration.**

3. Other forums (FORA? FIPA?) have looked at other class criteria, loosely based on how much damage they could do if they run amok (such as kinetic energy for UAVs). It depends on the purposes of the class definitions (the aforementioned one for safety concerns).

4. Should reduce the UGV flavor.

5. There is a question on whether obstacle ?= threat. A thought is that, when an entity poses threat, it becomes an obstacle.

6. Subdivisions of **Semi-Autonomous – By Exception** and **Semi-Autonomous – By Permission** were proposed. While there might have been too much detail in terms of categorizing **modes of control**, these could be very useful in categorizing **HRI** effects on the **autonomy levels**.

7. The current implementations focus on the soldier, as opposed to another **UMS**, to be the lead to provide the intelligence to develop the safe and tactically relevant path for the **UMS** to follow. This reduces the sensing, processing, and reasoning requirements for the unmanned follower vehicle. Since a soldier has developed the path, it should be valid. The only obstacles that the **UMS** are susceptible to are those that appear after the lead vehicle has passed, in which case the follower vehicle has some limited obstacle detection and avoidance capabilities. The key is to have the follower traverse the exact same path (within a very small lateral deviation) as the lead vehicle.

   As an example, consider open and rolling terrain with tall grass and some trees. A manned vehicle is able to maneuver through the terrain relatively easily at tactical cross-country speeds. A **UMS** without a path sees the tall grass and tress as obstacles. It can be traversed, but at a much slower speed than a manned vehicle because it cannot easily determine that this is a type of obstacle it can drive through. But now given the proven path of the lead vehicle and other information (such as speed), the **UMS** has confidence that the terrain is traversable and can exploit that fact to increase its speed. This is the whole idea behind the **robotic follower**, using human intelligence to provide a safe path to increase performance.

8. Should review and possibly include the terms used in the 10 levels in the Army Science Board Ad Hoc Study.

9. Does autonomy require mobility?

10. The following definitions require additional efforts:

    Levels of Control (UAV/ Unmanned Systems). FCS UAV control systems will be compliant with the Tactical Control System (TCS) ORD which defines five levels of UAV control:

    (a) Level One is the indirect receipt and direct retransmission of imagery and/or data.
    (b) Level Two is the receipt of imagery and/or data directly from the UAV and the functionality of previous level.
    (c) Level Three is the control of the UAV payload and the functionality of previous levels.
    (d) Level Four is control of the UAV, less takeoff and landing, and the functionality of previous levels.
    (e) Level Five is the full functionality and control of the UAV from takeoff to landing.

    The issues include:

    (1) Levels one and two do not speak to control at all, but simply to the receipt of data from a **UMS**.
    (2) The consensus obtained from Workshop #3 is for Control to be defined along the line of human authority and permission.
    (3) Control Levels are also widely used in hierarchical control theories and architectures, such as 4D/RCS, to define or specify commanding or authority levels in control systems. This concept is consistent with the aforementioned Workshop #3 consensus.
    (4) Whether and how these levels would be related to the autonomy levels.

11. Need to clarify the following issues:
    (1) More specific terms could be used to enhance the term "greater meaning" in **Fusion Levels.**
    (2) Is "a safe and tactical relevant route" required in **Robotic Follower**?

12. Need to investigate the following terms for their definitions, contexts, and whether to include them and in which sections:

    Common Operational Picture (COP).

    A single identical display of relevant information shared by more than one command; to facilitate collaborative planning and situational awareness.

    Common Relative Operational Picture.

    Also investigate whether to formally define the metrics that are being developed for the three axes of the autonomy level framework.

APPENDIX B: ACRONYMS

4D/RCS	NIST 4D/Real-time Control System Reference Model Architecture	http://www.isd.mel.nist.gov/projects/rcs/
AATD	Aviation Applied Technology Directorate, U.S. Army	
ACL	Autonomous Control Levels	
AFRL	Air Force Research Laboratory	http://www.afrl.af.mil/
ALFUS	Autonomy Levels for Unmanned Systems	
AMRDEC	(Army) Aviation and Missile Research, Development and Engineering Center	http://www.redstone.army.mil/amrdec/
ARL	Army Research Laboratory	http://www.arl.mil/main/Main/default.cfm
ATD	Advanced Technology Demonstrator	
ATR	Automatic Target Recognition	
BG	Behavior Generation	http://www.isd.mel.nist.gov/projects/rcs/
C3	Command, Control, and Communications	
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance	http://www.fas.org/irp/doddir/dod/c4isr/es.htm
CAT	Crew integration & Automation Testbed	http://www.tacom.army.mil/tardec/
COP	Common Operational Picture	
CROP	Common Relative Operational Picture	
DARPA	Defense Advanced Research Projects Agency	http://www.darpa.mil/
DCD	(Army) Directorate for Combat Development	
DoC	Department of Commerce	
DoD	Department of Defense	
DoE	Department of Energy	

DoT	Department of Transportation	
EmCon	Emission Condition	
EOB	Electronic Order of Battle	
EOD	Explosive Ordnance Disposal	
FCS	Future Combat Systems	http://www.boeing.com/fcs
FHWA	(DOT) Federal Highway Administration	
FM	Field Manual (US Army)	
FOUO	For official use only	
FWV	Fixed Wing Vehicle	
HCI	Human-Computer Interface	
HMI	Human-Machine Interface	
HMMWV	High Mobility Multipurpose Wheeled Vehicle	
HRI	Human-Robot Interface/Interaction	
h	hour	
INEEL	Idaho National Engineering and Environmental Lab	http://www.inel.gov/
ISD	NIST Intelligent Systems Division	http://www.isd.mel.nist.gov/
IPT	Integrated Product Team	
JAUS	Joint Architecture for Unmanned Systems	http://www.jauswg.org
LSI	Lead Systems Integrator	http://www.boeing.com/fcs
JPO	Joint Project Office	http://www.redstone.army.mil/ugvsjpo/
JRP	Joint Robotics Program	
JTA	Joint Technical Architecture	http://www-jta.itsi.disa.mil/
JTA-A	Joint Technical Architecture - Army	
LADAR	Laser Radar	
m	meter	http://physics.nist.gov/cuu/Units/
METT-TC	Mission, enemy, terrain, time - troops, civilians	
ms	millisecond	
min	minute	

NBC	Nuclear, Biological, and Chemical	
NIST	National Institute of Standards and Technology	http://www.nist.gov/
NLOS	Non-Line of Sight	
NRL	Naval Research Laboratory	http://www.nrl.navy.mil/
OODA	Observation, Orientation, Decision, Action	
ORD	Operational Requirement Document	
OSD	The Office of the Secretary of Defense	
ROE	Rules of Engagement	
RSTA	Reconnaissance, Surveillance, and Target Acquisition	
PCD	Procurement Control Drawing, (essentially a specification)	
RDECOM	(Army) Research, Development, and Engineering Command	
s	second	
SA	Situational Awareness	
SI	International System of Units	http://physics.nist.gov/cuu/Units/
SoS	System of Systems	
SP	Sensory Processing	http://www.isd.mel.nist.gov/projects/rcs/
SED	Software Engineering Directorate	http://www.redstone.army.mil/amrdec/directorates/ sed/index.htm#main
STANAG	NATO Standardization Agreement	
TACOM	U.S. Army Tank-Automotive and Armaments Command	http://www.tacom.army.mil/
TARDEC	Tank Automotive Research, Development and Engineering Center	http://www.tacom.army.mil/tardec/
TCS	Tactical Control System	
TTP	Tactics, Techniques and Procedures.	
UAMBL	Unit of Action Maneuver Battlelab	

UARV	Unmanned Armed Reconnaissance Vehicle	
UAV	Unmanned Aerial Vehicle	
UCAR	Unmanned Combat Armed Rotorcraft	http://www.boeing.com/defense-space/military/unmanned/ucar.html
UGS	Unattended Ground Sensors	
UCAV	Unmanned Combat Air Vehicle	http://www.darpa.mil/ucav/index.htm
UGV	Unmanned Ground Vehicle	
UML	Unified Modeling Language	
UMS	Unmanned System	
USV	Unmanned Surface Vehicles	
UUV	Unmanned Undersea Vehicles	http://www.onr.navy.mil/fncs/auto_ops/default.asp
UVA	Unmanned Vehicle Architecture	
UXO	Unexploded Ordnance	
VJ	Value Judgment	http://www.isd.mel.nist.gov/projects/rcs/
VRA	Vehicle Electronics (Vetronics) Reference Architecture	
WM	World modeling	http://www.isd.mel.nist.gov/projects/rcs/
WSTAWG	Weapon System Technical Architecture Working Group	http://wstawg.army.mil/
XUV	eXperimental Unmanned Vehicles	

REFERENCES

1. Houghton Mifflin Company, The American Heritage Dictionary.
2. 2003 JRP Master Plan. http://www.jointrobotics.com/activities_new/FY2003%20Joint%20Robotics%20Master%20Plan.pdf.
3. Albus, J. et al., 4D/RCS Reference Model Architecture, NISTIR 6910, National Institute of Standards and Technology, Gaithersburg, Maryland, August 2003. http://www.isd.mel.nist.gov/projects/rcs/.
4. http://www.csgnetwork.com/glossary.html.
5. Blasch, E and Plano, S., "JDL Level 5 fusion model: user refinement issues and applications in group tracking," SPIE Vol 4729, *Aerosense*, 2002, pp. 270-279.
6. TRADOC Pam 525-3-90, UA O&O Plan, derived from JP 1-02, Ft Huachuca White Paper, Fusion (13 January 03 (and previous versions), and Senior Leader's Meeting (ICT #4, with the Combined Arm's Center's "10 Big Ideas."
7. W.A.Sander. Information Fusion. In International Military and Defense Encyclopedia, T.N.Dupuy, et al., eds, Vol.3, G-L, pp.1259-1265. Brassey's, Inc., 1993.
8. Joint Directors of Laboratories (JDL), Technology Panel on C3 (TPC3), Data Fusion SubPanel (DFSP).
9. Objective Force Fusion White paper dated 14 March 2003.
10. Robotic Follower ATD Management Plan, TARDEC, 2000.
11. Paraphrased from "Technology Development for Army Unmanned Ground Vehicles", pp. 25-26, Board on Army Science and Technology, The National Academy of Sciences, 2002.
12. Webster's II New Riverside University Dictionary, Houghton Mifflin Co., 1988.
13. Joint Publication 1-02, "DOD Dictionary of Military and Associated Terms", http://www.dtic.mil/doctrine/jel/doddict/.
14. Institute of Electrical and Electronics Engineers. *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*. New York, NY: 1990.
15. Automatic Test Equipment, www.pmforum.org/library/glossary, Wideman Comparative Glossary of Project Management Terms v2.1, May 2001.
16. FMECA Project Website: About the Project, www.fpni.net, Fluid Power Net International, 1998.
17. *Towards Architecture-based Self-Healing Systems*, Eric M. Doshofy et al, Institute for Software Research, WOSS (Workshop On Self-healing Systems) '02, Nov 18-19, 2002, Charleston, SC.
18. Intelligent Sensor, www.allboutmems.com/glossary, All About MEMS (MicroElectroMechanical Systems), 2002.
19. Concept derived from work developed in TRADOC Pam 525-3-90, Maneuver O&O.
20. Webster's New World Dictionary, Third College Edition.
21. Organizational Concepts for the Sensor-to-Shooter World The Impact of Real-Time Information on Airpower Targeting, WILLIAM G. CHAPMAN, Major, USAF School of Advanced Airpower Studies.
22. Derived from conceptual work in TRADOC Pam 525-3-90, Maneuver O&O.
23. US Army Field Manual (FM) 3-20.15.
24. Paraphrased from "Technology Development for Army Unmanned Ground Vehicles", pp. 25-26, Board on Army Science and Technology, The National Academy of Sciences, 2002.
25. U.S. Army Unit of Action O&O dated 30 June 2003.
26. U.S. Army FM 30-10, Military Geographic Intelligence (Terrain) and FM 34-130, Intelligence Preparation of the Battlefield.

27. TRADOC Pamphlet 525-41, Topographic Support for Terrain Visualization and TRADOC Pamphlet 525-70, Battlefield Visualization Concept.
28. Bruce T. Clough, “Metrics, Schmetrics! How The Heck Do You Determine A UAV’s Autonomy Anyway?” Proceedings of the Performance Metrics for Intelligent Systems Workshop, Gaithersburg, Maryland, 2002.
29. Army Science Board, Ad Hoc Study on Human Robot Interface Issues, Arlington, Virginia, 2002.
30. Knichel, David, Position Presentation for the Maneuver Support Center, Directorate of Combat Development, U.S. Army, the First Federal Agencies Ad Hoc Working Group Meeting for the Definition of the Autonomy Levels for Unmanned Systems, Gaithersburg, MD, July, 18, 2003.
31. James Albus, Position Presentation for National Institute of Standards and Technology, Intelligent Systems Division, the First Federal Agencies Ad Hoc Working Group Meeting for the Definition of the Autonomy Levels for Unmanned Systems, Gaithersburg, MD, July, 18, 2003.
32. Ryan W. Proud, et al., “Methods for Determining the Level of Autonomy to Design into a Human Spaceflight Vehicle: A Function Specific Approach,” 2003 PerMIS Workshop, Gaithersburg, MD, September 2003.