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Standard Guide for Unmanned Undersea Vehicles (UUV) Autonomy and Control¹

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INTRODUCTION

ASTM has prepared this series of standards to guide the development of autonomous unmanned underwater vehicles (UUVs). The standards address the key capabilities that a UUV system must possess in order to be considered autonomous and reconfigurable:

Autonomous— Capable of operating without operator input for extended periods of time. Implicit in this description is the requirement that the UUV's sortie accomplishes its assigned goal and makes the appropriate rendezvous for a successful recovery.

Reconfigurable— Capable of operating with multiple payloads. The top level requirement is established that the UUV systems will consist of

Payloads to complete specific system tasking such as environmental data collection, area surveillance, mine hunting, mine countermeasures, intelligence/surveillance/reconnaissance (ISR), or other scientific, military, or commercial objectives.

Vehicles that will transport the payloads to designated locations and be responsible for the launch and recovery of the vehicle/payload combination.

While the payload will be specific to the objective, the vehicle is likely to be less so. Nevertheless, commonality across all classes² of UUV with respect to such features as planning, communications, and post sortie analysis (PSA) is desirable. Commonality with regard to such features as launch and recovery and a common control interface with the payload should be preserved within the UUV class.

In accordance with this philosophy, ASTM identifies four standards to address UUV development and to promote compatibility and interoperability among UUVs:

- F2541 Guide for UUV Autonomy and Control
- WK11283 Guide for UUV Mission Payload Interface
- F2594 Guide for UUV Communications
- F2595 Guide for UUV Sensor Data Formats

The relationships among these standards are illustrated in Fig. 1. The first two standards address the UUV autonomy, command and control, and the physical interface between the UUV and its payload. The last two ASTM standards address the handling of the most valuable artifacts created by UUV systems: the data. Since there are many possibilities for communications links to exchange data, it is expected that the UUV procurement agency will provide specific guidance relative to these links and the appropriate use of the UUV communications standard. In a similar manner, specific guidance is expected for the appropriate use of the UUV data formats and data storage standard.

F2541—Standard Guide for UUV Autonomy and Control—The UUV autonomy and control guide defines the characteristics of an autonomous UUV system. While much of this guide applies to the vehicle and how the vehicle should perform in an autonomous state, the relationship of the payloads within the UUV system is also characterized. A high level depiction of the functional subsystems associated with a generic autonomous UUV system is presented. The important functional relationship established in this guide is the payload's subordinate role relative to the vehicle in terms of system safety. The payload is responsible for its own internal safety, but the vehicle is responsible for the safety of the vehicle-payload system. Terminology is defined to provide a common framework for the discussion of autonomous systems. System behaviors and capabilities are identified that tend to make a system independent of human operator input and provide varying levels of assurance that the UUV will perform its assigned task and successfully complete recovery. A three-axis sliding scale is presented to illustrate the system's level of autonomy (LOA) in terms of situational awareness,

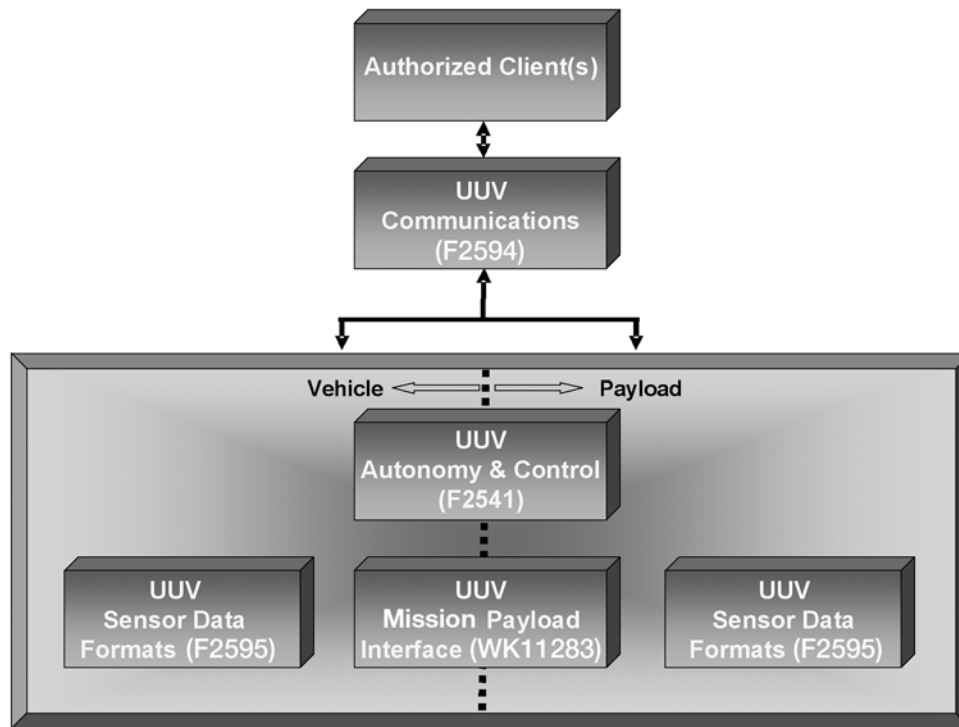


FIG. 1 Notional System Interfaces and Governing Standards

decision-making/planning/execution, and external interaction. The control interface (messages exchanged between the vehicle and the payload) is described and instantiations of this interface for the various classes of UUV are presented in associated appendices.

WK11283—Standard Guide for UUV Mission Payload Interface—The UUV mission payload interface guide is a physical and functional interface standard that guides:

The mechanical and electrical interface between the vehicle and the payload.

The functional relationship between the vehicle and the payload.

In-as-much-as a single physical interface standard cannot address all classes of UUVs, this guide describes the physical interfaces in the body of the guide and provides a guide to the instantiation for each of the classes. This guide reinforces the relationship between the vehicle and the payload and confirms the permission-request responsibility of the payload and the permission-granted/denied authority of the vehicle.

F2594—Standard Guide for UUV Communications—The UUV communications standard guides the development of offboard communications between the UUV system and the authorized clients, that is, those agents designated by the UUV operational authorities with responsibility for programming, operating, or maintaining a UUV, or a combination thereof. An authorized client may also represent an end user of UUV and payload mission data. Such a standard is required to provide for UUV interoperability with multiple authorized agents and to provide the authorized agents with interoperability with multiple UUVs (preferably across the different classes of UUVs). Optical, RF and acoustic methods of communication are considered. While RF communication is a matured communications mode and existing standards are referenced and adopted for offboard surface communication, underwater acoustic communication (ACOMMS) is an evolving field and interoperability between the different ACOMMS systems is also evolving. Typical ACOMMS systems and protocols are described with typical applications related to bandwidth and range. General comments are provided for optical communication as the use of this mode of communication may evolve in the future.

F2595—Standard Guide for UUV Sensor Data Formats—The UUV sensor data formats guide provides the UUV and payload designer with a series of commonly accepted data formats for

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² UUV Master Plan.

underwater sensors. These formats provide the opportunity for two-way interoperability. Their use facilitates the UUV system's ability to process historical environmental data for mission planning purposes. Likewise, use of these formats facilitates the end users' ability to catalog, analyze, and produce recommendations based on current field data. Fig. 1 suggests that both vehicle-specific data as well as payload sensor data should be stored in these data formats.

1. Scope

1.1 This guide covers the need for UUVs to operate autonomously, without constant human intervention, and with flexibility based on their payloads and missions places unique requirements on UUV developers. Because the UUV community is expected to expand both its developer base and its user base in the next several years, it recognizes that success relies upon a well-written standard. The standard must encourage compatibility and reconfigurability, provide a common language to describe functional capabilities, and enable meaningful quantitative performance evaluation.

1.2 The scope of this guide includes those characteristics in a UUV system which, when implemented in a detailed design, result in a UUV that is capable of operating for extended periods of time without external intervention. Implicit in this statement is the requirement that the UUV execute its designated sortie plan. Non-expendable UUVs must also return to a rendezvous point for recovery. The top level concept of such an autonomous system is presented in Fig. 3. The functional relationships identified in this block diagram will be discussed further in Section 4.

1.3 This guide contains a table of terminology so that autonomy and control can be described within the context of a common language, where all terms have consistent and clearly defined meaning. As introduced in Fig. 3, this guide defines high level functional capabilities of the autonomy controller,

the vehicle controller, and the payload controller. Correspondingly high level interfaces are also defined.

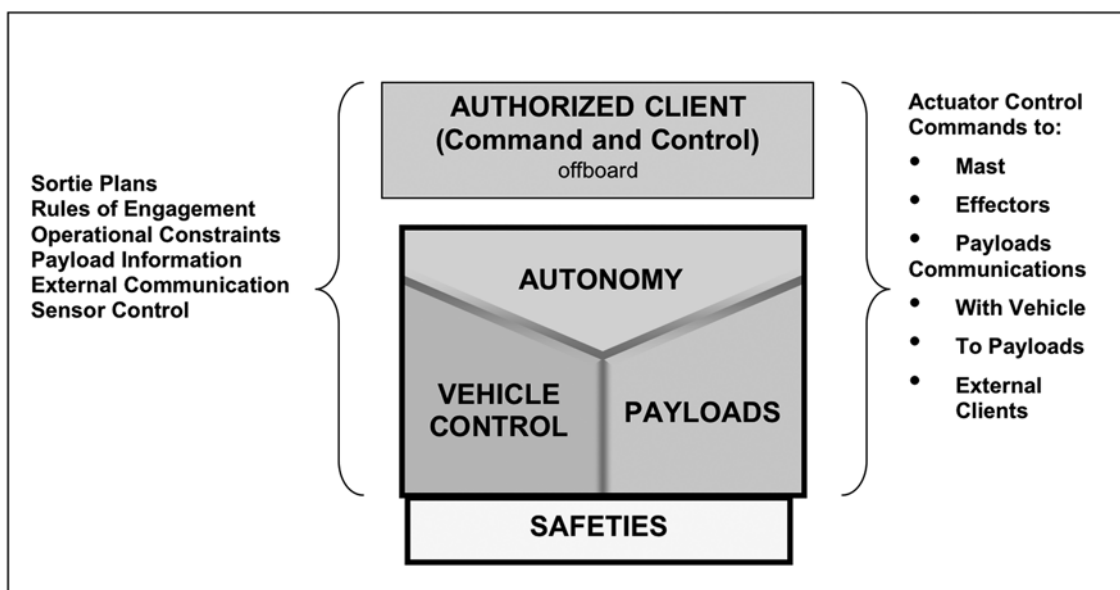
1.4 Section 5 presents the capabilities that an autonomous system is required to have. The table in this section concentrates on the functional capabilities of the total system, as opposed to the capabilities of the component controllers. A method for verification of the capability is also presented.

1.5 Section 6 presents a set of tables that index the system autonomy capabilities according to three criteria: Situational Awareness, Decision-making, Planning, and Control, and External Interactions. Such a set of qualifiers determines a Level of Autonomy (LOA) measurement for each of the three criteria. No attempt is made to combine these disparate measures into a single index.

1.6 The following are outside the scope of this guide and no part of this guide should be construed to prescribe requirements associated with these areas.

Payloads—outside of the generic functions of the Payload controller and the top level interfaces, the design and implementation of payload subsystems are not addressed in this guide.

Vehicles—outside of the generic function of the Vehicle controller and the top level interfaces, the design and implementation of the vehicle subsystems are not addressed in this guide.



NOTE 1—Internal boundaries between autonomy, vehicle control, and safeties are fuzzy, and different systems will have slightly different boundaries.

FIG. 2 Autonomy and Control Module External Interfaces

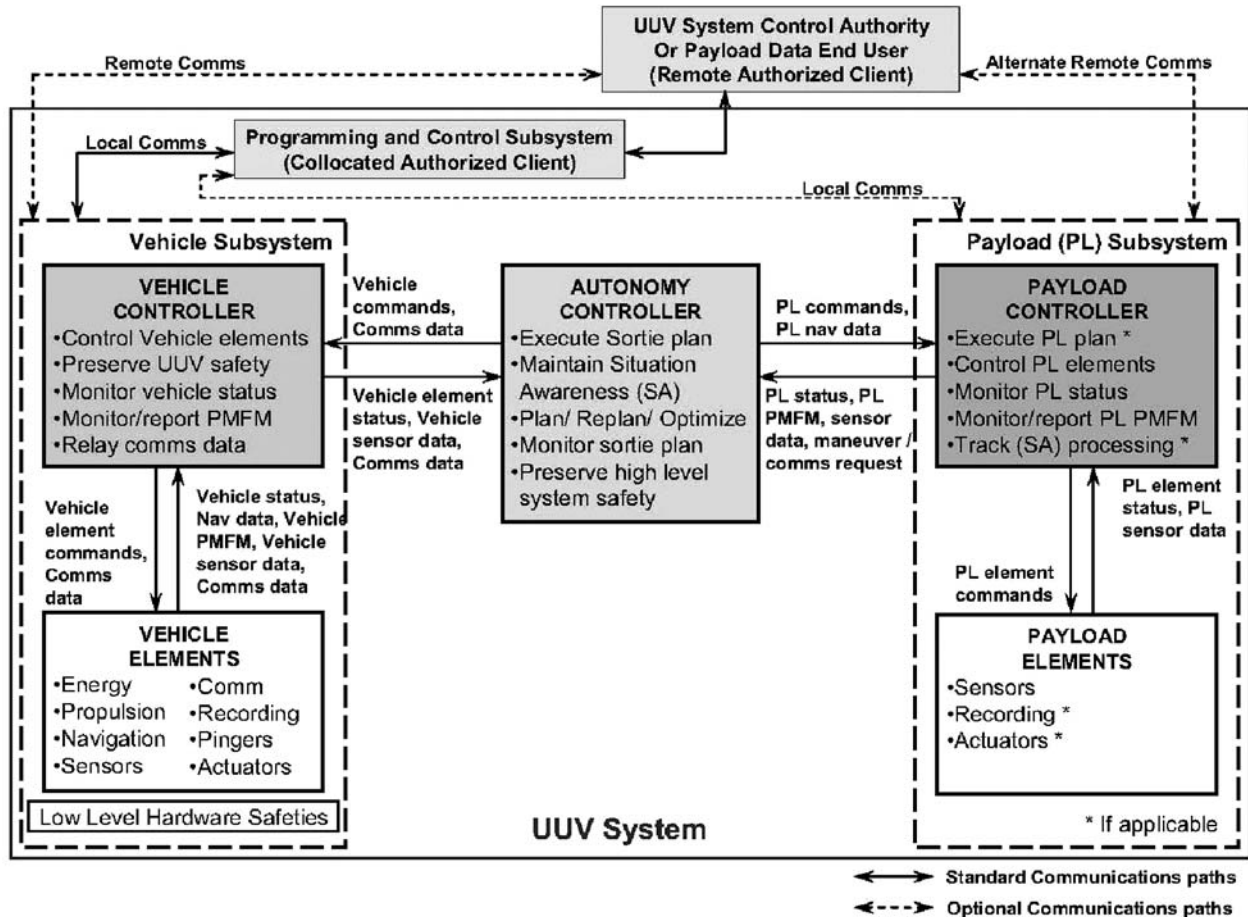


FIG. 3 Functional Allocation of Major UUV Autonomy and Control Components

Safety—this guide does not address safety concerns, if any, associated with the use of the UUV system. It is the responsibility of the system designer to establish appropriate safety and health practices and determine the applicability of the regulatory limitations prior to use.

Security—this guide does not address security concerns. It is the responsibility of the program referencing this guide to establish security mechanisms that are appropriate for the intended use of the UUV system and the requirements of the end-user of the system data.

1.7 These standards are intended to support the decision process for the acquisition and development of non-specific UUV systems. To the extent that UUV systems are specified, procured, and developed under a modular open system design approach, the autonomy standards presented herein will foster interoperability and reusability within the UUV community.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate*

safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:³

F2594 Guide for Unmanned Undersea Vehicle (UUV) Communications

F2595 Guide for Unmanned Undersea Vehicle (UUV) Sensor Data Formats

WK11283

2.2 IEEE Standard:⁴

IEEE 1003.23 IEEE Guide for Developing User Open System Environment (OSE) Profiles

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

⁴ Available from Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Ln., P.O. Box 1331, Piscataway, NJ 08854-1331, <http://www.ieee.org>.

2.3 NIST Document:⁵

NIST Special Publication 1011 Autonomy Levels for Unmanned Systems (ALFUS) Framework, Volume I: Terminology

2.4 STANAG Standard:⁶

NATO Standardization Agency (NSA), Standardisation Agreement (STANAG), STANAG 4586 Edition 2, June 2004

3. Terminology

3.1 The term *autonomy* and its associated components often have different interpretations. A first step in the standards process is to converge on terminology. This terminology is derived from the NIST Special Publication 1011. The NIST work focused on generic unmanned systems (UMS) and this guide is focused on unmanned underwater vehicles (UUV). Incorporation of the NIST terminology is intended to take advantage of the groundwork that has already been laid and extend it to the underwater realm. See **Table 1**.

4. Functional Allocation

4.1 *Functional Decomposition*—Identified herein is a functional breakdown of the UUV control system with an attempt made to draw the interface lines between the functional components that support maximum ability to have interchangeable components. High level components:

- Vehicle control
- Payload control
- Autonomous control
- On-board safety systems
- Communications

Details of each of these are provided below and tabulated in **Table 2**.

4.2 Vehicle Control:

4.2.1 Responsibility:

4.2.1.1 Mobility, energy, and navigation subsystems.

4.2.1.2 Maneuvering vehicle as commanded.

4.2.1.3 *Operating Subsystems Required for Unmanned Vehicle Control*—(1) sensors, ballast systems, propulsion, and maneuvering subsystems, (2) homing and docking sensors, and (3) navigation, guidance, and control.

4.2.1.4 *Maintaining Vehicle Capabilities Database*—Estimated energy remaining, max/min speed, turn-rates, etc.

4.2.1.5 Monitoring and reporting vehicle/subsystem health to interested parties.

4.2.1.6 Monitoring and reacting to vehicle subsystem hazard conditions (for example, ground fault) or subsystem casualties (for example, ballast pump failure).

4.3 Autonomous Control:

4.3.1 Responsibility:

4.3.1.1 *Sortie Planning (see LOA)*—*a priori* resource allocation and activity planning, path planning, real-time contingency, and real-time retasking.

4.3.1.2 *Sortie Execution/Management (see LOA)*:

(1) *Safe Vehicle Operation*—(1) Enforcing sortie constraints (for example, operational envelope), (2) updating and maintaining situational awareness databases, and (3) real-time obstacle/terrain/contact avoidance.

(2) Resource Monitoring.

(3) Payload Employment.

(4) *Oversight and Reporting*—Sortie summary file.

(5) Communications and GPS Scheduling.

4.3.1.3 *Situation Awareness (see LOA)*—Sensor fusion and monitoring whether achieving sortie goals.

4.4 Payload Control:

4.4.1 Responsibility:

4.4.1.1 *Operating Payloads as Directed*—Ensuring appropriate configuration status.

4.4.1.2 Monitoring and reporting payload health.

4.4.1.3 *Situation Awareness (see LOA)*—Sensor processing and sensor fusion.

4.4.1.4 Passing “smart” payload requests for consideration.

4.4.1.5 Safety of payload.

4.4.1.6 Controlling future payloads

4.5 Communications:

4.5.1 Responsibility:

4.5.1.1 Perform all off-board communications,

4.5.1.2 Operation of communications devices and link maintenance,

4.5.1.3 Tactical message formatting,

4.5.1.4 Encryption/key handling, and

4.5.1.5 Maintain/report link performance estimates

4.6 Onboard Safety Systems:

4.6.1 Responsibility:

4.6.1.1 *Hardware Depth Cutoffs*—Prevent vehicle from transiting beyond safe depth.

4.6.1.2 *Leaks/Temp/Over/Undervoltage*—Prevent catastrophic vehicle failure.

4.6.2 Watchdog Functions:

4.6.2.1 Monitor processor integrity and function

4.6.2.2 Monitor critical communication links for integrity and activity

4.6.2.3 Monitor status and integrity of other critical vehicle functions

4.7 **Fig. 4** provides a high level depiction of a UUV’s functional subsystems. Also included in this diagram are the functional interfaces. Functional subsystems require a 1:1 mapping to a hardware subsystem. For example, many current UUV systems include a single processor incorporating both autonomous and vehicle control functionality.

4.8 *Functional Interfaces*—In the effort to standardize UUV control systems, the high level interfaces between the functional components need to be identified. **Table 2** identifies proposed high level interfaces.

4.8.1 Once the high level interface information can be agreed upon, the next step down is to identify detailed interface and message content.

5. UUV Capabilities

5.1 Autonomy and control are becoming ever more important components of UUV functionality.

⁵ Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, <http://www.nist.gov>.

⁶ Available from NATO Standardization Agency, North Atlantic Treaty Organization, 1110 Brussels, Belgium.

TABLE 1 Terminology

NOTE 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.

NOTE 2—Boldface is used to indicate the terms defined in this guide.

NOTE 3—Braces { } are used to indicate that the definition is adopted (that is, a direct cut-and-paste or close to it, from the cited reference.

NOTE 4—Brackets [] are used to relate the stated definitions to the cited reference(s).

NOTE 5—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)...

Term	Definition
Action	(A) The effector state of the "OODA Loop" (Observation, Orientation, Decision, Action) where the Decision is implemented. (B) A sequence of low-level commands. (C) A closed-loop control rule composed of a set of sub-system commands (and/or other actions) with appropriate feedback, designed to maintain and/or achieve specific conditions .
Anomaly	Any unanticipated event that requires modification to UUV operations.
Authorized Client	An agent designated by the chain of command with responsibility for programming, operating, and/or maintaining a UUV . An Authorized Client can be a collaborating partner or other source external to the UUV . The UUV must be capable of recognizing an authorized client in order to accept input from this source.
Autonomous ^A	Self-governing {1}. Refers to the operation of an Unmanned Undersea Vehicle (UUV) in response to its tasking from authorized clients . Factors describing such operation are defined by level of autonomy Autonomous Collaboration: ^B The ability of a UUV to collaborate with one or more manned vehicles or UUVs without the need for an external controlling element.
Autonomy ^A	(A) The condition or quality of being self-governing {1} (B) A UUV's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as assigned by its authorized client(s) . Associated terms: Autonomy Level or Level of Autonomy^A Set(s) of orthogonal axes, identifying a UUV's capability for performing autonomous missions. The following axes are defined for Levels of Autonomy: Levels of Situation Awareness. See Situation Awareness Levels . Levels of Decision-making, Planning and Control. See Decision-making, Planning and Control Levels . Levels of External Interaction. See External Interaction Levels . Levels of Collaboration. Collaboration Levels will be added in a future revision to this standard. Additional factors, such as tasking complexity and environmental difficulty, affect the rating of the difficulty of the task, sortie, or mission .
Behavior	A series of actions or maneuvers a UUV can perform. Behaviors may be scripted into the sortie plan or spawned as a response to events which occur during the Sortie .
Built-in Test ^B	Equipment or software embedded in operational components or systems, as opposed to external support units, which perform a test or sequence of test to verify mechanical or electrical continuity of hardware, or the proper automatic sequencing data processing, and readout of hardware or software systems.
Capabilities	A description of what the UUV system, with its onboard systems, can do, that is, the immutable physical and operational characteristics of a particular UUV operation. Capabilities can be defined at the mission level, that is, what sensor/payload capabilities the UUV brings to bear on the tasks at hand, or on the tactical level, such as speed, depth turn rate and endurance.
Classes of UUVs	The UUV Master Plan postulates four classes of vehicles: The Man-Portable class, which includes vehicles from about 25 to 100 pounds displacement, with an endurance of 10 - 20 h. There is no specific hull shape for this class. The Light Weight Vehicle (LWV) class, which is nominally 12.75 in. in diameter and displaces about 500 lb. Payload increases six- to twelve-fold over the man-portable class and endurance is doubled. The Heavy Weight Vehicle (HWV) class, which is 21 in. in diameter, displaces about 3000 lb, and provides another factor of two improvement in endurance capability. This class includes UUVs compatible with torpedo tubes on submarines. The Large Vehicle class will be approximately 10 long-tons displacement and compatible with both surface ship (Littoral Combat Ship (LCS)) and submarine (SSNs with hangar or "plug," and SSGN) use.
Client.	See Authorized Client
Collaboration ^A	The process by which multiple manned or unmanned systems jointly work together by sharing data, (such as coordinates of their maneuvers) and local Common Relevant Operational Picture (CROP) , or by acquiring intelligence to perform a mission synergistically, that is, perform better than each could have alone. Associated terms: Collaboration Levels or Level of Collaboration—Levels to Be Defined in a future revision. Teaming—To Be Defined.
Command (primitive)	A low-level open-loop instruction initiating a sensor, actuator, or processing operation.
Common Relevant Operating Picture. (CROP)	A set of data defining the local environment in which the UUV is operating sufficient to allow collaboration and/or control of the UUV through authorized clients . Examples of data in the CROP include location of the UUV , threats, targets, and environmental data.

TABLE 1 *Continued*

Term	Definition
Concept of Operation (CONOPS). A Concept of Operations (CONOPS)	A document that identifies the operators, organizations, systems, or entities that are employed in the execution of an activity. In addition to identifying the actors, the CONOPS also specifies the interactions between and among the actors.
Condition	A description of the system's configuration (or state) that may or may not represent reality.
Constraints	A prescribed restriction on the set of valid system states. Constraints may apply (but are not limited) to internal vehicle resources (for example, battery capacity, CPU cycles), to vehicle position and attitude (for example, vehicle is not allowed into certain unsafe zones), to time (for example, overall mission time). Constraints may apply to actions , objectives , goals and the planning function when calculating outputs.
Contingency	An unintended condition that may be anticipated in the sortie Plan or the sortie Rules , or both.
Controlling Element ^A	An Authorized Client that has the ability to program or operate a UUV remotely.
Data Fusion	See Fusion ^B
Decision-making, Planning and Control	The ability of a UUV to autonomously perform activity planning, execution and monitoring. Associated Terms: Decision-making, Planning and Control Levels or Levels of Decision-making Planning and Control . One of the three orthogonal axes used to define Levels of Autonomy for a UUV. The following are the defined Levels of Decision-making Planning and Control : Direct Control —Execution of externally defined commands. No decision-making within the system. Sequenced execution of actions —Execution of externally defined sequence of actions. Limited decision-making within scope of defined actions (that is, to affect completion of the actions). Adaptive execution of actions —Execution of externally defined actions . Closes loop on the actions . Limited decision-making to reorder, insert and resume actions . "Adaptive" applies to action reordering and insertion of conditional actions . Objective achievement —Combine actions to achieve a single objective at a time. Multiple Objective Achievement —Simplistic combining multiple objectives. Joint Objective Achievement —Balance multiple objectives.
Dynamic mission planning.	See mission planning ^A
Effector	Device that translates a commanded action into a physical action on the vehicle
Environment ^A	(A) Used as a general reference, environment includes the generic, natural conditions; for example, weather, climate, ocean conditions, terrain, vegetation, etc. (B) Constitutes spatial resources available to the UUV for execution of actions , or achievement of objectives and goals . (C) Provides the spatial dimensions of the UUV's state space.
External Interaction	The level of required interaction between a UUV and any authorized client(s) to achieve mission goals . Associated terms: External Interaction Levels or Levels of External Interaction —One of the three orthogonal axes used to define Levels of Autonomy for a UUV. The following are the defined Levels of External Interaction : Tele-operation ^A —The client, using video feedback and/or other sensor feedback, directly controls the UUV via a "continuous" communication method. The UUV takes no initiative. Remote Control Operation —A client examines all actions before they are executed. Semi-Autonomous Operation —The UUV requires client feedback to address anomalies and/or predefined conditions. Fully autonomous Operation —The UUV is expected to operate without client intervention from the moment of launch until return, although tasking guidelines are likely to include the possibility of in-course communication and intervention.
External Intervention ^A	The ability for an authorized client to provide UUV direction in a normally fully autonomous behavior due to some extenuating circumstances. An unanticipated action or input by the authorized client to exert control over the UUV.
Fault Tolerance ^A	The ability of a system or component to continue normal operation despite the presence of hardware or software faults [2]
Fully Autonomous	See under Level of External Interaction ^A
Fusion	Also referred to as Information Fusion or Data Fusion . ^B (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 reason out the significance of those correlations [2, 3]. 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 result [3].
Geodetic Capability	The ability of a UUV to determine its location absolutely, rather than relative to a local datum
Goal ^A	A desired outcome that is not directly expressible in terms of objectives
Hazard Avoidance ^A	Similar to obstacle avoidance except that the subjects are not limited to physical objects but also include adversarial situations, as either assessed by the UUV's perception functions or provided through the Human Robotic Interactions , that are to be avoided.
Information Fusion	See Fusion ^B
Markers (physical or electronic) ^A	A visual or electronic (for example, reflecting or acoustic) aid used to label a designated point for such tactical purposes as route following, determination of bearings, courses, or location, and key items or points of interest, including minefield markers and area NBC decontamination markers.