Autonomy-Assessment Criteria for Underwater Vehicles

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***Abstract*— Autonomous Underwater Vehicles (AUVs) are getting progressively sophisticated by increasing their self-governance capabilities which allow them to deal with more and more complex missions. However, there is still not a common agreement on the aspects that should be evaluated to know what level of autonomy AUVs provide. This paper reviews the current approaches to assess autonomous behavior in self-governed vehicles. It recaps the capabilities and perspectives taken into account as aspects to evaluate autonomy in unmanned systems from different domains. This provides the foundations to develop and propose assessment criteria for AUVs. This paper also proposes potential metrics for undersea autonomy in order to determine the degree of autonomy in AUVs. A case study based on a generic AUV is presented to show how the autonomy-assessment criteria for underwater vehicles can be applied.**

***Index Terms*—Underwater Autonomy, Unmanned Undersea Vehicles, Metric Assessment of Autonomy.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are getting progressively sophisticated by increasing their self-governance capabilities which allow them to deal with more and more complex missions. In spite of the fact that undersea autonomy is a key system requirement in AUVs, there is still not a common agreement on the aspects that should be evaluated to know whether AUVs satisfy the Degree of Autonomy (DoA) expected. This measure establishes the AUV utility in terms of how autonomous it is or how much autonomy it has.

Well-defined criteria are essential to know what and how has to be assessed in order to determine the DoA of AUV(s). Moreover, a clear definition of assessment criteria for autonomous AUV attributes can assist developers in selecting the most suitable architecture for AUVs. The challenge is to know what should be measured from the AUVs, and what metrics should be applied (based on the above measures) to determine their DoA.

In order to tackle the above issue, this paper reviews the current approaches to assess autonomous behavior in self-governed vehicles by recapping the aspects taken into account to evaluate autonomy in unmanned systems from different domains. This provides the foundations to develop and propose an aspect-based framework for autonomy-assessment criteria.

The framework aspects basically come from the perspectives adopted (i.e. underwater autonomy with respect to what, involving interactive behavior), and the system capabilities (i.e. autonomous processing and communication, involving underwater navigation, guidance, control, etc.) considered when evaluating AUVs. They are analyzed in order to quantitatively define the DoA for AUVs by means of metrics. In addition, the aspects give an insight into autonomous characteristics of AUVs that involve types, limits, and approaches of autonomy as well as concepts such as multi-dimensional and adjustable autonomy.

Based on the DoA, AUVs can be evaluated as to their ability to automatically make decisions, implement their choices, and solve problems in an autonomous manner. The DoA is a number that requires of a scalable reference to be compared with in order to know what autonomous capabilities are provided by AUVs for such a DoA. The reference proposed in the current research work is the Level of Autonomy (LoA) in AUV(s), and based on a scale inspired by autonomous control levels defined for military and aerospace systems.

The motivation to know the LoA from AUV(s) is that its/their autonomous capabilities can be ‘quantified’ so AUVs can be compared with other based on an underwater autonomy of reference. This becomes important in cases such as selecting an AUV or a group of them for a particular underwater mission, specifying what DoA is expected for development or operation of AUV(s), or identifying weaker and stronger architectures and designs of underwater autonomy. Ultimately, it is useful to study suitability of AUVs for different missions assigned.

The rest of the paper is structured as follows. Section II presents the background for this research work by reviewing and defining relevant concept for the assessment process. Section III shows a classification of existing autonomy levels. Section IV studies the measurable capabilities considered by current research works for autonomy assessment. Section V describes the assessment criteria proposed for underwater autonomy, and shows application examples based on a generic AUV platform. Last Sections are devoted to the conclusions, and future direction for this research.

II. Background

In order to consider autonomy and its assessment in more detail, this Section first describes some concepts and definitions that are relevant in the discussion.

It is generally accepted that an automated system is one that does not make choices for itself, but follows a script in which the choice out of all possible courses of action has already been made. If the system encounters an unplanned-for situation, it stops and waits for human help. Thus for an automated system, choices have either already been made or encoded, or they must be made externally. An autonomous system, however, does make choices on its own. It tries to accomplish its objectives locally, without human intervention, even when encountering uncertainty or unanticipated events. However, autonomous systems do have an automatic and automated decision-making process.

Autonomy is a quality factor with a continuous spectrum that is calculated though the DoA. This metrics is a real number by which a meaning for each DoA calculated is impossible (and probably without sense). Therefore, a discrete autonomy scale (autonomy levels) is required to quantitatively realize what autonomous capabilities are provided by AUVs according to the calculated DoA.

III. Classification of Autonomy Levels

Before looking at quantifiable capabilities for autonomy, the autonomy levels that have been created in the most relevant research works are first identified. They are defined by following the essential concept of autonomy, i.e. in terms of independence to make choices, and implement such decisions.

Early attempts to define the DoA in autonomous systems have been linked to metrics. It proved difficult to find a definition for the LoA based on general metrics. Most have therefore been based on task-specific metrics defined according to the investigation domain. Such efforts mainly came from contributions by Los Alamos National Laboratory [22], Draper Laboratory [21], and the Air Force Research Laboratory [6]. There is also a particular approach from the US Army that is taken into account by the US Navy for autonomous vehicles in support of naval operations [2]. Collectively, they are a useful starting point for attempts at generalization.

Table I summarizes the key characteristics of these main existing autonomy-assessment criteria for autonomous systems. The numbers of levels they take into account are different but the ranges of DoA are the same. The ability measures vary from one approach to other but all of them address the three basic computational elements: sensing, processing (including communicating), and actuating.

TABLE I. Characteristics of the main assessment criteria for autonomous systems

Contributor	Acronym	Name	Reference	Number of Levels	Ability Measures	Domain
Los Alamos National Laboratory	MAP	Mobility Acquisition Protection	[22]	6 + external events	Mobility Acquisition Protection	Any
Draper Laboratory	3DIS	3D Intelligence Space	[21]	4	Mobility control Task planning Situational awareness	Any
Air Force Research Laboratory	Initial ACL	Autonomous Control Level	[6]	10 + human-like	Perception/Situational awareness Analysis/Decision making Communication/Cooperation	Aeronautics
Air Force Research Laboratory	Final ACL	Autonomous Control Level	[6]	11	Observe Orient Decide Act (OODA)	Aeronautics
US Army	AS	Army Scale	[2]	10	Observation, Perception, and Situation Awareness Decision-making ability Capability	Military
NASA	AAS	Automation and Autonomy Scale	[28]	8	Observe Orient Decide Act (OODA)	Astronautics

IV. Measurable Capabilities for Autonomy

Various approaches have been proposed to assess autonomous behaviors in self-governed/directed vehicles. This Section recaps the various viewpoints adopted by researchers, and identifies the system capabilities taken into account to evaluate autonomy in unmanned systems.

A. Current Approaches to Assess Autonomy

The literature review in this section is basically focused on the following perspectives.

- An autonomy classification based on the context in which agents (autonomous entities) interact. An approach is proposed as to environment, agent interaction, agent organization, system user, and internal agent in an attempt to classify different autonomies in Multi-Agent Systems (MAS) [19]. The proposed classification is by itself an assessment criterion for autonomy.
- The performance measures framework for unmanned systems (PerMFUS) [1], based on ALFUS [20], proposes a tree-aspect approach to evaluate the performance in unmanned systems. The aspects are missions, environment, and systems. They correspond to mission complexity, environmental complexity, and

human independence or operator independence or autonomy level respectively in ALFUS.

- A broader consideration for assessment criteria is proposed at an entrepreneurial level by covering criteria for Autonomous Test and Evaluation (ATE), and ATE Enterprise (ATEE) [5]. This approach addresses a wider viewpoint than the two above approaches by taking into account development and business issues of autonomous systems.
- An assessment criterion based on levels of autonomy for different system capabilities [6]. The autonomy degree of unmanned vehicles is specified according to the operational and functional system capabilities as to the ability of such systems to survive in the world.

Following the above perspectives and taking them as foundations, a classification of the existing assessment criteria can be done based on the different perspective dimensions, and the autonomy provided from the systems' capabilities. Each refereed approach listed in the table shows what system capability is considered, and what perspective dimension is taken to evaluate it. Some approaches such as [6] make a categorization of the levels of autonomy for each system capability.

Table II shows a classification of the current autonomy assessment criteria ('perspectives') based on the above approaches, and for twenty research works representative of the state of the art. This table groups related concerns from researchers that analyze assessment criteria for autonomy. They take into account similar perspectives by using different but equivalent names.

TABLE II. CLASSIFICATION OF THE EXISTING ASSESSMENT CRITERIA FOR AUTONOMOUS SYSTEMS

Perspective	System Capability					
	Motion	Acquisition	Protection	Problem-solving	Communication	Perception
Organization				[5], [10], [11], [20]	[2], [10]	[2]
User	[1]	[1], [14]		[5], [7], [13]	[1]	[1], [3]
Interaction	[1], [17]	[1]		[5], [7], [13], [18]	[1], [4], [6], [14], [11], [20]	[1], [3], [18]
Environment	[1], [8]	[1], [14]		[5], [7]	[1], [6]	[1], [3], [6]
Intra-action	[1], [5], [6], [10], [11], [14], [15], [17], [19], [20], [22]	[1]. [8], [14], [19], [22]	[22]	[5], [6], [7], [13], [19]	[1], [6], [11], [20]	[2], [3], [5], [6], [11], [20]
Mission	[1], [15], [18], [20]	[1], [8], [5], [16]	[2]	[2], [5], [7], [10]	[1], [2], [11], [20]	[1], [2], [3], [5], [12], [16]
Autonomous Test & Evaluation (ATE)	[5]	[5]		[5]	[5]	[5]
Autonomous Test & Evaluation Enterprise (ATEE)	[5]	[5]		[5]	[5]	[5]

B. *Categorization of the Measurement Approaches*

Figure 1 shows how the researchers' perspectives are distributed according to the criteria approaches proposed.

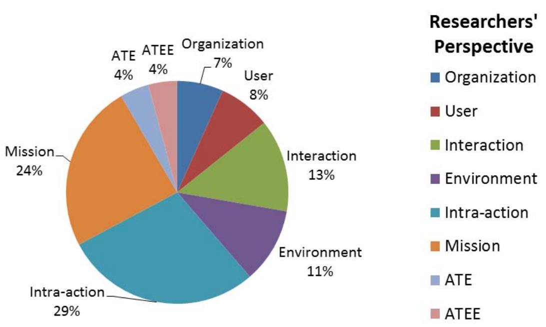

Fig. 1. Distribution of the exiting assessment criteria by perspectives.

The mission and intra-action perspectives are the most considered ones, and the ATE and ATEE are the least considered ones. The self-autonomy (intra-action) is the most evaluated by researchers. This makes sense since it is about the internal behavior of the vehicles. Then, it is followed by the goal-autonomy (mission), and the social-autonomy (interaction).

Figure 2 shows how the system capabilities studied by researchers are distributed according to the criteria approaches proposed.

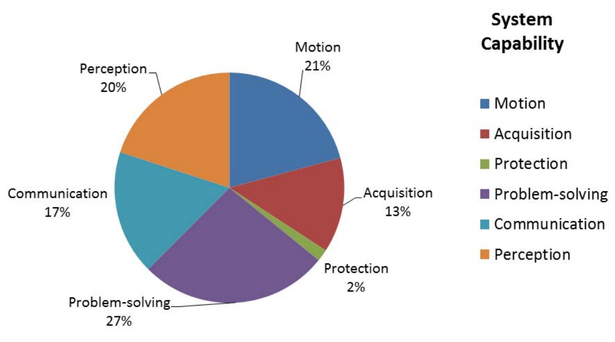

Fig. 2. Distribution of the exiting assessment criteria by capabilities.

The problem-solving, motion, and perception capabilities are the most considered ones, and the protection is the least considered one. The problem-solving is the most evaluated by researchers. This makes sense since it is the key capability of the autonomy. Then, it is followed by the motion, and the perception capabilities.

The particular interests for this investigation are the assessment criteria approaches of autonomy for marine vehicles. There are a variety of useful measurements that can characterize the engineering quality of unmanned vehicle simulation, intelligent autonomy, and operator control station software. These can be roughly categorized as response of system components to a range of initial input, parameters human factors of operator mission management and situational awareness, and response of system components to changes in the simulated warfare environment during execution [15]. Other approaches focus on particular marine missions such as underwater operations with a main concern: power consumption, e.g. oceanographic surveys. The fundamental difficulty in this approach is the coupling of space and time through the AUV survey trajectory. Combined with the finite velocity and battery life of an AUV, this imposes serious constraints on the extent of the survey domain and on the spatial and temporal survey resolutions [16]. A metrics to quantify autonomy in AUVs can be based on control bits, total messages size, contact time, and total mission time [17]. The ASTM-F2541 standard for autonomy and control of AUVs proposes three assessment criteria for the autonomy system capabilities based on the different aspects of the deliberative robotic layer, i.e. situation awareness, decision-making, planning and control, and external interaction [18].

From table II, concern from researchers that work on the assessment criteria for maritime autonomy can be identified for the following system capabilities: "Motion"; only autonomy from the motion capability is analyzed from the interaction, intra-action, and mission perspectives. "Acquisition", "Problem-solving", and "Perception"; only autonomy from the motion capability is analyzed from the interaction, and mission perspectives. All this information is from research works in marine systems.

V. Assessment Framework for Maritime Autonomy

This Section presents the autonomy-assessment framework proposed for AUVs. A key aspect of the framework is the criteria to determine the DoA for the AUV(s) under evaluation. The framework developed is inspired by the previous approaches from different autonomy domains as presented in Section II and III. From them two basic arguments are stated. (1) Autonomy cannot be measure by means of system performance. (2) There is a difference between the autonomy an AUV can have by nature (innate autonomous behavior as manufactured; it is called passive autonomy), and the autonomy it can provides once a mission is given (adjustable autonomy; it is called active autonomy). Thus, the former involves a capability-based assessment framework. The latter involves a goal-based assessment framework. This paper only focusses on the former framework.

A. Autonomy-Assessment Criteria

The first step to develop a framework is to clearly specify the assessment criteria by means of well-defined autonomy levels. They are defined for three main AUV contexts:

- Intra-AUV: this involves the intra-actions (internal actions) of the AUV(s) that only take place in its interior. It defines a boundary that does not go beyond a single vehicle. This why it is classified as 'itself'.
- Inter-AUV: this involves the interactions of the AUV(s) that take place in the AUV surroundings, i.e. environment, operator, and other systems. It defines a boundary that does not go beyond individual vehicle interactions. This why it divided into and classified as 'System', 'User', and 'Environment'.
- Supra-AUV: this involves the actions of a group of AUVs as joint actions (e.g. a fleet of AUVs as a whole autonomous underwater system). It takes into account the organizational structure in which the AUVs act, and their interactions take place. This why it is classified as 'norm'.

Thus, the framework considers different autonomies (autonomy with respect to the contextual aspects) as similarly identified in an existing autonomy classification [19]. Table III shows the LoA with respect to the five above contexts. The scale from 0 to 9 is defined to specify the LoA with respect to 'itself', 'system', 'user', 'environment', and 'norm'. This table is the output of the framework since the DoA obtained from the AUVs under assessment are taken to this table to know what LoA correspond to such AUVs.

The DoA of AUV(s) with respect to each context is obtained by following the definition of autonomy (Section II). Therefore, the assessment framework has to assess the decision-making capability as well as the enforcement capability to make the actions happen. This is taken into account by the Observe-Orient-Decide-Act (OODA) loop [26]. Observe, Orient, and Decide correspond to the decision-making process. The study on autonomy is not just to make decisions and enforce them (Act) but also solve problems. To be able to solve problems, a system must be able to evaluate the situation (solution). Thus, the problem-solving process is a decision-making process plus Act plus Check or OODA plus Check (OODAC).

The AUV capabilities studied come from the combination of the two above loops (i.e. OODAC). They match the loop steps as follows. Observe implies 'Definition' to identify and determine the problem, Orient implies 'Exploration' of alternatives as possible solutions, Decision implies 'Selection' of an alternative, Act implies 'Implementation' of the solution, and Check implies 'Verification' of the situation (after solution applied).

Table IV shows what is looked for from each of the above capabilities with respect to the five contexts taken into account. As stated in Section II, autonomous systems have automated problem-solving process. Thus, what is evaluated in the AUV capabilities is automation, i.e. how automatized is the process or how much automation it has. The level of automation is introduced in table IV, similar to the LoA but different.

TABLE III. CHARACTERISTICS OF THE MAIN ASSESSMENT CRITERIA FOR AUTONOMOUS UNDERWATER VEHICLES (AUVS)

Level of Autonomy	Intra-AUV	Inter-AUV			Supra-AUV
	Itself	**System**	**User**	**Environment**	**Norm**
9	Fully self-autonomous	Fully autonomous to control other underwater systems	Fully autonomous control for underwater missions	Behaviour not imposed by underwater environment at all	Fully autonomous from any underwater norm, rule, or law
8	Automated underwater choices but not covering all possible underwater choices	Automated planning but limited re-planning for other underwater systems	Automated planning but limited re-planning to underwater missions	Robust response to any underwater events	Huge freedom to break underwater norm, rule, or law
7	Automated but restricted underwater choices	Automated planning, and pre-defined re-planning for other underwater systems	Automated planning, and pre-defined re-planning to underwater missions	Limited response to any underwater events	Freedom to break underwater norm, rule, or law
6	Automated but influenced underwater choices	Automated planning for other underwater systems	Automated planning to underwater missions	Robust response to many unanticipated, and anticipated underwater events	Little freedom to break underwater norm, rule, or law
5	Automated but inferred underwater choices	Automated but limited planning for other underwater systems	Automated but limited planning to underwater missions	Limited response to may unanticipated, and anticipated underwater events	Huge freedom to ignore but little freedom break underwater norm, rule, or law
4	Automated but pre-defined underwater choices	Automated but pre-defined planning for other underwater systems	Automated but pre-defined planning to underwater missions	Robust response to few unanticipated, and anticipated underwater events	Huge freedom to ignore but little freedom break underwater norm, rule, or law
3	Externally pre-loaded alternative states and actions	Pre-loaded alternative plans for other underwater systems	Pre-loaded alternative plans for underwater missions	Limited response to few unanticipated, and anticipated underwater events	Huge freedom to ignore underwater norm, rule, or law
2	Externally pre-defined states and actions	Pre-planned underwater missions for other underwater systems	Pre-planned underwater missions	Robust response to anticipated underwater events	Freedom to ignore underwater norm, rule, or law
1	Externally controlled with remote monitoring of its states and actions	Remotely control from other underwater systems with remote monitoring of its states	Remotely controlled with remote monitoring of its states	Limited response to anticipated underwater events	Little freedom to ignore underwater norm, rule, or law
0	Externally controlled	Remotely controlled for other underwater systems	Remotely controlled for underwater missions	Behaviour imposed by underwater environment	Fully controlled by any underwater norm, rule, or law

TABLE IV. CHARACTERISTICS OF THE MAIN ASSESSMENT CRITERIA FOR AUTONOMOUS UNDERWATER VEHICLES (AUVS)

	Problem-solving				
	Decision-making			**Action-checking**	
	Definition	**Exploration**	**Selection**	**Implementation**	**Verification**
Norm	Observation to identification of underwater norms, rules, or laws (policies)	Orientation (generation of alternatives) based on knowledge of underwater norms, rules, or laws (policies)	Selection of behaviours that break underwater norms, rules, or laws (policies)	Execution of actions that break underwater norms, rules, or laws (policies)	Evolution checking of actions performed that can break underwater norms, rules, or laws (policies)
Environment	Observation to identification of underwater environment complexity (including changes)	Orientation (generation of alternatives) based on knowledge of underwater environments	Selection of behaviours that are imposed by underwater environmental conditions	Execution of actions that are imposed by underwater environmental conditions	Evolution checking of actions imposed by underwater environmental conditions
User	Observation to identification of underwater missions given by users	Orientation (generation of alternatives) based on knowledge of different underwater missions	Selection of behaviours that to carry out assigned underwater missions	Execution of actions that carry out assigned underwater missions	Evolution checking of actions performed to carry out the assigned underwater missions
System	Observation to identification of interaction with other underwater systems (including similar ones)	Orientation (generation of alternatives) based on knowledge of interaction with other underwater systems (including similar ones)	Selection of behaviours that interact with other underwater systems (including similar ones)	Execution of actions that interact with other underwater systems (including similar ones)	Evolution checking of actions performed to interact with other underwater systems (including similar ones)
Itself	Internal and external observation to identification of interaction with the rest of the world	Orientation (generation of alternatives) based on knowledge of interaction with the rest of the world	Selection of behaviours that interact with the rest of the world	Execution of actions that interact with the rest of the world	Evolution checking of actions performed to interact with the rest of the world

B. Autonomy-Assessment Approaches

Two different approaches are proposed. A generic AUV (non-real) is used for assessment with each approach.

1) Approach A: automated capabilities given by levels of automation (no domain involved)

The levels of automation for each of the stages (capabilities) of the problem-solving process are given according the scale defined for the human-machine interaction (Appendix). This scale is valid for the interaction between the user and the AUV but it can be easily adapted in order to be used for the interaction between the AUV and the 'norm', 'system', and 'environment' contexts, including intra-actions (itself).

The DoA α regarding each context is calculated as the average of the LoA δ obtained as follows:

$$\alpha_1 = (\delta_D + \delta_E + \delta_S + \delta_I + \delta_V) / n. \quad (1)$$

Where:

δ_D: LoA of the Definition capability.

δ_E: LoA of the Exploration capability.

δ_S: LoA of the Selection capability.

δ_I: LoA of the Implementation capability.

δ_V: LoA of the Verification capability.

n: amount of LoA taken into account (five LoA).

2) Approach B: System capabilities as reference to calculate the levels of automation

The levels of automation for each of the stages of the problem-solving process are given by the relation between the automated capabilities provided by the AUV(s) under study, and the full capabilities an ideal AUV(s) should have, listed as standard AUV capabilities. Thus, calculating the percentage of each capability with respect to the full list of them that an AUV is expected to have, provides a numerical value that can be placed in the cell of table IV.

The DoA α regarding each context is calculated as the average of the LoA δ obtained as follows:

$$\alpha_2 = ((\eta_{D(AUV)} / \eta_{D(Std)})*10 + (\eta_{E(AUV)} / \eta_{E(Std)})*10 + (\eta_{S(AUV)} / \eta_{S(Std)})*10 + (\eta_{I(AUV)} / \eta_{I(Std)})*10 + (\eta_{V(AUV)} / \eta_{V(Std)})*10) / n. \quad (2)$$

η_D: amount of behaviors as Definition capabilities

η_E: amount of behaviors as Exploration capabilities

η_S: amount of behaviors as Selection capabilities

η_I: amount of behaviors as Implementation capabilities

η_V: amount of behaviors as Verification capabilities

n: amount of LoA taken into account (five LoA)

Where n = 5, then:

$$\alpha_2 = (\eta_{D(AUV)} / \eta_{D(Std)} + \eta_{E(AUV)} / \eta_{E(Std)} + \eta_{S(AUV)} / \eta_{S(Std)} + \eta_{I(AUV)} / \eta_{I(Std)} + \eta_{V(AUV)} / \eta_{V(Std)}) * 2. \quad (3)$$

C. Case Study

A generic AUV is studied. It has hypothetical problem-solving capabilities, i.e. Definition, Exploration, Selection, Implementation, and Verification as defined by the autonomy-assessment criteria.

1) Approach A

The hypothetical AUV capabilities for problem-solving produce levels of automation as specified in table V.

TABLE V. LEVELS OF AUTOMATION A GENERIC AUV

	Definition	Exploration	Selection	Implementation	Verification
Norm	1	4	8	5	3
Environment	4	5	4	3	3
User	7	6	8	2	4
System	2	1	5	2	2
Itself	8	4	6	7	7

The autonomy degrees obtained for each context are: $\alpha_{Norm} = 4.2$, $\alpha_{Environment} = 3.8$, $\alpha_{User} = 4.8$, $\alpha_{System} = 2.4$, and $\alpha_{Itself} = 6.4$. These DoA means the following levels of autonomy according to the table III. The autonomy levels of the generic AUV according to the above Autonomy degrees are summarized in table VI. Each LoA and autonomy meaning are from table III.

TABLE VI. LEVELS OF AUTONOMY OBTAINED FOR THE GENERIC AUV UNDER STUDY

	DoA	LoA	Autonomy meaning
Norm	4.2	4	Huge freedom to ignore but little freedom break norm, rule, or law
Environment	3.8	4	Automated but limited planning to underwater missions
User	4.8	5	Pre-planned missions for other underwater systems
System	2.4	2	Robust response to few unanticipated and anticipated underwater events
Itself	6.4	6	Automated but influenced underwater choices

Figure 3 shows a radar-like score card representation of the five-dimensional autonomy of the generic AUV under study.

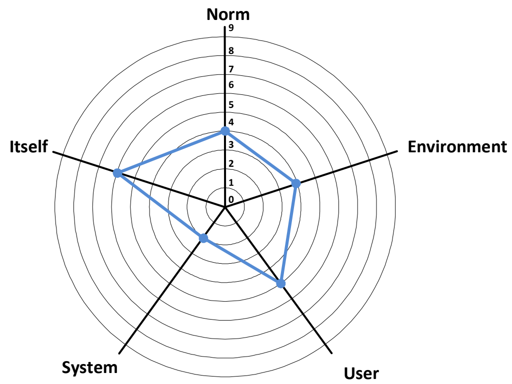

Fig. 3. Five-dimensional autonomy of the generic AUV according to approach A

2) *Approach B*

The levels of automation are not used in this approach to specify the five autonomy capabilities of the AUV studied. Instead, the above formula is utilized to specify each DoA. It is a combination between the standard capabilities (full specification of all the capabilities expected for an ideal AUV), and the capabilities provided by the generic AUV under study.

Table VII shows the numbers obtained after applying the above formula.

TABLE VII. OF AUTOMATION A GENERIC AUV

	Definition	Exploration	Selection	Implementation	Verification
Norm	0.15	0.45	0.85	0.50	0.35
Environment	0.40	0.50	0.40	0.35	0.30
User	0.75	0.65	0.80	0.20	0.45
System	0.20	0.15	0.55	0.25	0.20
Itself	0.85	0.45	0.60	0.70	0.75

The Autonomy degrees obtained for each context are: $\alpha_{Norm} = 4.6$, $\alpha_{Environment} = 3.9$, $\alpha_{User} = 5.7$, $\alpha_{System} = 2.7$, and $\alpha_{Itself} = 6.7$. These DoA means the following levels of autonomy according to the Table III. The autonomy levels of the generic AUV according to the above Autonomy degrees are summarized in Table VIII. Each LoA and autonomy meaning are from table III.

TABLE VIII. LEVELS OF AUTONOMY OBTAINED FOR THE GENERIC AUV UNDER STUDY

	DoA	LoA	Autonomy meaning
Norm	4.6	4	Huge freedom to ignore but little freedom break norm, rule, or law
Environment	3.9	4	Automated but limited planning to underwater missions
User	5.7	6	Automated planning to underwater missions
System	2.7	3	Pre-loaded alternative plans for other underwater systems
Itself	6.7	7	Automated but influenced underwater choices

Figure 4 shows a radar-like representation of the five-dimensional autonomy of the generic AUV under study.

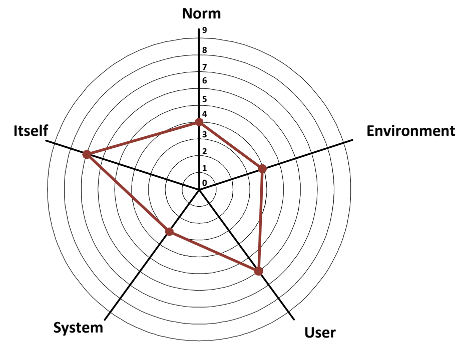

Fig. 4. Five-dimensional autonomy of the generic AUV according to approach B

D. *Comparison of Approaches*

Figure 5 shows each LoA obtained for the generic AUV according to the two approaches proposed.

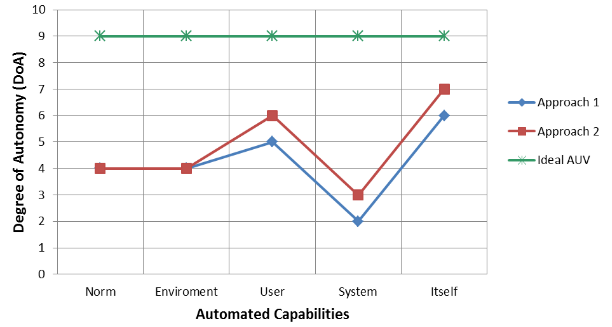

Fig. 5. Comparison among refinement techniques

Both approaches produce similar level of autonomy. Same results are obtained for the LoA with respect to the norm and the environment. There is one level up of difference for the reaming LoA regarding the user, the system, and itself.

Autonomy levels obtained from approach A are values that do not have any reference as to what capabilities a fully AUV should have. They only take into account the automated capabilities to autonomously perform underwater tasks. On the other hand, Autonomy levels obtained from approach B are relative results to the automated capabilities an ideal AUV should have. They provide a degree given by the relation between what automated capability a studied AUV has, and what automated capabilities a fully AUV should have. The second approach is more accurate than the first one since it is quantifying the percentage of automated capabilities provided by the AUV under study against the ideal AUV capabilities. The ideal AUV is that has 9 for each LoA.

VI. CONCLUSIONS

Autonomy-assessment criteria have been developed. Two approaches to estimate passive autonomy have been proposed, and analyzed. The application of these criteria has been showed by means of a generic AUV, and provides a way to quantify its autonomous capabilities based on a LoA scale. The approaches have focused on the passive autonomy provided by AUVs as a potential autonomous capability to automatically make decision, and potentially solve problems. The LoA scale is expected to be standard where anyone working with AUVs has a 'common language' when dealing with AUVs, and other people in the same field. The criteria have been initially applied to autonomous undersea systems but could be expanded to other application domains such as autonomous systems for space, air, or land.

The autonomy-assessment criteria proposed in this paper is the foundation for the next research direction. It will refine the measurement of passive autonomy metrics and focus on the active maritime autonomy, and also the development of a testbed-based framework to evaluate autonomy of unmanned maritime vehicles. The active DoA will depend on the mission assigned (goal, and sub-goals).

APPENDIX

The following table has a classification for the levels of automation. It is a scale defined for levels of automation in human-machine interaction [27], and has to be adapted to meet the AUV capabilities, including the scale (i.e. from 0 to 9 instead of 1 to 10).

Automation	Level of Automation	Description
Extremely-high	10	The system decides everything, acts autonomously, ignoring the human.
Super-high	9	The system informs the human only if it, the computer, decides to.
Ultra-high	8	The system informs the human only if asked,
Very-high	7	The system executes automatically, and then necessarily informs the human.
High	6	The system allows the human a restricted time to veto before automatic execution.
Low	5	The system executes the above suggestion if the human approves.
Very-low	4	The system suggests one alternative.
Ultra-low	3	The system narrows the selection down to a few.
Super-low	2	The system offers a complete set of decision / action alternatives.
Extremely-low	1	The system offers no assistance. Human must take all decisions and actions.

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