Cooperative Autonomous Marine Vehicle Motion Control in the scope of the EU GREX Project: Theory and Practice

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***Abstract*—This paper describes the core of the research work done by the ISR/IST team on cooperative Autonomous Marine Vehicle (AMV) motion control in the scope of the EU Project GREX - coordination and control of cooperating heterogeneous unmanned systems in uncertain environments. The first part of the paper affords the reader a concise introduction to the general problem of cooperative motion control of fleets of AMVs by highlighting illustrative mission scenarios developed collectively by the GREX partners and summarizing the main challenges that they pose to system engineers. This is followed by the description of a general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and communication losses that is rooted in a solid control-theoretic framework. The results of simulations with the $NetMar_{SyS}$ - Networked Marine Systems Simulator - of ISR/IST are presented and show the efficacy of the algorithms developed for cooperative motion control. The last part of the paper focuses on practical issues and describes the results of tests at sea in the Azores, in the Summer of 2008. The paper concludes with a critical review of the work done and a discussion of theoretical and practical implementation issues that warrant further research and development effort.**

I. Introduction

The ever increasing sophistication of autonomous marine vehicles (AMVs) is steadily paving the way for the execution of complex missions without direct supervision of human operators. A key enabling element for the execution of such missions is the availability of advance systems for motion control of AMVs. The past few decades have witnessed considerable interest in this area. The problems of motion control can be roughly classified into three groups: *i)* point stabilization, where the goal is to stabilize a vehicle at a given target point with a desired orientation; *ii)* trajectory tracking, where the vehicle is required to track a time parameterized reference, and *iii)* path following, where the vehicle is required to converge to and follow a desired geometric path, without a timing law assigned to it.

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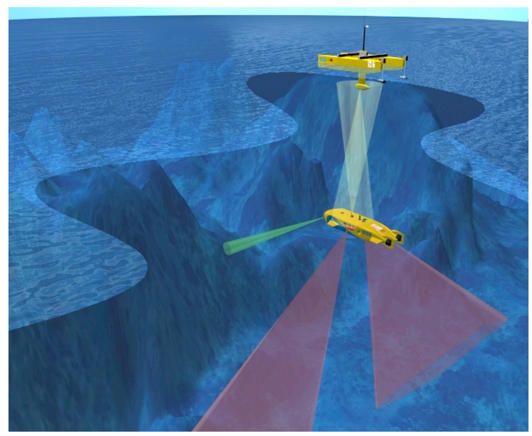

Fig. 1. Cooperative control of two (surface and underwater) autonomous marine vehicles for data gathering at sea .

Current research goes well beyond single vehicle control. In fact, recently there has been widespread interest in the problem of cooperative motion control of fleets of AMVs. A particular important scenario that motivates the cooperation of multiple autonomous vehicles and poses great challenges to systems engineers, both from a theoretical and practical standpoint, is automatic ocean exploration/monitoring for scientific and commercial purposes. In this scenario, one can immediately identify two main disadvantages of using a single, heavily equipped vehicle: lack of robustness to system failures and inefficiency due to the fact that the vehicle may need to wander significantly to collect data over a large spatial domain. A cooperative group of vehicles connected via a mobile communications network has the potential to overcome these limitations. It can also reconfigure the network in response to environmental parameters in order to increase mission performance and optimize the strategies for detection and measurement of vector/scalar fields and features of particular interest. Furthermore, in a cooperative mission scenario each vehicle may only be required to carry a single sensor (per environmental variable of interest) making each of the vehicles in the formation less complex, thus increasing its reliability.

As an example, Fig. 1 captures a conceptually simple mission scenario where an autonomous surface craft (ASC) and an autonomous underwater vehicle (AUV) maneuver in synchronism along two spatial paths, while aligning themselves along the same vertical line, so as to fully exploit the good properties of the acoustic communications channel under these conditions. This is in striking contrast to what happens when communications take place at slant range, for this reduces drastically the bandwidth of the channel, especially due to multipath effects in shallow water operations.

Cooperative Autonomous Marine Vehicle Motion Control is one of the core ideas exploited in the scope of the EU GREX project, entitled *Coordination and control of cooperating heterogeneous unmanned systems in uncertain environments* [1]. Both theoretical and practical issues are addressed in the scope of the project. It is worth to stress that from a theoretical standpoint, the coordination of autonomous robotic vehicles involves the design of distributed control laws in the face of disrupted inter-vehicle communications, uncertainty, and imperfect or partial measurements. This is particular significant in the case of underwater vehicles. It was only recently that these subjects have started to be tackled formally, and considerable research remains to be done to derive multiple vehicle control laws that can yield good performance in the presence of severe communication constraints. For previous work along these lines, the reader is referred to [32, 30, 31, 17, 3, 14, 22, 7, 18, 33, 19] and the references therein.

The first part of the paper affords the reader a concise introduction to the general problem of cooperative motion control of fleets of AMVs, pointing out examples of important mission scenarios and the main challenges to systems engineers. Solutions to crucial classes of single and multiple motion control problems are mentioned and some of them are illustrated through realistic computer simulations. The last part of the paper focuses on practical issues and describes the results of tests at sea in the Azores, in the Summer of 2008. To this effect, use was made of a number of building blocks (middleware system) developed by the GREX project consortium to seamlessly integrate vehicles with heterogeneous architectures and capabilities into a team capable of executing advanced cooperative missions at sea. From a practical standpoint, special emphasis was placed on the steps taken towards the development and testing of a multiple vehicle primitive called *Cooperative Target Tracking* that allows for one or more autonomous vehicles to estimate the motion of a target and follow the corresponding path from a safe distance. The paper concludes with a critical review of the work done and a discussion of issues that warrant further research and development effort.

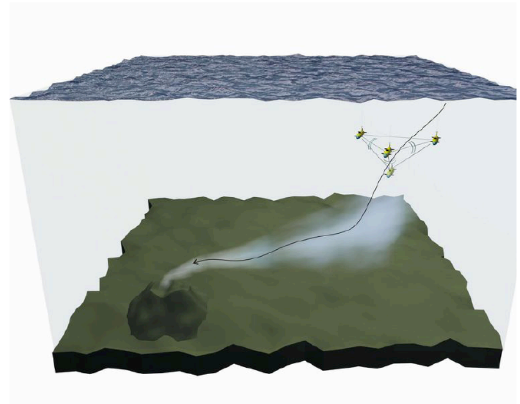

Fig. 2. The quest for hydrothermal vents.

II. Practical motivation

In what follows we summarize three types of mission-scenarios discussed and defined in detail by the GREX partner group. The mission scenarios envisioned are rooted in challenging problems in the field of marine science. They also bring out the ever increasing important role that marine technology is having in terms of affording marine scientists the tools that are needed to explore and exploit the ocean. We place the focus on missions for which two basic ingredients are required: *i)* the missions require the use of several intelligent autonomous vehicles equipped with appropriate instrumentation, and *ii)* inter-vehicle coordination and mission control is dynamic and highly dependent on the type of information obtained as the missions unfold.

Scenario 1: The quest for hydrothermal vents

Marine scientists (including geologists and biologists) have by now amassed considerable knowledge about deep water hydrothermal vents and their intriguing ecosystems and chemosynthetic life forms. The vents hold considerable potential for the biotechnological industry and are a window on the evolution of life on planet Earth. They are also spectacular and generate widespread public interest. In the Azores, besides well known deepwater vents that occur along the mid-Atlantic ridge, there is strong indication that hydrothermal vents exist at $150\,m$ depth, around the D. João de Castro Bank [16], but this has not been confirmed yet. There is therefore a need to develop efficient methodologies to detect intermediate depth vents because of their far reaching implication in the study of the biological responses to an environment wedged between deep and shallow waters.

The mission proposed is based on the knowledge that vents produce methane that does not dissolve quickly in the water. This in turn allows for its detection and for the measurement of the gradient of its concentration using methane sensors. The two step mission starts with a fast survey of a given area using a fleet of AUVs equipped with acoustic sensors. The map produced will allow for the examination of geological features (acting as indicators of the possible presence of vents)

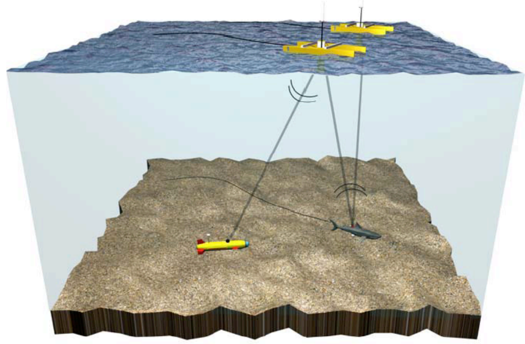

Fig. 3. Fish-data downloading.

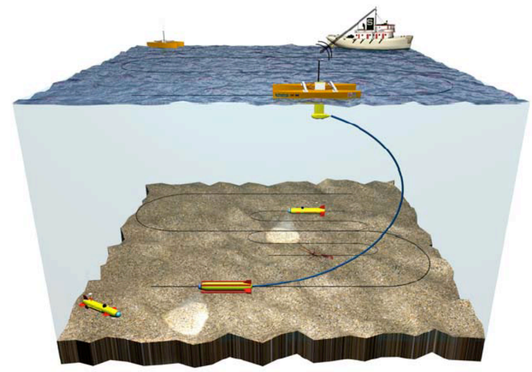

Fig. 4. Marine Habitat Mapping.

that will guide the choice of smaller inspection areas. Once a smaller area is found, a fleet of vehicles equipped with methane sensors can be deployed, as depicted in figure 2. The vehicle baseline configuration is such that spatial estimates of the gradient of the methane concentration can be computed cooperatively. It is up to the fleet to manoeuvre so as to seek the region of higher concentration, and thus the localisation of the vent.

The scenario described requires multiple vehicle motion coordination based on the type of information (methane concentration) that is acquired as the mission progresses. The mission poses formidable challenges to systems designers due to the need to develop a distributed, multi-vehicle coordination scheme (requiring robust vehicle localization, navigation, and control) in the presence of stringent underwater communication constraints.

Scenario 2: Fish-data downloading

In the last few years, marine scientists have been using passive and active telemetry devices to tag fish with data collecting devices. This technology has triggered new studies that are significantly improving our understanding of fundamental phenomena such as the dispersal, spawning dynamics, or thermoregulatory mechanisms of marine animals, but most importantly they are opening a new window in the framework of the spatial management of marine living resources. Critical impacts include the use of spatial behaviour in fisheries stock assessment and the design of Marine Protected Areas.

Although tag technology has improved, the major problem is the difficult of getting the data back from the tagged fish. A swarm of AUVs in cooperation with one or more surface craft would be able to perform a search task to locate a tagged fish. Figure 3 illustrates this scenario. Two or more autonomous surface vehicles (ASVs) move in the same direction, while keeping a desired formation pattern (e.g. in line). Equipped with acoustic receivers, they sweep the water column as they move along and listen to the sounds emitted by the acoustic tags. By using more than one ASV, the position of the tags can be determined with adequate precision.

Upon detecting one or more tags, one of the ASVs communicates to a group of AUVs the positions of those tags using an acoustic communication network. It is then up to the AUVs to negotiate the tags that they will target and track with a given accuracy (typically, not worse than 100 meters), for a period of time sufficient enough to download the tag data. Upon conclusion of the fish-data download task, the AUVs manoeuvre back to the vicinity of the steadily moving ASVs, to wait for further instructions.

This methodology dispenses with the deployment of fixed underwater units and is specially suited to scan a given volume of the ocean in a fast and expedite manner. In this interesting scenario, the AUVs are equipped with acoustic pingers for navigation purposes. They are further equipped with acoustic modems allowing for direct communications with the ASVs. We thus have all the ingredients of a complex, albeit powerful network involving different players, whereby the ASVs play the triple role of tag position detectors, AUV position detectors, and communication relay stations from the AUVs to a support ship or even to shore. The benefit of such communication relay is that it can be deployed and monitored from shore. Underwater experiments can be viewed and/or controlled by more scientific users than using a ship offshore. Costs can be reduced and the number or quality of experiments increased.

Scenario 3: Marine Habitat Mapping

Habitat maps of the marine environment, that is, maps containing data on the bathymetry and nature of the seabed as well as on the type and localization of biological species, are key to an in-depth understanding of the distribution and extent of marine habitats. Knowledge of the distribution of marine habitats serves to establish sensible approaches to the conservation needs of each habitat and to facilitate a better management of the marine environment through an understanding of how particular human activities are undertaken in relation to marine habitats. This will in turn allow for the establishment of policies capable of ensuring sustainable development. This subject is receiving widespread attention worldwide because of its far reaching implications and has

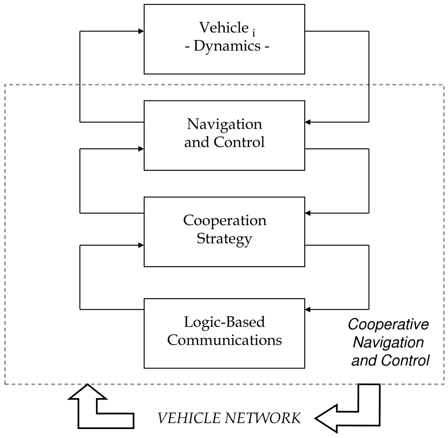

Fig. 5. A general architecture for multiple vehicle cooperation.

led to the definition of a number of guidelines and directives for the study and preservation of marine habitats.

The mission scenario for marine habitat mapping proposed here was greatly influenced by and aims to automate and improve classical procedures that are normally used by marine scientists. The key ideas can be explained by referring Fig. 4 . For simplicity of exposition, we start by focusing on the ASV/ROV ensemble in the figure, where the ROV is connected to the ASV through a thin umbilical for fast data transmission. In this scenario, the ASV executes a lawn mowing manoeuvre above the seabed automatically, while the ROV executes a similar manoeuvre in cooperation with the ASV. Using this set-up, the ROV transmits pictures of the seabed back to the support ship (and thus to the scientist in charge) via a radio link installed on-board the ASV. A number of AUVs stay dormant either on the seabed or at the sea surface. Upon detection of interesting patterns on the seabed by the scientist in charge, a signal is sent to a selected member of the AUV fleet (via an acoustic communication link installed on-board the ASV), to dispatch it to the spot detected so as to map the surrounding region in great detail. Meanwhile, the ASV/ROV ensemble continues to execute the lawn mowing manoeuvre in search of other sites of interest. With the methodology proposed, sites that are interesting from an ecological viewpoint are easily detected along the transects.

To execute the abovementioned challenging missions, a number of autonomous vehicles must work in cooperation, under high level human supervision. This entails the development of advanced systems for cooperative motion control and navigation in the presence of severe underwater communication constraints, together with the respective software and hardware architectures.

III. A GENERAL ARCHITECTURE FOR MULTIPLE VEHICLE COOPERATION

This section summarizes the main bulk of the work done towards the development of *Cooperative Motion Control Systems* for multiple autonomous vehicles. The first part describes a very general architecture for multiple vehicle cooperation that emerged naturally in the scope of the GREX project. The second part details key single and multiple vehicle motion control primitives that were judged appropriate for practical implementation of the architecture developed on a set of multiple heterogeneous vehicles.

A. Cooperative Motion Control System

The systems that are at the root of the architecture for multiple vehicle cooperation developed in the scope of GREX are depicted in figure 5. See [3] for a fast paced introduction to the subject. The scheme depicted is quite general and captures the basic trends in current research.

Each vehicle is equipped with a navigation and control system that uses local information as well as information provided by a subset of the other vehicles over the communication network, so as to make the vehicle maneuver in cooperation with the whole formation. Navigation is in charge of computing the vehicle's state (e.g. position and velocity). Control accepts references for selected variables, together with the corresponding navigation data, and computes actuator commands so as to drive tracking errors to zero. The cooperation strategy block is responsible for implementing *cooperative navigation and control*. Its role is twofold: *i)* for *control* purposes, it issues high level synchronization commands to the local vehicle based on information available over the network (e.g. speed commands to achieve synchronization of a number of vehicles executing path following maneuvers); *ii)* For *navigation* purposes, it merges local navigation data acquired with the vehicle itself as well as by a subset of the other vehicles. This is especially relevant in situations where only some of the vehicle can carry accurate navigation suites, whereas the others must rely on less precise sensor suites, complemented with information that is exchanged over the network. Finally, the system named *logic-based communications* is responsible for supervising the flow of information (to and from a subset of the other vehicles), which we assume is asynchronous, occurs on a discrete-time basis, has latency, and is subject to transmission failures.

Central to the above scheme is the fact that each vehicle can only exchange information with a subset of the remaining group of vehicles. Furthermore, and because of the intrinsic nature of the underwater communications channel, communications should be parsimonious and take place at a very low data rate. This calls for the implementation of systems to decide when and what minimum information should be transmitted from each of the vehicles to its neighbours. Interestingly enough, analogous constraints appear in the vibrant area of networked control systems, from which interesting and fruitful techniques can be borrowed.

Close inspection of the general architecture for multiple vehicle cooperation described above reveals the plethora of problems to be solved:

i) Cooperative Control (CC) (e.g. cooperative path following and cooperative trajectory tracking),
ii) Cooperative Navigation (CN), and
iii) CC and CN under strict communication constraints over a faulty, possibly switched network.

In the scope of the GREX project, considerable work was done to advance design tools to tackle the above problems. References [6, 4, 2, 19] and [17, 18, 3, 7, 8, 33, 11, 10, 12, 34, 35, 20] include relevant technical aspects of the research effort towards the development of advanced schemes for single and multiple vehicle control. See [32, 13, 26, 15, 23, 30, 28, 31, 36, 25, 29, 14, 22] and the references therein for a balanced view of the state of progress in the area. The results obtained so far hold potential for application. To the best of our knowledge, some of the work reported is pioneering in that it effectively addresses explicitly time-varying communication networks with temporary failures and latency in the transmissions, and logic-based communications aimed at reducing the amount of discrete-time data to be transmitted among the vehicles. The results obtained were instrumental in defining, together with the GREX partners, a library of Single and Multiple Vehicle Primitives (MVPs) for motion control that are described in the next section.

B. Single and Multiple Vehicle Primitives

The work envisioned in the scope of the GREX project aims at affording system designers the tools to develop, using a "bottom-up" approach, the modules that are needed to implement a true Multi Vehicle Mission Control System for a fleet of autonomous vehicles.

Based on the mission scenarios and the general architecture for multiple vehicle cooperation described in the previous sections, a set of Multiple Vehicle Primitives (MVPs) for coordinated motion control were developed. The definition of the primitives and the algorithms for their implementation take into account the fact that the vehicles considered have complex dynamics, exhibit large parameter uncertainty, are often underactuated, and must perform well in the presence of unknown, shifting ocean currents. During the first part of the project, the attention was focused on the development of primitives enabling the following tasks:

- Point Stabilization, Path Following, and Trajectory Tracking of single marine vehicles with complex dynamics.
- Path Planning for multiple vehicles.
- Cooperative Path Following of multiple vehicles.
- Cooperative Target Following and Cooperative Target Tracking of multiple vehicles.
- Cooperative Manoeuvring in the presence of tight communication constraints by exploiting recent research results on Networked Control Systems.
- All of the above in the presence of sensor and actuator faults.

In the following, we provide a brief description of each of the tasks listed above and point out relevant bibliography that describes the motion control algorithm solutions developed by the ISR/IST team.

Point Stabilization (also referred to as *Go to Point*) refers to the problem of steering a vehicle to a point with a desired orientation (in the absence of currents), or simply to a desired point without a desired orientation (in the presence of currents). The algorithms derived are reported in [6, 4].

Path Following. In this task, the objective is to steer a vehicle towards a path and make it follow that path with an assigned speed profile. Notice that there are no explicit temporal specifications, that is, the vehicle is not required to be a certain point at a desired time. Rather, what is relevant is for the vehicle to traverse the path, albeit with a speed that may be path dependent. Algorithms are reported in [17, 33, 2, 34].

Trajectory Tracking. In contrast with the Path Following objectives, what is now required is that the vehicle track a desired temporal/spatial trajectory. Timing constraints become important for this task. In practice, trajectory tracking systems are harder to design (when compared with Path Following systems) and may yield jerky maneuvers and large actuator activity. This is because of tight temporal constraints [5, 9]. In this respect, Path Following strategies usually lead to more benign maneuvers. However, there are instances in which one is forced to adopt trajectory tracking strategies (for example, when one wishes to investigate a phenomenon that is strongly time-dependent). Algorithms are summarized in [2].

Path Planning for multiple vehicles.

Multiple vehicle path planning methods build necessarily on key concepts and algorithms for single vehicle path following. However, they go one step further in that they must explicitly take into account such issues as inter-vehicle collision avoidance and simultaneous times of arrival. See [21] and the references therein.

The literature on path planning is vast and the methodologies used are quite diverse. Classical methodologies aim at computing feasible strategies off-line that minimize a chosen cost criterion. More recently, new methodologies have come to the forum where the objective is to generate paths on-line, in response to environmental data, so as to optimize the process of data acquisition over a selected area. In the scope of GREX we focused on the problem that arises when multiple vehicles are scattered in the water and it is required that they safely reach the starting location of a cooperative mission with a desired formation pattern and assigned terminal speeds (Go-To-Formation manoeuver). The cost criteria of interest may include minimizing travel time or energy expenditure. The key objective was to obtain path planning methods that are effective, computationally easy to implement, and lend themselves to real-time applications.

The techniques that we developed for multiple vehicle path planning are based upon and extend the work reported in [24] for unmanned air vehicles. See [20] and [21] for recent work on the subject, with applications to autonomous marine vehicles. Explained in intuitive terms, the key idea exploited is to separate spatial and temporal specifications, effectively decoupling the process of spatial path computation from that of computing the desired speed profiles for the vehicles along those paths. The first step yields the vehicles' spatial profiles and takes into consideration geometrical constraints; the second addresses time related requirements that may include, among others, initial and final speeds, deconfliction in time, and simultaneous times of arrival. Decoupling the spatial and temporal constraints can be done by parameterizing each path as a set of polynomials in terms of a generic variable τ and introducing a polynomial function $\eta(\tau)$that specifies the rate of evolution of τ with time, that is, $d\tau/dt = \eta(\tau)$. By restricting the polynomials to be of low degree, the number of parameters used during the computation of the optimal paths is kept to a minimum. Once the order of the polynomial parameterizations has been decided, it becomes possible to solve the multiple vehicle optimization problem of interest (e.g., simultaneous time of arrival under specified deconfliction and energy expenditure constraints) by resorting to any proven direct search method [27].

Cooperative Path Following. In this case, a fleet of vehicles is required to track a series of pre-defined spatial paths, while holding a desired formation pattern at a desired formation speed. The implementation of the corresponding MVP calls for the execution of a path following algorithm for each of the vehicles, together with a synchronization algorithm that changes the nominal speeds of the vehicles so as to achieve the desired synchronism. The basic algorithms are described in [17, 3, 18, 11, 7, 10, 34, 19], and take into account explicitly the topology of the inter-vehicle communication network.

Cooperative Target Following (CTF) and Cooperative Target Tracking (CTT). The CTF and CTT tasks enable a group of vehicles to follow (in space) and track (in space and time) a moving target, respectively. The CTF refers to the situation where the group of vehicles follows the path traversed by the target, without stringent temporal constraints. This is done by observing the target motion, extracting from it a spatial reference path, and following it. No further objective is attempted, and the distance between the group of vehicles and the target is left uncontrolled. As an example, we cite the situation where a manned vessel leads (shows the way to) a group of marine craft through a harbour area where obstacles are present. By observing the motion of the manned vessel, the group of vehicles learns a safe path across the harbour and follows it accurately (doing by imitation). The CTT is similar to CFT, except that it is now required for the group of vehicles to maintain a desired along-path distance from the target. Instead of traversing the path defined by the target at leisure, the group of vehicles is required to adjust its overall speed so as to keep a desired distance to the target. These two problems are far from trivial in the case when the trajectory to be tracked is not available a priori, but is instead defined implicitly by the unknown motion of a target vehicle. Interestingly, enough, both problems can be solved by converting them into an equivalent path following problem. This is done by having at least one vehicle in the formation observe the motion of the target and fit a parameterized path to it over a short, receding time window. The parameters of the consecutive segments of paths thus obtained are then broadcast to the other vehicles, and a coordinated path following algorithm executed.

Cooperative Manoeuvring in the presence of tight communication constraints. This task refers to the problem of developing MVPs for Cooperative Path Following and Cooperative Target Following and Target Tracking in the presence of varying communication topologies, communication losses, and delays. The latter is especially relevant in view of the small speed of propagation of sound in the water. Solutions are proposed in [3, 18, 19]. In [3], solutions are described that addresses explicitly the fact that underwater communications occur at discrete intervals of time and reduces drastically the frequencies at which the vehicles communicate. To the best of our knowledge, previous work along these lines was not available in the literature for multiple underwater vehicle control. The new solution adopted borrows from related work in networked control and holds potential for further refinement aimed at striking an adequate balance between performance and energy spent to communicate.

IV. Simulation results

In this section we show results of simulations that illustrate the performance that can be achieved with the motion control algorithms mentioned before. The simulations were done using the Networked Marine Systems Simulator ($NetMar_{SyS}$), a software suite developed at ISR/IST in the scope of GREX to simulate different types of cooperative missions involving a variable number of heterogeneous marine craft, each with its own dynamics [35]. The high level of detail with which the environment can be modeled affords end-users the tools that are necessary to take into account both the effect of water currents on the vehicle dynamics as well as the delays and environmental noise that affect underwater communications. The simulation kernel developed so far paves the way for future developments aiming at incorporating more sophisticated acoustic communication models and communication protocols, together with interfaces to allow seamless distributed software and hardware-in-the-loop simulation.

The $NetMar_{SyS}$ interface is divided into four main areas: mission environment, mission specifications, vehicles, and output interface. The mission environment area includes three different menus: water current, coordination strategy (which defines the inter-vehicle communication topology), and communication channel. The mission specifications area includes a list of possible missions to be executed, e.g. Cooperative Path Following and Cooperative Target Tracking. The area devoted to vehicles contains a file with a number of different vehicle blocks (kinematics and dynamics). Here, the user can choose the number and the type of vehicles in the formation. Finally, an output interface enables the visualization of mission results and the creation of videos from the simulations.

The simulator has been instrumental in evaluating the efficacy of selected algorithms for motion control of marine vehicles. By incorporating blocks that emulate the actual

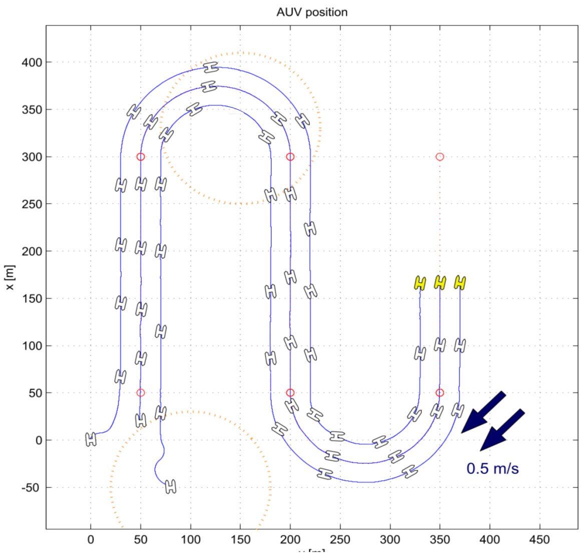

Fig. 6. Cooperative path-following of three Autonomous Surface Craft (ASC) under communication constraints.

software code that is implemented on-board the different vehicles, the simulator has also been a valuable tool to evaluate the software for the implementation of MVPs, and in fact has played a key role in the preparation for the first series of field tests in the Azores, in the Summer of 2008.

A. An illustrative 2D example

In this section, we discuss the set-up and results of a co-operative path-following mission involving three autonomous surface craft. Stated intuitively, the goal is to make the vehicles follow a set of lawn-mowing paths (see Fig. 6) and align themselves along a perpendicular to the paths. The mission is defined as the succession of lines and arcs given in the table below. The desired speed of the vehicle at the center is constant and equal to $1.5m/s$

[b]

n	Type	Start (x, y)	Center (x, y)	End (x, y)	Speed (m/s)
1	Line	(50,50)	-	(300,50)	1.5
2	+Arc	(300,50)	(300,125)	(300,200)	1.5
3	Line	(300,200)	-	(50,200)	1.5
4	-Arc	(50,200)	(50,275)	(50,350)	1.5
5	Line	(50,350)	-	(300,350)	1.5

In the simulation, we also considered a water current with a speed of 0.5 m/s, and two circular "dark areas" where communications are severely limited, see figure 6. The figure shows the trajectories of the three surface vehicles obtained with NetMarSyS. The vehicles begin the trajectories out of formation but reach the desired formation rapidly. Along the first arc, at the top of the figure, communication is limited and the vehicles rapidly fall out of synchronization. Once the vehicles leave the "dark area" and re-start the exchange of data, they recover the formation.

Figure 7 shows the communication flow among the three vehicles. It can be seen that the volume of successfully exchanged messages is lower for vehicle 3 at the beginning of the trajectory, when it is inside one of the dark areas. The same applies to all three vehicles when they reach the first curve segment of the path and enter the second dark area. Figure 8 a) shows, for the three surface craft, the evolution of parameter γ that indicates the position of the vehicle along the trajectory, in meters. When the value of this parameter is the same for all vehicles, the vehicles are in formation. This does not happen at the beginning of the trajectory and for some time after the first curve, where communications are lost. The same conclusions can be drawn from Fig. 8 b), that shows the evolution of the coordination error obtained as a sum of single differences of the parameter γ of the three vehicles.

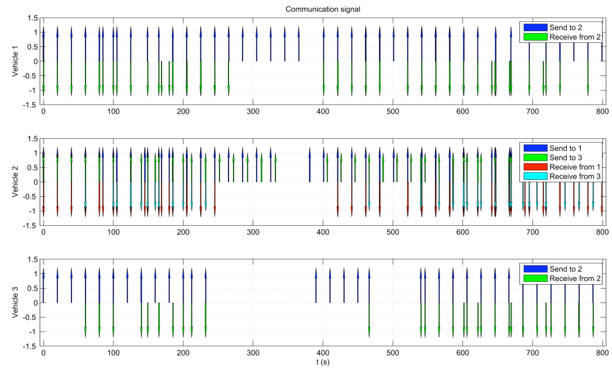

Fig. 7. Data exchange among the three vehicles.

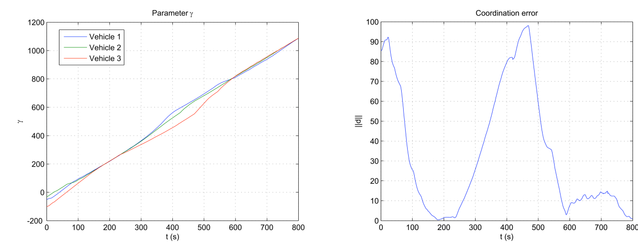

Fig. 8. Evolution of the (a) position parameter γ for the three vehicles and (b) the coordination error.

B. An illustrative 3D example

This section illustrates the application of the results in [3] to coordinate three AUVs moving in three-dimensional space. The AUVs are required to follow paths of the form

$$\mathbf{p}_{d_i}(\gamma_i) = \left[c_i \cos(\tfrac{2\pi}{T}\gamma_i + \phi_d), c_i \sin(\tfrac{2\pi}{T}\gamma_i + \phi_d), d\gamma_i\right],$$

with $c_1 = 20\,\mathrm{m}$, $c_2 = 15\,\mathrm{m}$, $c_3 = 25\,\mathrm{m}$, $d = 0.05\,\mathrm{m}$, $T = 400$, and $\phi_d = -\frac{3\pi}{4}$. The initial positions are $\mathbf{p}_1 = (10\,\mathrm{m}, -15\,\mathrm{m}, -5\,\mathrm{m})$, $\mathbf{p}_2 = (5\,\mathrm{m}, 0\,\mathrm{m}, 0\,\mathrm{m})$, $\mathbf{p}_3 = (20\,\mathrm{m}, -25\,\mathrm{m}, 5\,\mathrm{m})$. The vehicles start at rest and the normalized reference speed was set to $v_r = 1$. The vehicles are also required to keep a formation pattern that consists of having them aligned along a straight line in the plane. Furthermore, AUV 1 is allowed to communicate with AUVs 2 and 3, but the latter two do not communicate between themselves directly. To further illustrate the behavior of the proposed cooperative path-following control architecture, we

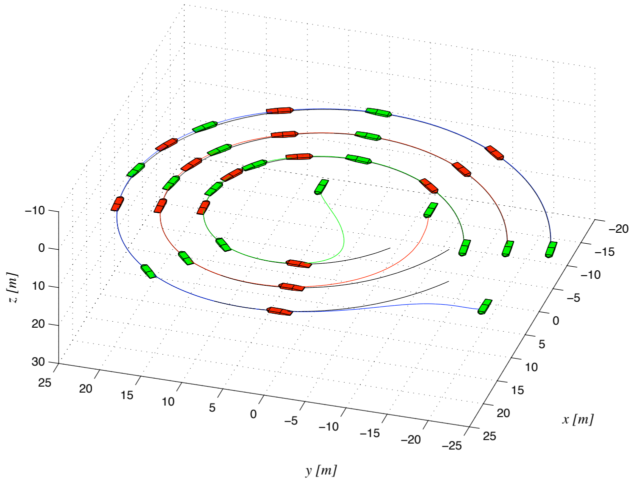

Fig. 9. Coordinated path-following of 3 AUVs, with logic-based communication.

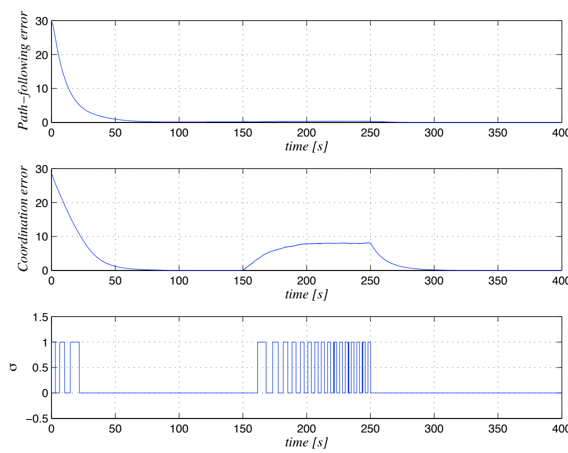

Fig. 10. Path-following error, coordination error $|\gamma_1 - \gamma_2| + |\gamma_1 - \gamma_3|$, and communication signal σ.

also force the following scenario: from $t = 150\,s$ to $t = 250\,s$, AUV 1 is only capable of following its path with $\dot{\gamma}_1 = 0.5$. Figure 9 shows the trajectories of the AUVs and Fig. 10 the evolution of the overall path-following error $\sum_{i=1}^{3} \|p_i - p_{di}\|$, coordination error $|\gamma_1 - \gamma_2| + |\gamma_1 - \gamma_3|$, and the communication signal σ. The signal $\sigma \in \{0, 1\}$ indicates, by switching its value, when communications occur. Before $t = 150\,s$, the vehicles adjust their speeds to meet the formation requirements and the coordination errors converge to zero. Note the reduced number of communications exchanged during that period. In fact, the vehicles only need to communicate a few times during the transient phase. When AUV 1 is forced to slow down from $t \in [150, 250]$ (without transmitting explicitly to its neighborhoods its new reference velocity), the communication rate increases in order to keep the coordination error bounded.

Fig. 11. The DELFIM$_x$ ASV (left) and the manned vessel Aguas Vivas (right).

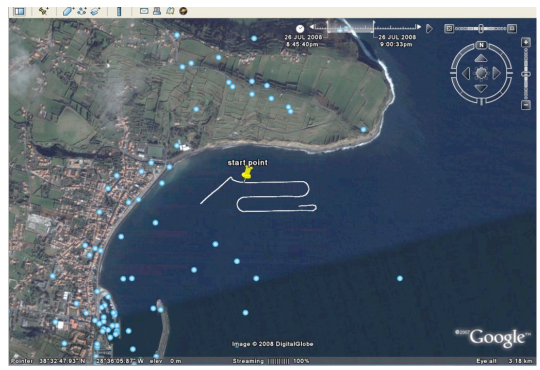

Fig. 12. Results of the first GREX mission at sea with the DELFIMx: Going-to and Following a Lawn-Mowing Maneuver.

V. Experimental results

In July 2008 the first series of GREX field tests took place at Horta, Faial, in the archipelago of the Azores. The tests were instrumental in bringing together the different partners to perform hardware and software integration and paved the way for full development of the tools that are needed for multiple vehicle cooperative control and navigation.

It was early decided that one of the tests would involve two surface vehicles undergoing joint motion: the Aguas Vivas manned vessel and the DELFIMx autonomous surface vehicle equipped with a dedicated GREX computer, both shown in

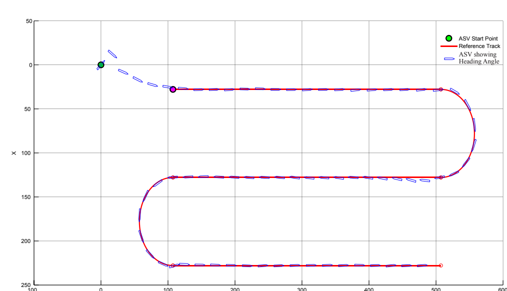

Fig. 13. Experimental results of the DELFIM$_x$ performing a lawn mowing maneuver in the Azores, PT.

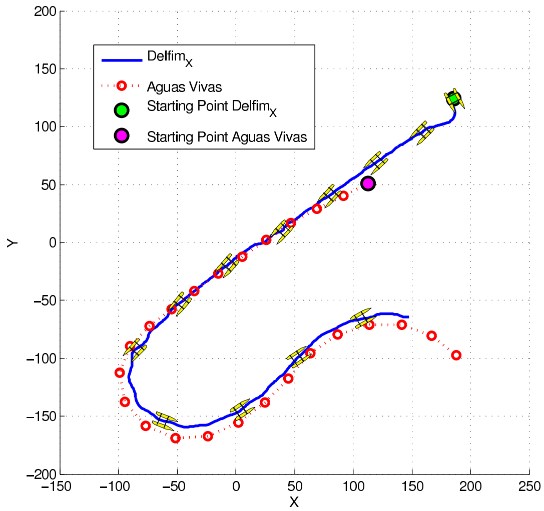

Fig. 14. Experimental results of the DELFIM$_x$ performing a target following maneuver in the Azores, PT.

Fig. 11. The DELFIM$_x$ is an autonomous surface craft that was designed and built at the Instituto Superior Técnico, Lisbon, Portugal. It is a small Catamaran 4.5m long and 2.4m wide, with a mass of 380kg. Propulsion is ensured by three-bladed propellers driven by electrical motors. The maximum speed of the vehicle with respect to the water is 3.0m/s. The vehicle is equipped with on-board resident systems for navigation, guidance and control, and mission control. Navigation is done by integrating motion sensor data obtained from an attitude reference unit, a Doppler Log unit, and a DGPS (Differential Global Positioning System). Transmissions between the vehicle and its support vessel, or between the vehicle and a control center installed on-shore are achieved via a radio link with a range of 10km. The vehicle has a wing shaped central structure that is lowered during operations at sea. Installed at the bottom of this structure is a low drag body that can carry acoustic transducers, including those used to communicate with submerged craft.

Two vehicles primitives were executed with success: Path Following (PF) and Target Following (TF). Figures 12 and 13 show the details of a lawnmowing PF maneuver executed by DELFIMx. To test the Target Following primitive, the AGUAS VIVAS manned vessel underwent arbitrary motion at sea while transmitting its GPS position to DELFIM$_x$. Based on the GPS information received, DELFIMx identified online, using a path fitting algorithm, the path segments traversed by Aguas Vivas (line segments or segments of arcs identified over short receding time windows) and followed these paths at a set speed by invoking repeatedly the PF primitive. As a consequence, DELFIMx maneuvered well along the overall path "defined by" Aguas Vivas, not known a priori. The results of this maneuver are shown in Figure 14. The tests proved extremely important in evaluating the performance of the algorithms developed for path following and target following, the aerial communication channel between Aguas Vivas and DELFIMx, and the efficacy of the software/hardware architecture adopted within the project, namely that of the GREX computer installed on-board the DELFIMx.

VI. Conclusions

The paper described the key thrust of the work done by ISR/IST team on cooperative Autonomous Marine Vehicle (AMV) motion control in the scope of the EU Project GREX - coordination and control of cooperating heterogeneous unmanned systems in uncertain environments. To better ground the work on realistic scientific applications, a number of mission scenarios defined by the partner group were described. A general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and communication losses was proposed. The architecture implementation relies on a number of Single and Multiple Vehicle Primitives, the development of which was rooted in solid control theory. The algorithms developed were fully tested in simulation using the $NetMar_{SyS}$ - Networked Marine Systems Simulator - developed by ISR/IST. The same simulator was used to do hardware in the loop simulations prior to tests at sea, in the Azores, in the Summer of 2008. The field tests were instrumental in evaluating the performance of the algorithms developed for path following and target following, the aerial communication channel between Aguas Vivas and DELFIMx, and the efficacy of the software/hardware architecture adopted by the project team.

Future work will address the testing of other Multiple Vehicles Primitives (including Go-To-Formation and Cooperative Target Tracking) and the definition of a final set of integrated tests at sea, followed by their execution in the Azores in the Fall of 2009.

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