Cooperative Control of Multiple Marine Vehicles

Theoretical Challenges and Practical Issues

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Abstract: This paper is a brief overview of some of the theoretical and practical issues that arise in the process of developing advanced motion control systems for cooperative multiple autonomous marine vehicles (AMVs). Many of the problems addressed have been formulated in the scope of the EU GREX project, entitled Coordination and Control of Cooperating Heterogeneous Unmanned Systems in Uncertain Environments. The paper offers a concise introduction to the general problem of cooperative motion control that is well rooted in illustrative mission scenarios developed collectively by the GREX partners. 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. 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 paper concludes with a description of representative results obtained during a series of tests at sea in the Azores, in 2008.

1. INTRODUCTION

Worldwide, there has been increasing interest in the use of autonomous marine vehicles (AMVs) to execute missions of increasing complexity 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 objective is for the vehicle to converge to and follow a desired geometric path, without an explicit timing law assigned to it.

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 their reliability.

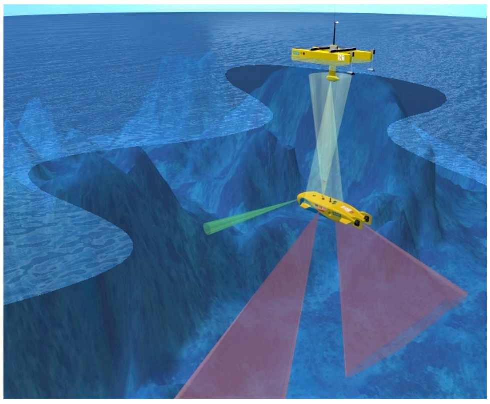

Fig. 1. Cooperative control of two (surface and underwater) autonomous marine vehicles for data gathering at sea.

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

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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* GREX [2006–2009]. 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 Stilwell and Bishop [Dec. 2000], Skjetne et al. [2002, 2004], Ghabcheloo et al. [2006], Aguiar and Pascoal [2007a], Arkak [2007], Ihle et al. [2007], Aguiar et al. [2007b], Ghabcheloo et al. [2007], Vanni et al. [2007], Ghabcheloo et al. [2009a] and the references therein.

The structure of the paper is as follows. Section 2 motivates the problem of cooperative multiple vehicle control with the help of a representative scientific mission scenario. Section 3 describes a general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and communication losses. Section 4 contains the results of computer simulations aimed at assessing the efficacy of the algorithms developed for cooperative motion control. Section 5 contains experimental results. Finally, Section 6 summarizes the main results obtained and discusses briefly issues that warrant further research and development work.

2. PRACTICAL MOTIVATION

This section describes one of the many representative mission scenarios that were discussed and defined in detail by the GREX partner group. The mission scenario envisioned is rooted in challenging problems in the field of marine science. It also brings 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.

Marine Habitat Mapping

Habitat maps of the marine environment containing information on the bathymetry and nature of the seabed, as well as on the type and localization of biological species, are of key importance to an in-depth understanding of the distribution and extent 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. 2 . 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

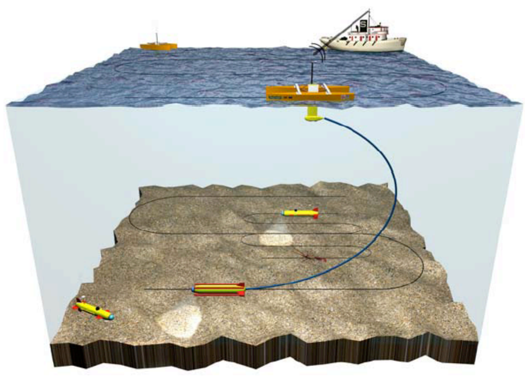

Fig. 2. Marine Habitat Mapping Scenario.

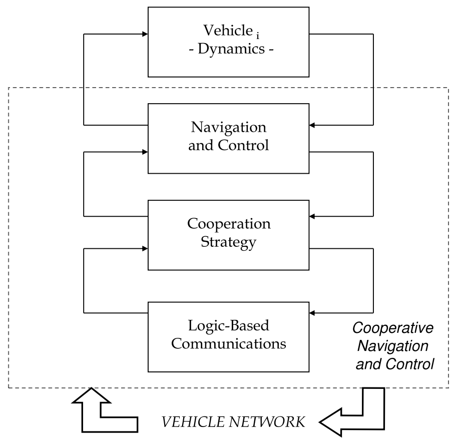

Fig. 3. A general architecture for multiple vehicle cooperative control.

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 above and other 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.

3. 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.

3.1 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 Fig. 3. See Aguiar and Pascoal [2007a] 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.

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 Aguiar et al. [2007a], Aguiar and Pascoal [2007b], Aguiar and Hespanha [2007], Ghabcheloo et al. [2009a] and Ghabcheloo et al. [2006, 2007], Aguiar and Pascoal [2007a], Aguiar et al. [2007b,c], Vanni et al. [2007], Almeida et al. [2007], Aguiar et al. [2008a], Almeida et al. [2008], Vanni et al. [2008b,a], Ghabcheloo et al. [2009b] include relevant technical aspects of the research effort towards the development of advanced schemes for single and multiple vehicle control. See Stilwell and Bishop [Dec. 2000], Alonge et al. [2001], Klein et al. [2008], Breivik and Fossen [2005], Jiang [2002], Skjetne et al. [2002], Lefeber et al. [2003], Skjetne et al. [2004], Zhang et al. [2007], Klein et al. [2007], Sepulchre et al. [2007], Arkak [2007], Ihle et al. [2007] 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.

3.2 Single and Multiple Vehicle Primitives

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 Aguiar et al. [2007a], Aguiar and Pascoal [2007b].

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 Ghabcheloo et al. [2006], Vanni et al. [2007], Aguiar and Hespanha [2007], Vanni et al. [2008b].

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 Aguiar et al. [2005, 2008b]. 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 Aguiar and Hespanha [2007].

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 Häusler et al. [2009] 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 Kaminer et al. [2007] for unmanned air vehicles. See Ghabcheloo et al. [2009b] and Häusler et al. [2009] 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 Kolda et al. [2003].

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 Ghabcheloo et al. [2006], Aguiar and Pascoal [2007a], Ghabcheloo et al. [2007], Almeida et al. [2007], Aguiar et al. [2007b, 2008a], Vanni et al. [2008b], Ghabcheloo et al. [2009a], 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 are especially relevant in view of the small speed of propagation of sound in the water. Solutions are proposed in Aguiar and Pascoal [2007a], Ghabcheloo et al. [2007, 2009a]. In Aguiar and Pascoal [2007a], solutions are described that address explicitly the fact that underwater communications occur at discrete intervals of time, thus reducing 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.

4. 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 Vanni et al. [2008a]. The simulator 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

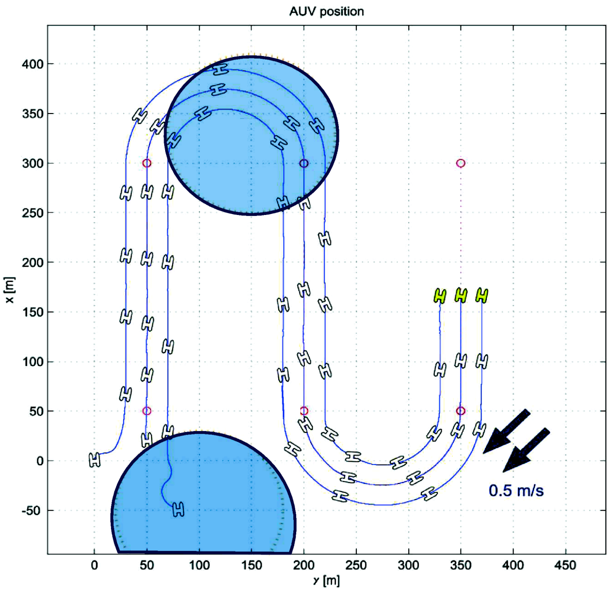

Fig. 4. Cooperative path-following of three Autonomous Surface Craft (ASC) under communication constraints.

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 generation of videos from the simulations.

An illustrative 2D example

In this section, we discuss the set-up and results of a cooperative 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. 4) and align themselves along a perpendicular to the paths. The mission is defined as the succession of lines and arcs given in the figure. The desired speed of the vehicle at the center is constant and equal to $1.5m/s$

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 Fig. 4. This was done to illustrate one type of constraint that may be present in the operation of marine vehicles in general. 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, communications are limited and the vehicles fall rapidly out of synchronization. Once the vehicles leave

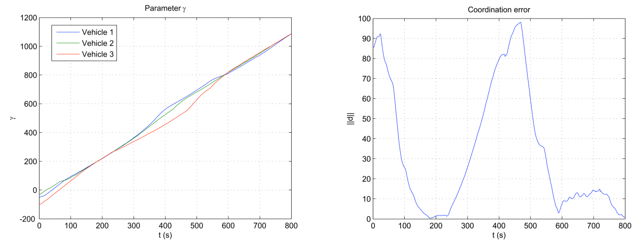

Fig. 5. Evolution of (a) position parameter γ for the three vehicles and (b) coordination error.

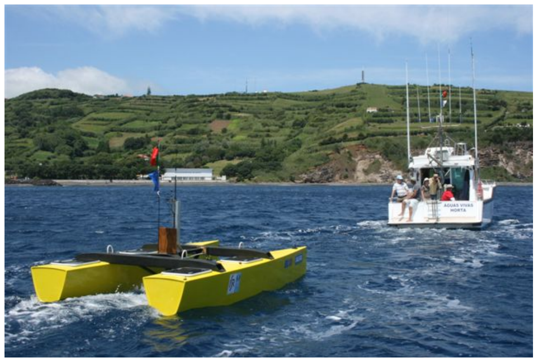

Fig. 6. The $DELFIM_X$ ASV (left) and the manned vessel Aguas Vivas (right).

the "dark area" and resume the exchanging of data, they recover the formation.

Figure 5 a) shows, for each of 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, they are said to be in formation. Formation is achieved neither at the beginning of the trajectory nor for some time after the first curve, when communication losses occur. The same conclusions can be drawn from Fig. 5 b), that shows the evolution of the coordination error defined as the summation of the absolute values of the pairwise differences of the γ parameters for the three vehicles.

5. 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 decided early on that one of the tests would involve two surface vehicles undergoing joint motion: the Aguas Vivas manned vessel and the $DELFIM_X$ autonomous surface vehicle equipped with a dedicated GREX computer, both shown in Fig. 6. 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

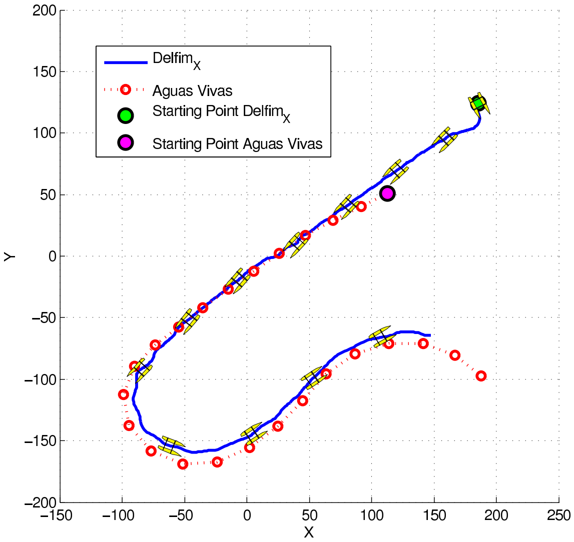

Fig. 7. Experimental results of the $DELFIM_X$ performing a target following maneuver in the Azores, PT.

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.

Two vehicles primitives were executed with success: Path Following (PF) and Target Following (TF). 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, $DELFIM_X$ identified on-line, 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, $DELFIM_X$ maneuvered well along the overall path "defined by" Aguas Vivas, not known a priori. The results of this maneuver are shown in Fig. 7. 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 $DELFIM_X$, and the efficacy of the software/hardware architecture adopted within the project, namely that of the GREX computer installed on-board the $DELFIM_X$.

6. CONCLUSIONS

The paper described the key thrust of the work done by the ISR/IST team on cooperative Autonomous Marine Vehicle (AMV) motion control in the scope of the EU Project GREX. A general architecture for cooperative marine vehicle control was proposed and tested in simulation. Tests carried out at sea were instrumental in evaluating the efficacy of the general set-up adopted for for multiple vehicle control and the supporting software and hardware architectures. Future work will address the preparation and execution of the final set of integrated tests with the members of the GREX consortium.

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