GOAL DRIVEN PLANNING AND ADAPTIVITY FOR AUVS

Hervé Ayreault, Frederic Dabe
GESMA, Groupe d'Etudes Sous-Marines de l'Atlantique
BP42 – 29240 Brest Armées – France
{herve.ayreault, frederic.dabe}@dga.defense.gouv.fr

Magali Barbier
ONERA, Office National d'Etudes et de Recherches Aérospatiales, Toulouse Center
BP 4025 – 31055 Toulouse cedex 4 – France
Magali.Barbier@onera.fr

Stéphane Nicolas, Gaël Kermet
PROLEXIA, 865 avenue de Bruxelles – 83500 La Seyne-sur-mer – France
{snicolas, gkermet}@prolexia.fr

Abstract

Environmental knowledge is increasing every day but it is neither comprehensive nor perfect. For unsupervised long mission, it is difficult to mitigate with these environmental uncertainties. Therefore, an embedded system is required to allow automatic re-planning with respect to real environmental data collected during the mission. In order to achieve this re-planning function, the information system must be able to deal with the goals that led to the initial mission planning.

GESMA, in cooperation with ONERA and PROLEXIA, develops a software architecture with four levels of autonomy from teleoperated mission to fully autonomous goal driven mission. The 3rd level is described in this paper; at this level, the mission is defined by a set of objective areas where a survey procedure is performed. The onboard hardware architecture is implemented on three computers whereas the software architecture has been developed around ProCoSA. The Man Machine Interface on one hand facilitates the offline preparation of a mission and on the other hand supervises the online tracking of the vehicle. Planning algorithms online compute new itineraries and trajectories according to the occurrence of critical events. On-going tests are performed both by simulation and at sea.

The paper will present the different autonomy levels of the onboard architecture, the way there are implemented on the AUV, optimization algorithms, operators MMI and results of on-going tests.

Introduction

Research on autonomy for unmanned vehicles is performed in robotic, aerial and spatial fields. The autonomy is characterized by the level of interaction between the vehicle and the operator (human in general): the more abstract the operator decisions are, the more autonomous the vehicle is. There are between teleoperated vehicles (no autonomy) and fully autonomous vehicles (no operator intervention) several ways to allow a system to control its own behavior during its mission [1].

When the vehicle moves in a partially known and dynamic environment, one way to make the vehicle autonomous is to implement onboard decisional capabilities. They allow the vehicle to perform its mission even when the initial plan prepared offline is no more valid. Decision capabilities, which guaranty the adaptivity of the vehicle, must be implemented in an architecture in order to close the loop {perception, situation evaluation, decision, and action}. The capacity to integrate environmental information via sensors and to evaluate the current state is indeed essential for the vehicle to assure its own safety and a minimum level of autonomy.

Figure 1 - Redermor AUV

GESMA works on autonomy projects for several years. One is devoted to the development of an autonomous system for the execution of missions in a partially known environment. The choice was made to implement several levels of increasing autonomy while conducting in parallel sea trials to validate each implementation. Sea trials are conducted with the Redermor AUV. In this project, ONERA develops the onboard decisional architecture, whereas PROLEXIA develops the man machine interface.

The paper first describes the selected levels of autonomy in relation with the type of mission to be performed. The second paragraph describes the architecture for one high decisional autonomous level. A man-machine interface to prepare the mission and to supervise it is thus presented in the third paragraph. The fourth chapter introduces the event generation by data acquisition and treatment. The main decisional task (fifth part) is the computation of a new plan when the current plan fails: optimization algorithms are implemented to allow the online reaction to events; therefore, the goal driven deliberative planning products a plan of actions based on a set of high level goals and constraints. On-going tests given in the sixth part highlight the interest of the architecture when event occurs and modify the security, the mission goal or the measurement process. We conclude about this research which could conduct to an operational product.

Selected levels of autonomy and missions

The teleoperation is seen as the 0 level: the operator uses a control box to move the vehicle. Main tests of the vehicle have been performed within this level: battery, communication, sonar, and other sensors…

At the 1st level, an ordered set of elementary controls prepared by the operator describes the mission. 16 controls combining the following and the modification of main variables have thus been implemented. Main variables are duration, speed, heading, immersion, altitude and examples of control are “follow the current heading during X seconds”, “go to the X immersion with the same heading”, “turn until the X heading”. Then, the onboard system, through a commands interface software program, online computes consigns sent to the actuators of the vehicle.

At the 2nd level, operator defines a set of segments (straight line trajectories). Onboard, a planning software computes the course changes between the end of a segment and the beginning of the next one. A guidance software program computes 1st level elementary controls to follow the different parts of the obtained plan. An emergency plan is also regularly updated to allow the vehicle to join one of the pre-defined recuperation areas if an emergency event occurs.

At the 3rd level, the mission is defined by a set of mission areas where a survey procedure is performed. The environment is defined by bathymetry, currents, forbidden areas and non-navigable water data. The planning software program has then to compute the 2D itinerary (the order to join the mission areas), the 4D trajectory between mission areas, and the survey planning. The guidance is similar to the one of the 2nd level, and the navigation to the one of the 1st level. As for the 2nd level, in order to be adaptive, the onboard architecture must be able to react to events, which modify the initial planning.

The full autonomy is seen as the 4th level: the vehicle does its best to perform the global mission without communication with the operator. In real situation, this autonomous level is currently not applicable for the whole duration of a mission. Some critical decisions have to be validated by an operator; some delicate tasks also require human intervention. However, the needs in terms of autonomy vary during a mission, and a solution could be to adjust the level according to the evaluated situation. For example, the 4th level is required when communication links are – intentionally or not – cut off. These adjusts could thus be performed by the vehicle or by the operator [2].

This paper focuses on the 3rd autonomy level.

Onboard architecture

3 computers and 13 distributed Can interfaces with computation capabilities are installed on the platform. Serial link, Can Bus, I2C and Ethernet connections are available for all types of payload integration and data exchange.

The 13 Can interfaces are dedicated to the vehicle itself and support the 0 and 1st level functions, for example fins controllers, or battery monitoring.

One of the computers (OA1) is in charge of complex and real time vehicle functions. The supervision and mission planning is implemented in an other computer (OA2). Levels 2, 3 and 4 are executed on that platform.

Two computers (OA2 & OA3) are used for sonar payload controls and treatments like Computer Aided Detection and Classification algorithms for mine warfare. This program has already been tested and can generate Mine Like Contacts as events for future re-planning.

The mission control software has Ethernet interfaces and a specific driver allows communication with the Can bus. It has a modular design in order to facilitate development, integration and tests. Its architecture separates physically the 0 and 1st level from the others. On figure 2, the yellow boxes model the decisional architecture, the blue box models the direct relationship between this architecture and the action level, the green box models the computation of consigns (1st level program), and the pink box models the event generation by data acquisition and treatment. The bottom boxes model the communication with the hardware architecture.

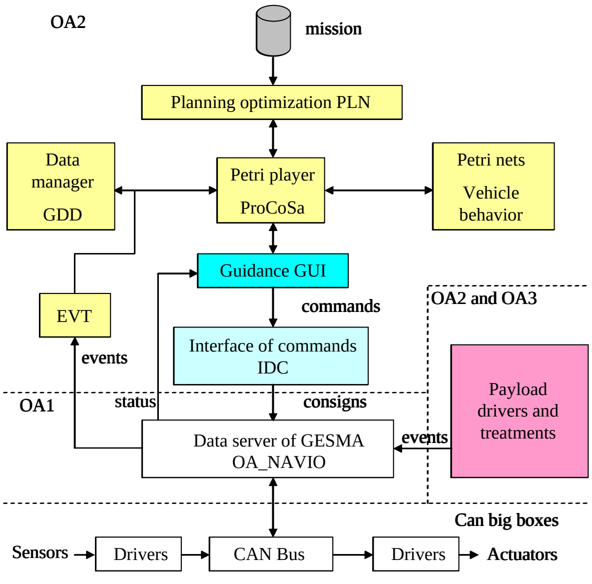


Figure 2 - Onboard architecture

The decisional architecture is based on the ProCoSA program [3], which was developed for programming and execution monitoring of autonomous systems. Behavior of the vehicle during the mission is described by Petri nets [4] (directed graphs with two kinds of nodes, called places and transitions); in ProCoSA, places represent the considered behavior internal states and transitions indicate the phenomenon that change the behavior execution state. The Petri Player of ProCoSA is the complex automate which runs the system in accordance with Petri nets and computation software such as the planning and guidance programs.

Man-Machine Interface

The Man Machine Interface, named IOVAS, provides several graphical tools to prepare, check and supervise missions of different kinds of vehicles: AUVs, ships.

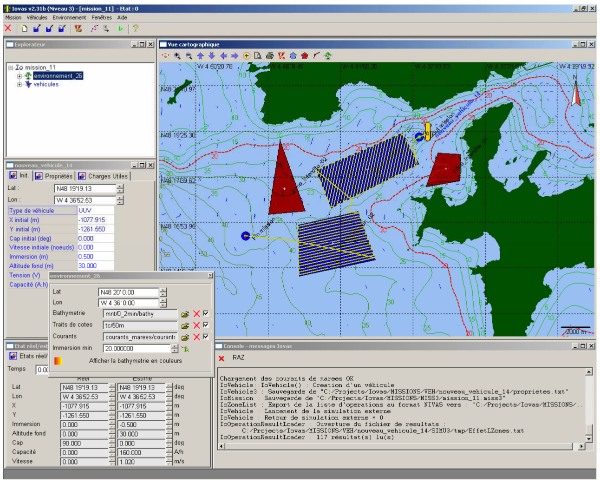
The preparation tool (Figure 3 and Figure 4) allows to graphically define the vehicles configuration and constraints and to design the tasks sequence to be executed by each of them. Each task definition is dynamically checked with the environment data (altitude to ground, forbidden areas, current) and with the vehicle's constraints like max autonomy, max immersion, min altitude, max speed etc.

The preparation tool displays bathymetric lines, currents (arrows) and forbidden areas to help the operator to prepare the mission.

During the preparation process, at any time, the operator can validate the mission by running the planning algorithm. The predicted trajectory is then displayed over the map.

Two levels of tasks can be defined:

- 1st level tasks: definition of elementary controls like "Follow heading ALPHA at an immersion Z for time T".
- 3rd level tasks: definition of objectives (in our case geographic areas to survey with associated payloads).



mission_11
environnement_26
vehicules

Lat : N48 19'19.13
Lon : W 4 36'52.53

Type de véhicule	UUV
X initial (m)	-1077.915
Y initial (m)	-1261.550
Cap initial (deg)	0.000
Vitesse initiale (noeuds)	0.000
Immersion (m)	0.500
Altitude fond (m)	30.000
Tension (V)	
Capacité (A.h)	

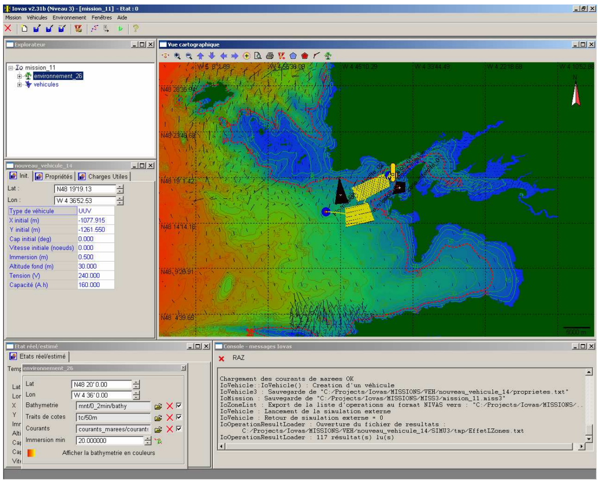
Lat N48 20' 0.00
Lon W 4 36' 0.00
Bathymetrie mnt/0_2min/bathy ☑
Traits de cotes tc/50m ☑
Courants courants_marees/courant ☑
Immersion min 20.000000

Temps 0.00

	Réel	Estimé	
Lat	N48 19'19.13	N48 19'19.13	deg
Lon	W 4 36'52.53	W 4 36'52.53	deg
X	-1077.915	-1077.915	m
Y	-1261.550	-1261.550	m
Immersion	0.000	-0.500	m
Altitude fond	0.000	30.000	m
Cap	90.000	0.000	deg
Capacité	0.000	160.000	A/h
Vitesse	0.000	1.020	m/s

```
Chargement des courants de marees OK
IoVehicle::IoVehicle() : Creation d'un véhicule
IoVehicle3 : Sauvegarde de "C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/proprietes.txt"
IoMission : Sauvegarde de "C:/Projects/Iovas/MISSIONS/MISS3/mission_11.miss3"
IoZoneList : Export de la liste d'operations au format NIVAS vers : "C:/Projects/Iovas/MISSIONS/..
IoVehicle : Lancement de la simulation externe
IoVehicle : Retour de simulation externe = 0
IoOperationResultLoader : Ouverture du fichier de resultats :
      C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/SIMU3/tmp/EffetLZones.txt
IoOperationResultLoader : 117 résultat(s) lu(s)
```

Figure 3 - Preparation interface



mission_11
environnement_26
vehicules

Lat : N48 19'19.13
Lon : W 4 36'52.53

Type de véhicule	UUV
X initial (m)	-1077.915
Y initial (m)	-1261.550
Cap initial (deg)	0.000
Vitesse initiale (noeuds)	0.000
Immersion (m)	0.500
Altitude fond (m)	30.000
Tension (V)	240.000
Capacité (A.h)	160.000

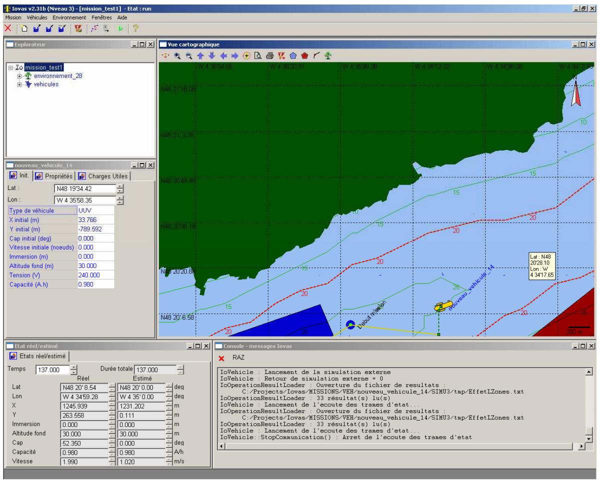
Lat N48 20' 0.00
Lon W 4 36' 0.00
Bathymetrie mnt/0_2min/bathy ☑
Traits de cotes tc/50m ☑
Courants courants_marees/courant ☑
Immersion min 20.000000

```
Chargement des courants de marees OK
IoVehicle::IoVehicle() : Creation d'un véhicule
IoVehicle3 : Sauvegarde de "C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/proprietes.txt"
IoMission : Sauvegarde de "C:/Projects/Iovas/MISSIONS/MISS3/mission_11.miss3"
IoZoneList : Export de la liste d'operations au format NIVAS vers : "C:/Projects/Iovas/MISSIONS/..
IoVehicle : Lancement de la simulation externe
IoVehicle : Retour de simulation externe = 0
IoOperationResultLoader : Ouverture du fichier de resultats :
      C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/SIMU3/tmp/EffetLZones.txt
IoOperationResultLoader : 117 résultat(s) lu(s)
```

Figure 4 - MMI environmental data

The supervision tool (Figure 5) is used to track the vehicles positions in real-time using data coming from acoustic links, short base line tracking system or GPS serial links.

It displays each vehicle's trajectory and detailed status if available (heading, immersion, altitude, energy). The real trajectories can be compared in real time with the planned ones.



Lat : N48 19'34.42

Lon : W 4 35'58.35

Type de véhicule	UUV
X initial (m)	33.766
Y initial (m)	-789.592
Cap initial (deg)	0.000
Vitesse initiale (noeuds)	0.000
Immersion (m)	0.000
Altitude fond (m)	30.000
Tension (V)	240.000
Capacité (A.h)	0.980

Temps 137.000 Durée totale 137.000

	Réel	Estimé	
Lat	N48 20' 8.54	N48 20' 0.00	deg
Lon	W 4 34'59.28	W 4 35' 0.00	deg
X	1245.939	1231.202	m
Y	263.558	0.111	m
Immersion	0.000	0.000	m
Altitude fond	30.000	30.000	m
Cap	52.350	0.000	deg
Capacité	0.980	0.980	A/h
Vitesse	1.990	1.020	m/s

Lat : N48 20'28.10 Lon : W 4 34'17.65

```
IoVehicle : Lancement de la simulation externe
IoVehicle : Retour de simulation externe = 0
IoOperationResultLoader : Ouverture du fichier de resultats :
      C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/SIMU3/tmp/EffetLZones.txt
IoOperationResultLoader : 33 résultat(s) lu(s)
IoVehicle : Lancement de l'ecoute des trames d'etat...
IoOperationResultLoader : Ouverture du fichier de resultats :
      C:/Projects/Iovas/MISSIONS/VEH/nouveau_vehicule_14/SIMU3/tmp/EffetLZones.txt
IoOperationResultLoader : 33 résultat(s) lu(s)
IoVehicle : Lancement de l'ecoute des trames d'etat...
IoVehicle::StopCommunication() : Arret de l'ecoute des trames d'etat
```

Figure 5 - Supervision interface

Events generation, Data treatment

AUV mission planning is performed for specific tasks or goals. Its efficiency depends on its capacity to integrate environmental information and sensors status and is therefore related to AUV security insurance, mission optimization and data quality insurance.

For AUV security, the mission planning must consider bathymetry, known obstacles, density variation. Currents are also important information to guaranty the energy consumption and therefore the feasibility of the mission (AUV must have enough energy to come back). Bathycelerimetry distribution might also influence the acoustic communication for supervised mission.

Mission optimization is important for mission efficiency which is a high operational requirement. Assuming that the mission is defined by a set of operation areas, the optimization can be as simple as calculating the geometric shortest path or as complex as computing a path while optimizing energy consumption related to tides and currents.

Data quality is relative to exhaustivity, accuracy and confidence. The mission planning must guaranty perfect sonar coverage and overlap whatever the bathymetry is. It must take into account navigation errors due to seabed characteristics (Doppler doesn't like mud) or too strong currents that might induce unstability. Another requirement would be to have heading perpendicular to sand ripples for sonar acquisition.

Therefore, many events can affect AUV mission and require onboard re-planning. At that time, GESMA efforts mainly focus on two different kinds of events.

- Real time currents assessment is one of them as it might influence survey heading and energy consumption. Different solutions to get current values are evaluated like parameters identification, DVL/ADCP sensor, and electromagnetic probe.
- Regarding mine warfare, it is very important to increase the level of efficiency of Computer Aided Detection algorithms. Onboard re-planning for multi-aspect sonar acquisition of mine like contacts is one of the main GESMA objectives in a near future. Mission re-planning to take into account low level of efficiency due to environmental conditions (sand ripples or reverberation for examples) will be the next step.

Planning algorithms

The objective of the planning function is to compute the movements of the vehicle for the achievement of the mission. This computation is performed offline during the preparation of the mission to allow the operator to see its feasibility and the estimated vehicle behavior. Onboard and online, the function gives autonomy to the vehicle. A global online computation of all the movements by only one algorithm hasn't been considered for several reasons: the number of constraints is high and could lead to a complex algorithm, the computation duration has to be relatively short, some problems could be locally solved. The decision was then taken to develop several planning algorithms.

As the mission is defined by a set of objectives, the first algorithm computes an itinerary that is it orders the objectives. In this 2D search, objectives are modeled by their geometric centroid waypoint. A mission graph is built with the objective waypoints, the start and the end waypoints. The costs of the edges are computed taking into account the current and the non-navigable areas. For each pair of waypoints in the mission graph, a Dijkstra algorithm finds iteratively the shortest path which is built on a sort of reduced visibility graph that allows avoiding known obstacles (Figure 6). The cost matrix is not symmetric because of the current. A Little algorithm [5] looks then for a Hamiltonian path of lowest cost in the mission graph.

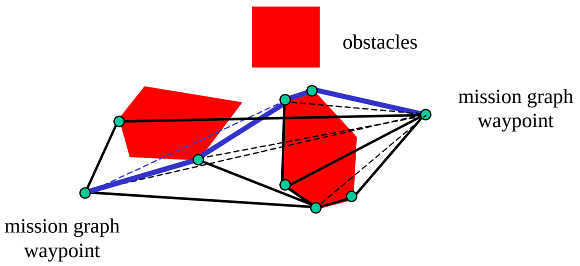


Figure 6 - Shortest path between two waypoints of the mission graph

The second algorithm computes the actions to achieve a survey operation. The operative sequence is composed of linear trajectory followings and course changes. To consider sonar constraints, the survey is made at steady altitude. The main direction of the survey depends on the direction of the estimated current.

The third algorithm computes the 4D trajectory between each pair of the itinerary. The itinerary is followed at nominal steady speed. Between each pair of objective areas, we assume that the vehicle follows a steady immersion, even when it avoids non-navigable areas (Figure 7). This modeling allows limiting the risk due to the bathymetry uncertainties. The trajectory avoids non-navigable areas with relevant course changes. The slope of the ascents and descents considers the constraints of the vehicle. If the maximum slope can't be respected, course changes are added to the trajectory.

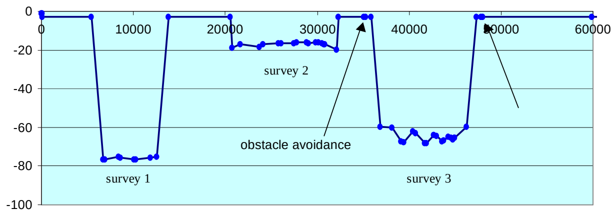


Figure 7 - Trajectory immersion (m.) vs. trajectory length (m.) for a 3 objectives mission

The itinerary and operation planning algorithms are also implemented in the Man Machine Interface to allow an operator to prepare a mission. Figure 8 shows the application of the planning function on the 2D map of the MMI. Objective areas in blue are surveyed, forbidden areas in red and non-navigable areas (coastline in red, coast area in green) are avoided. Numerous tests have validated the planning function in typical and untypical missions.

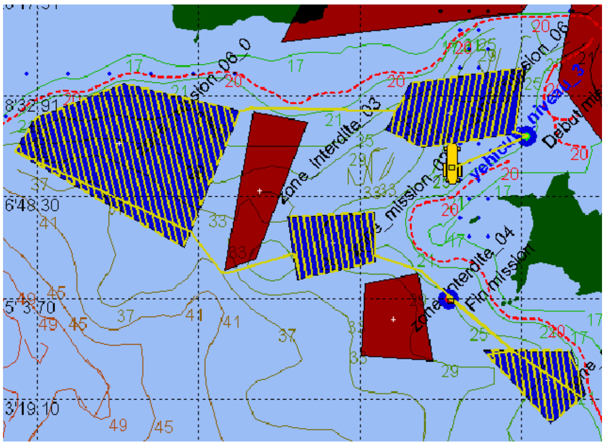


Figure 8 - Example of planning computation

The previous planning function gives its autonomy to the vehicle when used in response to the occurrence of events which invalid the current plan (either initial or already recomputed). Events are managed by the onboard architecture, which calls the different planning algorithms according to their level of criticity and the current status of the vehicle.

On-going tests

In May 2005, the level 1 was successfully validated at sea. It was a very important step as this level has direct interaction with the vehicle itself. It guaranties an easy software integration of all other levels that are already evaluated by simulation.

The 3rd level architecture has been validated by simulation, in nominal and re-planning situations. Three types of events have been successfully simulated:

- An alarm event forces the vehicle to move directly to the end waypoint: a new itinerary to avoid non-navigable areas then a new trajectory are computed.
- When arriving on an objective area, the real current is different from the predicted one and invalidates the already-computed survey: an operative sequence is computed taking into account new data.
- The operator asks for a local operation of inspection, for example to inspect a suspicious object. A specific operative sequence is planned then the vehicle resumes its mission.

The 3rd level will be tested at sea in March and April 06. An example of test will concern the current. False current data will be used to generate the initial planning. Once on the survey zone, real time measurement should start the re-planning process.

Conclusion and future work

If goal driven planning has proven to be feasible in simulation, the recent developments made by GESMA, ONERA and PROLEXIA push towards a fully operational system taking into account:

- Environmental data from hydrographic database and standards,
- A modular embedded architecture with evolutionary potential for onboard supervision and re-planning,
- A user friendly MMI giving advanced operator functions for goal mission preparation and supervision.

GESMA future works on autonomy will mainly focus on REA AUVs. Their missions are mainly characterized by the following points:

- The efficiency of the mission relies on the quality of the environmental data collected and the percentage of surveyed area.
- The REA AUVs are obviously operated in unknown environment (or even hostile for some military purpose).This lead to increased security and autonomy compare to survey mission.

As a response to these difficulties, GESMA will conduct works on:

- Re-planning capacity (adaptativity) that will take into account performance mapping. This performance mapping will assess in real time the quality of the collected environmental data. If a given threshold is not achieved, a new path planning is generated to improve the overall performance.
- Real time goal optimisation. Compare to classical goal driven mission in mine warfare, in the case of REA, the goal are modified in real time taking into account the collected environmental data like currents, bathymetry, and water density. For example, near shore mission can not be geographically limited in advance by an operator and the AUV needs to find the best reliable path to get as near as possible to the beach.

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