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***Abstract*— Because Autonomous Underwater Vehicles (AUVs) have limited perception and communication capabilities, designing efficient AUV flotillas is challenging. Existing solutions are often strongly related to (1) a specific kind of mission and (2) the nature of the considered AUVs. So, it is difficult to reuse these approaches when switching to another mission context. This paper proposes a generic multi-agent based layered architecture for designing and specifying AUV flotillas at a high level of abstraction, regardless of the AUVs characteristics and skills. To this end, an organizational model is used to ease and regulate interactions between heterogeneous AUVs and combined with a behavioral reactive approach for limiting communication.**

I. INTRODUCTION

Undersea environments are particularly challenging for robotics because they are highly dynamic and constrained. In such context, most trends of research focus on Autonomous Underwater Vehicles (AUVs) because they are particularly suited for missions in which global human control can not be achieved. Considering this application domain, the environmental characteristics require taking into account three major issues. Firstly, AUV navigation is hard to achieve as the Global Position System (GPS) can not be used underwater. Some research is being conducted to allow an AUV to locate autonomously from the sea floor. For known areas, terrain referenced navigation [1] could be a solution whereas simultaneous localization and mapping (SLAM) techniques [2] are being studied to deal with unknown environments. Secondly the environment is particularly dynamic due to disturbances caused by waves, ocean currents or the inevitable moving objects and animals. Current control approaches enable effectively controlling AUV displacement. Lastly, perception and communication capabilities are very restricted underwater. Only sound waves enable long range communications. However, their uses raise numerous problems such as low data rate, multi-path, propagation delays, interferences, etc.

Undersea missions typically have large areas to cover while AUV are not able to carry heavy payload because of the space and energetic limitation. Therefore, research efforts are being done on Multi-AUV approaches which rely on using several AUVs considered as a flotilla [3]. Mainly inspired by terrestrial and aerial robotics, formal approaches of centralized and decentralized control have been developed. Usually, they are focused on achieving and maintaining a particular shape for the flotilla as a whole using strategies like leader-follower [4], artificial potentials and virtual structures [5], mainly in the missions of area coverage. However, such approaches lack robustness and do not scale because they depend on reliable communication and do not take sufficiently into account the nature of the communication medium [3]. Furthermore, they also do not cope with a potential heterogeneity of the AUVs in the flotilla. Vehicles with lower performance penalize the whole group. Different skills and capabilities can not be exploited, which limits the type of missions that could be considered.

Considering these issues, the degree of autonomy of each AUV is a crucial parameter. Indeed, increasing AUV's autonomy means that (1) less communications are required and (2) the AUV does not depend on the characteristics of others. So, recent approaches (e.g. [6], [3]) successfully use the Multi-Agent Systems (MAS) paradigm because it explicitly deals with such concepts: MAS are composed of autonomous entities (agents) that interact to achieve their goals, thus producing a global behavior [7]. In the scope of multi-AUV, the autonomy of an AUV has to be related with the idea that this AUV should communicate with others as less as possible. This is crucial with respect to underwater coordination because communication reliability is not a valid hypothesis [3]. Furthermore, coordination between autonomous entities has been intensively studied in the MAS research domain. Finally, using a MAS perspective, another goal is to cope with AUVs heterogeneity. Indeed, an experimental mission often involves several research or industrial teams. Usually, each team develops specific robots in terms of functionalities and capabilities for communication. Although great in theory, this heterogeneity raises incompatibility and complexity problems in practice.

Following this trend of research, this paper proposes a generic multi-agent based layered architecture for designing and specifying AUV flotillas at a high level of abstraction, regardless of AUVs characteristics and skills. This paper describes how this approach addresses some of the limitations found in similar existing approaches, especially by providing a reusable AUV framework which is not related to a specific kind of mission.

This paper is organized as follows. Section II describes the problem of the multi-vehicles coordination in underwater environment. In section III, an organizational approach is presented. It allows a multi-agent representation of the flotilla and facilitates multi-vehicle cooperation. Sections IV, V, VI describe the three layers of the architecture. Section VII presents simulation results obtained using a preliminary version of the architecture in the scope of a multi-AUV area mapping scenario. Section VIII concludes the paper.

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II. MAS AND AUV FLOTILLA

As stated in the introduction, the coordination of AUV flotilla could be tackled from a multi-agent perspective. Research works that use such a perspective aim at giving more autonomy to AUVs and coping with more complex missions requiring heterogeneous vehicles with various capabilities. In such systems, many tasks are shared and performed by several AUVs in the frame of a common goal.

A. Existing Approaches

MAS based software architectures have been developed to conduct the management and the execution of missions in multi-AUV. Usually, these are adaptation of single-AUV [8] or application of current cooperative robotics [6]. Online distributed mission planner and task allocation mechanisms are employed. Currently, classical multi-agent approaches are used. In DEMIR-FC [6], a bidding system based on the Contract Net Protocol allows to select task executers. In [3], a Hierarchical Task Network (HTN) mission representation is associated with a blackboard system to share tasks among the flotilla. Multi-AUV systems may also require to consider situations wherein communication is not possible. Strategies such as AUVs actions prediction [3] or rendezvous point synchronization [9] also address this issue using a MAS approach.

B. Limitations of Existing Approaches

Existing approaches involve complex communications. In [6], the Contract Net Protocol engenders a lot of data exchanges. Communication has to be reliable to accomplish the mission effectively and to avoid redundant execution of tasks. In [3], the blackboard system requires regular broadcasting of the entire mission's state. Therefore, the communication load is related to the complexity of the mission and the number of participants, so that the approach does not scale easily.

As the number of AUVs increases, the mechanisms used in existing architectures for mission planning, allocation and execution of coordinated tasks become increasingly complex. In [3], each AUV should know the entire mission's state and all the AUVs informations and tasks distribution to take decisions. To maintain these variables up-to-date when communication is not possible, a prediction mechanism is used wherein other AUVs are simulated. This mechanism can become very complex as the flotilla becomes large and/or is composed of heterogeneous AUVs. Considered flotillas are therefore limited to few homogeneous AUVs.

Previous approaches restrict the complexity of the system by considering highly homogeneous AUVs in terms of hardware architecture. Means and protocols of communication are imposed on all vehicles in the flotilla. Architectures are extremely dependent on the task allocation process. So, flotilla can only be composed by AUVs which have been designed according to specific requirements and can not integrate other approaches.

C. Proposed Approach

The approach that will now be described aims at addressing these limitations. To this end, the proposed software architecture, namely REMORAS, relies on explicitly representation of the flotilla organization. Doing so, the goal is to simplify mission planning, task allocations and interactions between AUVs regardless of their internal functioning. REMORAS is designed for multi-robot cooperation in restricted communication domain. It allows heterogeneous AUVs to coordinate with respect to various underwater missions. The main idea is to combine an organizational approach [10] with a reactive mechanism [11].

III. USING AN ORGANIZATIONAL VIEW OF MAS

In MAS, there exists two different levels at which the system could be designed and studied: The micro level that focuses on the internal architecture of the agents, and the macro level which addresses the MAS as a whole, from a global point of view. Classical multi-vehicle approaches, especially the works cited in the previous section, are designed by considering a micro level perspective. At this level, studies are conducted on the robot's states, the relations between these states and the overall behavior of the agent. Actions and interactions are entirely determined from the "internal state" of the robot. Such approaches may be called "agent centered multi-agent systems" (ACMAS) [10].

Following an ACMAS perspective, agents are supposed to be autonomous and no constraint is placed on the way they interact. However, this freedom has the effect of increasing the complexity of the agent's behavior because it has to manage how and with which agents it cooperates. In practice, this eventually imposes strong homogeneity on the agents: Limiting complexity is obtained by using robots with very similar architectures and employing same languages. So the multi-vehicle cooperation becomes very dependent of the robot's hardware. On the contrary, organizational concepts allow to design and study MAS at the macro level. In such a perspective, an organization could be considered as a means used by social actors to regulate and rule their interactions, thus limiting coordination actions [12]. Indeed, there is a growing interest regarding the use of organizational concepts within the multi-robot domain. Terms such as "team", "role", "formation", "teamwork structure" and so on, are now used in domains where robots must cooperate (e.g. soccer [13] or military robots).

To overcome ACMAS limitations in the scope of our research domain, we propose to adopt the principles of "organization centered multi-agent system" (OCMAS) [10] and provide an organizational structure to the AUV flotilla. The Agent/Group/Role (AGR) model gives a general framework to design OCMAS (cf. Fig. 1). AGR is a very concise model which has many advantages with respect to our objectives. (1) AGR allows to modelize various **artificial organizations** according to various AUV missions. (2) Because AGR does not assume anything about the cognitive or the hardware characteristics of agents, it is very suited for organizing **heterogeneous agents**: Skills, services offered or agents func-

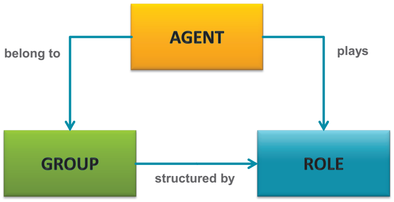

Fig. 1. The three core concepts of the AGR model

tions are simply characterized by the generic term "Role", independently of the technical details. (3) Heterogeneity of communications is handled by using different groups since agents may communicate only within their groups. Furthermore, role and group concepts also ease to **regulate interactions**: Interaction protocols are only defined in the scope of two roles. (4) Finally, the model allows to design the system **with a great modularity**. Group boundaries may be placed between the different communities of agents. This limits the complexity of the system within each group and admits adding extra groups of agents without affecting the overall system.

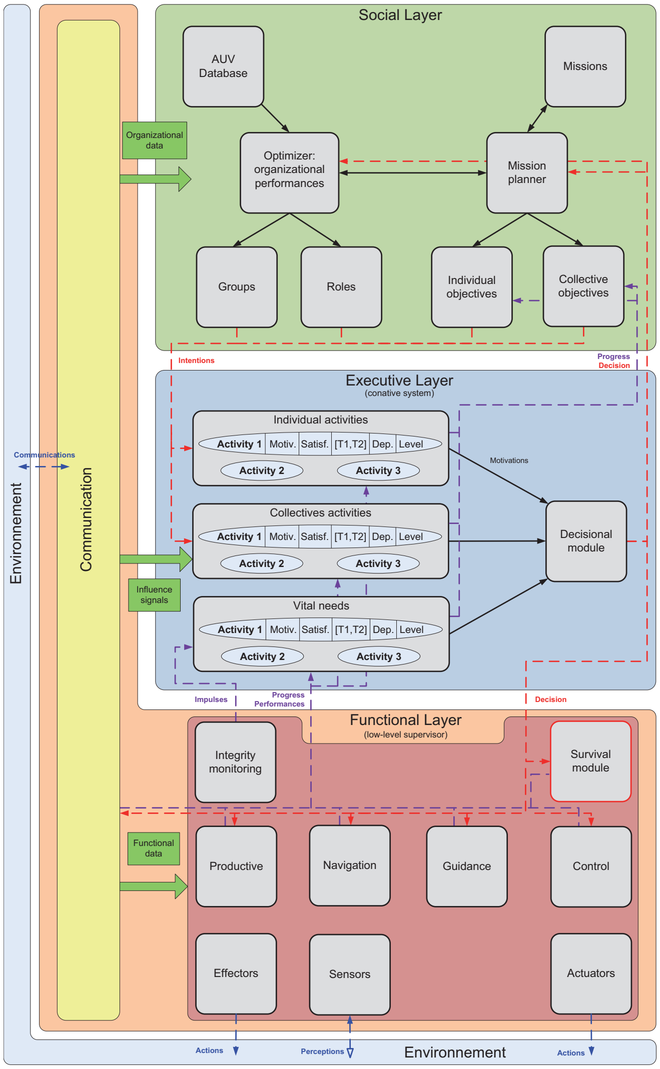

Fig. 2. REMORAS: a three-layer control architecture

These aspects allow to greatly simplify the agent's view of the system, especially in terms of cooperation. The communications required to coordinate the different AUVs are reduced, thus addressing one of the critical issue of the multi-AUV domain. Figure 2 shows an overview of the REMORAS architecture. The next section describes the social layer REMORAS architecture which integrates organizational aspects.

IV. SOCIAL LAYER

The *social layer* is a generic software layer which is absolutely independent of the agent that implements it. This layer can be considered as an additional module that allows AUVs to have an organizational representation of the flotilla and participate in this organization. The social layer is dissociated from the robot's mission control system which is charged of mission execution. It is therefore adapted to different AUV architectures.

A. Combining Organizational and Mission Viewpoint

The social layer is made of eight modules (cf. Fig. 2). Four modules allow to implement the AGR model (cf. section III) and give an organizational view of the flotilla to AUV:

AUV Database: It is a module that contains AUV information of the flotilla. It is not necessary for an AUV to know the information of all the flotilla. This information includes static data such as vehicle type, its physical characteristics (dimensions, speed boundaries, maximal depth, etc.) and its playable roles. If necessary, it may also include variable data such as autonomy, sensors status, etc.

Optimizer of organizational performances: This module allows forming groups of AUVs and allocating roles with respect to available resources in the AUV Database module (AUV number, characteristics, playable roles). This module interacts with the *Mission planner* module to optimize the formation of groups and the allocation of roles.

Groups and Roles: These are mapping modules associating each group and each role to a set of AUV identifiers.

This layer allows the AUVs to have a representation of the mission performed by the flotilla. It allows the AUVs to administer and distribute tasks, so that they are performed by the flotilla. The task structure of the mission is modeled b using the HTN (Hierarchical Task Network) formalism [14]. A HTN is a hierarchical set of abstract and elementary tasks. One or several methods are assigned to an abstract task and describe the way to achieve it, using other abstract or elementary tasks. Figure 3 shows some classical structures.

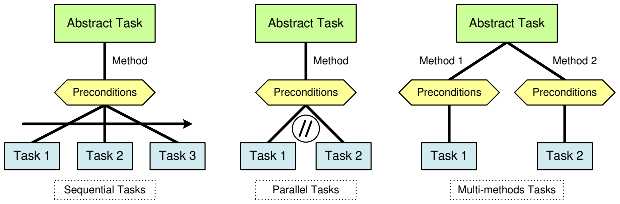

Fig. 3. Examples of HTN formalism

Four modules handle the missions of the flotilla and allocate the different objectives to AUVs:

Missions: It is a module mapping each group to a set of missions. A mission is a high level abstract task in the HTN formalism. It may be generated by the *Mission planner*.

Mission planner: This module allows generating and allocating several objectives to roles played by AUVs. It employs the methods dedicated to missions which are specified in the *Missions of Groups* module. Similarly, the planner may generate new missions. The concept of objective designates an abstract task in HTN formalism corresponding to an AUV goal to achieve. An objective is generic and does not define how it will be achieved. The module interacts with the *Optimizer of organizational performances* module to optimize missions and objectives allocation.

Individual objectives : This module associates each AUV identifier to a set of individual objectives which are executable by an AUV without interacting with others.

Collective objectives coordination: This module associates each role to a set of collective objectives which necessarily requires interacting with other AUVs.

Database and mapping modules may be initialized or directly supplied by received organizational data. The main characteristic of this layer is to actually combine an organizational approach with a more classical one for mission planning and objectives allocation. (1) A group is associated with one or several missions, which means that the cooperation of AUVs within a group occurs for achieving one or several common missions. (2) The role or the identifier of an AUV is associated with one or more objectives. The function of an agent is to perform tasks autonomously in a collective goal framework. Thus, coordination of actions between agents can be facilitated. (3) Finally, the concept of agent is not related to task concept in this generic layer. The other two layers of architecture are more specific to the characteristics of the agent.

B. Social Layer Requirements and Features

This layer is designed to enable robots with very heterogeneous hardware architectures to cooperate. It is not necessary that the whole flotilla implements the social layer but global system must respect some requirements. (1) At least one AUV per group must have this layer. (2) An AUV can be integrated into a group if it has the ability to interact with another AUV. (3) An AUV can not assign groups, roles, and allocate objectives to an AUV that is not a member of its group. The two first requirements ensure the connectivity of the flotilla and maintain a global organization. They enable the use of existing flotilla coordination approaches or vehicles with extremely limited hardware/software abilities. The third requirement provides security and modularity features. However, an AUV can plan a mission for a group to which it is not a member. This allows the formation of hierarchical organizations. The strategy of organizational information sharing between the AUVs is free. Information may be shared by many AUVs to promote robustness against failures, or conversely, informations can be more distributed to reduce communications.

V. EXECUTIVE LAYER

The executive layer describes the behavior of an AUV and thus models its *conative function*. Following an agent modeling perspective, this layer deals with how the AUV (1) processes perceptions (requests from other agents, social pressures, vital status), (2) combines them with its internal state (current objectives and activities) and then (3) decides the tasks to achieve.

A. The Satisfaction-Altruism Reactive Approach

The roles which are assigned to an AUV by the social layer correspond to a set of objectives to achieve. These objectives are processed by the executive layer so that they are converted into individual or collective activities described in the HTN formalism. Collective activities, which require cooperation and thus involve AUV interactions, are the most challenging for an AUV. In the underwater environment, actions coordination of heterogeneous vehicles is a major issue regarding the communication constraints. To cope with this issue, we propose a reactive approach, inspired by the satisfaction-altruism model [11]. The main idea of this approach is to combine, within the decision making process, the personal motivations of the AUV with external motivations coming from other AUVs by using very simple communication signals. Respecting satisfaction-altruist model, activities are in competition according to their trigger weight, called motivation. Three types of motivation are considered. (1) The motivation to perform a task depending on its importance and perception of stimuli triggers. (2) The motivation to continue the current task. (3) The motivation to answer to external requests. The first two motivations are related to how the personal objectives and activities of an agent are progressing. They involve the notion of *personal satisfaction* [15]. The latter motivation is of cooperative nature and evolves according to signals exchanged between agents. The signals emission enables an agent to reflect its personal satisfaction to others so that it may influence them by triggering their altruistic behaviors. So, the satisfaction-altruism model enables heterogeneous agents to cooperate intentionally and have altruistic reactions via low-level local interactions. It has been particularly effective for treating problems physically distributed and solving conflicts among agents [15].

In the scope of our approach, we use this model in conjunction with the organizational structure so that personal satisfactions are defined for each role played by an agent. So a communicating activity called “sending influence signals” (cf. Fig. 4) computes a personal satisfaction for each role and sends it to other agents within a group using a broadcast mode. Roles can thus influence each other. The progress of role’s activities execution affect the trigger motivation of another role’s activities. The personal satisfactions are coded on 8 bits between -128 and 127. These values correspond respectively to the extreme degrees of dissatisfaction or satisfaction of the played role Resulting influence signals are extremely simple and concise to cope with the limited bandwidth of underwater environment.

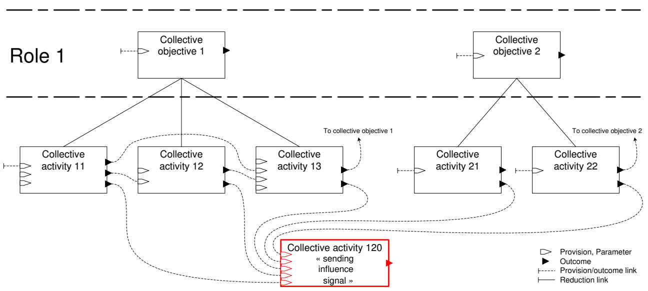

Fig. 4. Addition to “sending influence signals” activity

B. Decision Making

Three modules are defined according to the activities:

Individual activities: This module brings together activities which do not require coordination with other AUVs. However, they are parts of the group’s mission. The personal motivation of these activities are not sensitive to the influence signals sent by other AUVs.

Collective activities: This module involves activities which require cooperation with other AUVs in a group. These activities correspond to common goals shared by several agents or altruistic reactions exerted by the AUV toward another. As these activities progress, the influence signals are exchanged between agents so that motivations evolve accordingly and thus eventually trigger other collective activities.

Vital needs: This module includes activities that ensure the integrity of the AUV and which are triggered by internal impulses coming from measurements and perceptions performed by the functional layer. These activities are independent of influence signals sent by others.

All the preceding activities express motivations on the decisional system. The *decisional module* is in charge of selecting the activity to perform. In the satisfaction-altruism model, the goal with the most important motivation is selected and then combined with other compatible behaviors. Usually used for guidance activities, a goal vector is selected and a vector combination is performed to avoid obstacles and repulsive signals sent by others. This concept is here generalized and several types of compatible activities are identified. The **organizational activity** modifies the organization of its group by allocating roles and forming new groups. The **planning activity** plans missions for groups or allocates individual or collective objectives assigned to AUVs’ identifiers or roles. Usually, this activity must be performed in conjunction with an organizational activity. The **navigation activity** locates the AUV. Position may be global or relative to objects in the environment (others AUVs, the sea floor, etc.). The **guidance activity** determines the direction and speed references to be followed. The **control activity** determines a control law which computes the orders to send to actuators (motors, rudders, etc.) following the guidance reference. The **productive activity** performs working tasks. It can be activities of measurements, mapping or more creative activities such as manipulating objects, etc. The **communication activity** communicates a message to another AUV. The **survival activity** maintains the integrity of the AUV.

The *decisional module* is in charge of finding the best combination between activities. The selection algorithm forms sets of activities containing at most one activity by type. It considers those that must be performed simultaneously. Then, the motivation average of each activities set is compared. The best set is selected and forms what is called a *decision*.

VI. FUNCTIONAL LAYER

The functional layer aims to perform the activities selected by the executive layer. It executes the algorithms, manages the sensors and their data, actuates the effectors and processes data communicated between vehicles, etc. A low-level supervisor is responsible for scheduling tasks. Activities mentioned in subsection V-B are processed in the module of **navigation**, **guidance**, **control**, **productive**, **communication** and **survival**. The **sensors** module can acquire data from navigation or mission sensors. **Effectors** and **actuators** modules bring together respectively AUV’s effectors and the actuators controlling the AUV’s position and attitude. The *integrity monitoring module* ensures the physical integrity of the AUV by conducting internal measures (state of batteries, sensors, actuators, etc.) or external measures (distance to potential obstacles, the water pressure, etc.). It analyzes the risks for the AUV and sends impulses to the vital needs module of the executive layer. Each module evaluates the *progress* and the *performance* of the activity execution. They are sent to the executive layer and used by the motivational system for calculating the personal satisfactions of activities and evolving the trigger motivation.

The communication module is more singular. Its interface covers the different layers of architecture. It is configured with certain information on the AUV as its unique identifier as well as AUV’s data organization (the groups to which it belongs and the roles played in its groups). The emission of a communication signal is made in the context of the completion of a communication activity. Three types of data can be transmitted. The **organizational data** of the social layer are related to the organization of the flotilla or the allocation of missions or objectives. The **influence signals** of the executive layer correspond to the satisfaction level of the AUV’s role execution. The **functional data** of the functional layer data are used for the activity processing. They may be data concerning the location (position update, bathymetric map, sea marks, etc..), the guidance (direction, speed of another AUV, etc..) and so on. Message syntax and semantics are defined as follows. The <group-identifier>, <emitter-identifier> and <target> are used for identification purposes. The last one could refer to a single identified team member, a group or a role. The <message-type> notifies the semantic of the content and is used to dispatch the message to the corresponding layer. This may be organizational data, influence signals or functional data.

VII. SIMULATION RESULTS

A. Scenario

Preliminary version of the architecture has been implemented using the multi-agent simulation platform TurtleKit [16] which integrates the AGR organizational model. In the simulation, the organizational approach used by the social and the executive layers is implemented. As the purpose is to focus on these aspects, simulated functional layer is basic and interacts with a simplified 2D environment. The problems related to navigation, control and communication are not modeled here. The simulation scenario is an area exploration and mapping mission with one Autonomous Surface Vehicle (ASV) and three AUVs. Figure 5 shows the concrete organization which has been designed for this scenario.

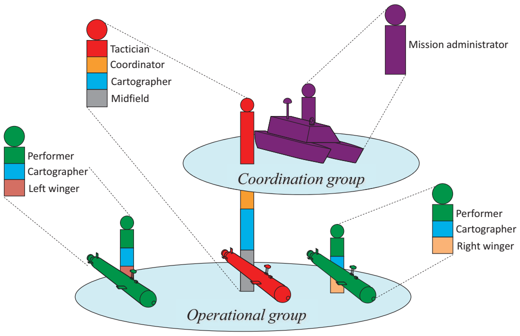

Fig. 5. AGR organization of the scenarios flotilla

At the beginning of the mission, all the AUVs' data are known by all AUVs. Two groups are initialized: The "Coordination group" is formed by an ASV and an AUV. The mission of the group consists to supervise the flotilla for achieving the exploration and mapping of an undersea area. The ASV plays the role of "Mission administrator". The "Tactician" is played by the AUV. They define together the strategy of the mission affected to the "Operational group". The "Operational group" is made of three AUVs and is supervised by the "Coordinator" AUV which is the same AUV playing the role of "Tactician" in the "Coordination group". The "Coordinator" organizes the group by allocating roles, thus plans the objectives of the AUVs. So, the AUVs, which plays the "Performer" role have their objectives automatically assigned and executed. At the end of the mission of each group, the corresponding AUVs have to come together at a given point. Table I summarizes the different AUVs' groups and roles allocation and the corresponding missions and objectives.

B. Results

The two groups start initially at coordinates $(0, 0)$. Each AUV interprets the objectives associated with its roles. The set of corresponding activities is generated by the executive layer of each AUV. Table II gives an example obtained by this process for AUV00. The AUVs use their own characteristics for generating the activities to perform. Especially, AUVs exploring activities are significantly different according to the embedded sensors. This property appears clearly during the execution of these activities after the consultation phase at 7.1 s. AUVs' trajectories are presented in Fig. 6. Figure 7 represents the temporal evolution of roles played by the different AUVs.

TABLE I

AUVS' GROUPS AND ROLES ALLOCATION

Groups	Mission	AUV Id	Roles	Objectives
Coordination	Supervision	ASV00	MissionAdministrator	GroupSupervision
				RendezVous (500,500)
		AUV00	Tactician	MissionGathering
				RendezVous (500,500)
Operational	AreaMapping	AUV00	Coordinator	GroupSupervision
				RendezVous (450,450)
		AUV01 AUV02	Performer	MissionGathering
				RendezVous (450,450)
		AUV00 AUV01 AUV02	Cartographer	Mapping
		AUV01	LeftWinger	Positioning
				Exploring [(350,100)(350,350)(600,350)(600,100)]
		AUV00	Midfield	Positioning
				Exploring [(100,100)(100,350)(350,350)(350,100)]
		AUV02	RightWinger	Positioning
				Exploring [(100,350)(100,600)(350,600)(350,350)]

TABLE II

AUV00: ACTIVITIES GENERATION

Roles	Objectives	Activities
Tactician	MissionGathering	LocalReactiveNavigation
		Following (Follower to MissionAministrator)
		PerformerSubordination
	RendezVous (500,500)	GlobalReactiveNavigation
		Homing (500,500)
Coordinator	GroupSupervision	GlobalReactiveNavigation
		Following (Leader to Performer)
		LeaderInformationGathering
		OrganizationalPerformanceOptimizer
		MissionPlanner
		LeaderInformationGathering
	RendezVous (450,450)	GlobalReactiveNavigation
		Homing (450,450)
Cartographer	Mapping	Mapping
Midfield	Positioning	Positioning(Top, Middle)
	Exploring [(100,100)(100,350)(350,350)(350,100)]	GlobalReactiveNavigation
		ZizagExploring Points grid: (112.5,112.5) (137.5,112.5) · · · (337.5,112.5) (112.5,137.5) (137.5,137.5) · · · (337.5,137.5) ⋮ ⋮ ⋮ (112.5,337.5) (137.5,337.5) · · · (337.5,337.5)

The "Mission administrator" (shown in purple on Fig. 6), first organizes the flotilla, plans and shares the mission of "Operational group" via the "Tactician", and then goes to the next rally point of its group in $(500, 500)$. AUV00 (shown in red on Fig. 6) neglects its role of "Tactician" in favor of roles held within the "Operational group". It allocates itself the roles of "Midfield" "Cartographer", and thus goes to the central area for mapping. At the same time, the "Left winger" and "Right winger"(green in Fig. 6) join theirs. In Fig. 6 (b), the different "Cartographer" are making zigzag paths to map their assigned areas. Respectively at 1774 s and 1738 s, AUV01 and AUV02 have finished their mapping and thus interrupt the activities associated with this role. Both AUVs then join the rallying point of their group at the point $(450, 450)$ via their "Performer" roles. For AUV00, the role of "Coordinator" takes over on so that it gives up exploration and mapping activities at 1908 s to join the rally point of the group for which it is responsible. At 2008 s, the AUVs within "Operational group" are meeting each other. The activity related to the "Tactician" role urges AUV00 to join the rally point of the "Coordination group" to which it belongs. Meanwhile, "Performer" AUVs of the "Operational group" follow the leader and then position themselves on the right or left side according to their "Winger" role. The simulation ends when the "Tactician" and the "Mission administrator" have reached the point $(500, 500)$ at 2036 s.

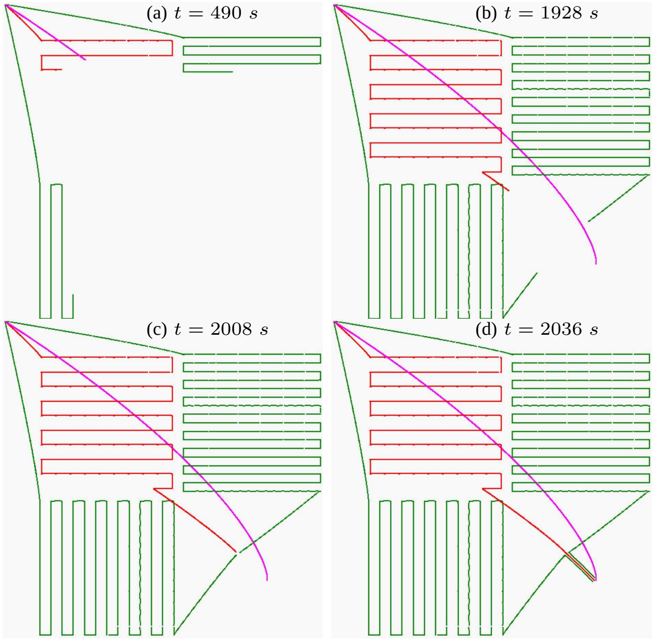

Fig. 6. Trajectories of vehicles

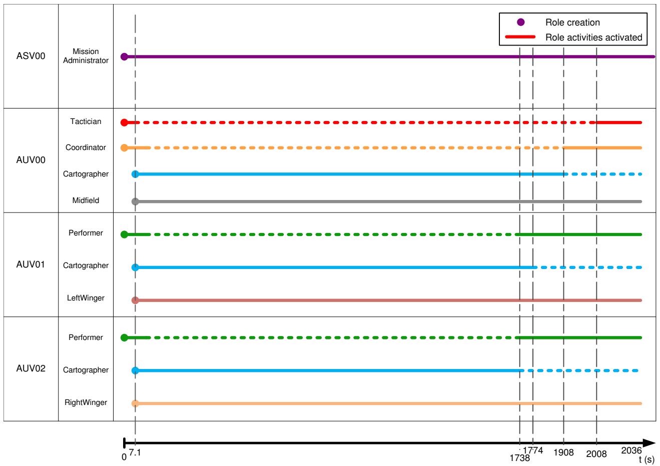

Fig. 7. Roles played by the AUVs

This simulation shows that the high level of abstraction used through groups and roles allows to simplify the missions development and the objectives distribution. The formation of two groups allows to disentangle the problem of preparing the overall strategy of the flotilla from its execution. A single role can be allocated to several AUVs, which facilitates the objectives planning. Moreover, interactions are established between two roles, thus the amount of transmitted data is reduced. Several objectives can be grouped into a single role. This abstract concept can therefore define both a hierarchical position in the organization, a geometric position or an action to proceed according to the context.

VIII. CONCLUSION

This paper has proposed a generic multi-agent based layered architecture which allows designing and specifying of AUV flotillas at a high level of abstraction, regardless of the AUVs characteristics and skills. The paper showed how an organizational approach enables defining artificial organizations of heterogeneous agents and regulating interactions with a great modularity. In the proposed architecture, this approach is implemented in a dedicated social layer. This allows to simplify the robot's view of the system and facilitates cooperation with others. This organizational structure is also fruitfully used in the executive layer for achieving a reactive behavioral approach based on the satisfaction-altruism model. This approach enables an AUV to perform activities of individual or collective nature via very simple interactions implemented as "influence signals". Simulation results show how heterogeneous AUVs can coordinate their activities, thanks to the proposed approach, in the scope of an area exploration and mapping mission.

REFERENCES

[1] B. Jalving, M. Mandt, O. K. Hagen, and F. Pøhner, "Terrain Referenced Navigation of AUVs and Submarines Using Multibeam Echo Sounders," in *Proc. of 2004 Undersea Defence Technology Europe*, no. 2027 in UDT'04, (Nice, France), 2004.

[2] J. J. Leonard, R. J. Rikoski, P. M. Newman, and M. Bosse, "Mapping Partially Observable Features from Multiple Uncertain Vantage Points," *The Int. Journal of Robotics Research*, vol. 21, pp. 943–975, 2002.

[3] C. C. Sotzing and D. M. Lane, "Improving the Coordination Efficiency of Limited-Communication Multi-Autonomus Underwater Vehicle Operations Using a Multiagent Architecture," *Journal of Field Robotics*, vol. 27, no. 4, pp. 412–429, 2010.

[4] R. Cui, S. S. Ge, B. V. E. How, and Y. S. Choo, "Leader-follower Formation Control of Underactuated AUVs with Leader Position Measurement," in *Proc. of the 2009 IEEE Int. Conf. on Robotics and Automation*, ICRA'09, (Kobe, Japan), pp. 979–984, IEEE, 2009.

[5] E. Fiorelli, N. E. Leonard, P. Bhatta, D. a. Paley, R. Bachmayer, and D. M. Fratantoni, "Multi-AUV Control and Adaptive Sampling in Monterey Bay," *IEEE Journal of Oceanic Engineering*, vol. 31, pp. 935–948, 2006.

[6] S. Sariel, T. Balch, and J. Stack, "Distributed Multi-AUV Coordination in Naval Mine Countermeasure Missions," Georgia Institute of Technology, College of Computing, Tech Report, GIT-GVU-06-04, 2006.

[7] J. Ferber, *Multi-Agent Systems. An Introduction to Distributed Artificial Intelligence.* London: Addison-Wesley, 1999.

[8] A. Belbachir, F. Ingrand, and S. Lacroix, "Localizing underwater targets using a cooperative AUV architecture," in *Proc. of the 2010 Int. Conf. on Machine and Web Intelligence*, ICMWI'10, (Algiers, Algeria), pp. 153–158, IEEE, 2010.

[9] A. Chapman and S. Sukkarieh, "A Protocol for Decentralized Multi-Vehicle Mapping with Limited Communication Connectivity," in *Proc. of the 2009 IEEE Int. Conf. on Robotics and Automation*, ICRA'09, (Kobe, Japan), pp. 357–362, IEEE, 2009.

[10] J. Ferber, O. Gutknecht, and F. Michel, *From Agents to Organizations: an Organizational View of Multi-Agent Systems*, vol. 2935 of *LNCS*, pp. 443–459. Springer Berlin / Heidelberg, 2003.

[11] O. Simonin and J. Ferber, "Modeling Self Satisfaction and Altruism to handle Action Selection and Reactive Cooperation," in *Proc. of the 6th Int. Conf. on the Simulation of Adaptative Behavior, From Animals to Animats*, SAB'2000, (Paris, France), pp. 314–323, 2000.

[12] M. Crozier and E. Friedberg, *L'acteur et le système. Les contraintes de l'action collective.* Le seuil ed., 1981.

[13] P. Stone and M. Veloso, "Task Decomposition, Dynamic Role Assignment, and Low-Bandwidth Communication for Real-Time Strategic Teamwork," *Artificial Intelligence*, vol. 110, pp. 241–273, 1999.

[14] K. Erol, J. Hendler, and D. S. Nau, "HTN Planning: Complexity and Expressivity," in *Proc. of the 12th Nat. Conf. on Artificial Intelligence*, AAAI'94, (Seattle, WA, USA), pp. 1123–1128, AAAI Press, 1994.

[15] J. Chapelle, O. Simonin, and J. Ferber, "How Situated Agents can Learn to Cooperate by Monitoring their Neighbors' Satisfaction," in *Proc. of the 15th European Conf. on Artificial Intelligence*, ECAI'02, (Lyon, France), pp. 68–72, IOS Press, 2002.

[16] F. Michel, G. Beurier, and J. Ferber, "The TurtleKit Simulation Platform: Application to Complex Systems," in *Proc. of the 1st Int. Conf. on Signal \& Image Technology and Internet-Based Systems, Workshops Sessions*, SITIS 2005, (Yaoundé, Cameroon), pp. 122–128, IEEE, 2005.