Ocean Observation With Coordinated Robotic Platforms

Coordination Algorithms Maintain Vehicle Formation

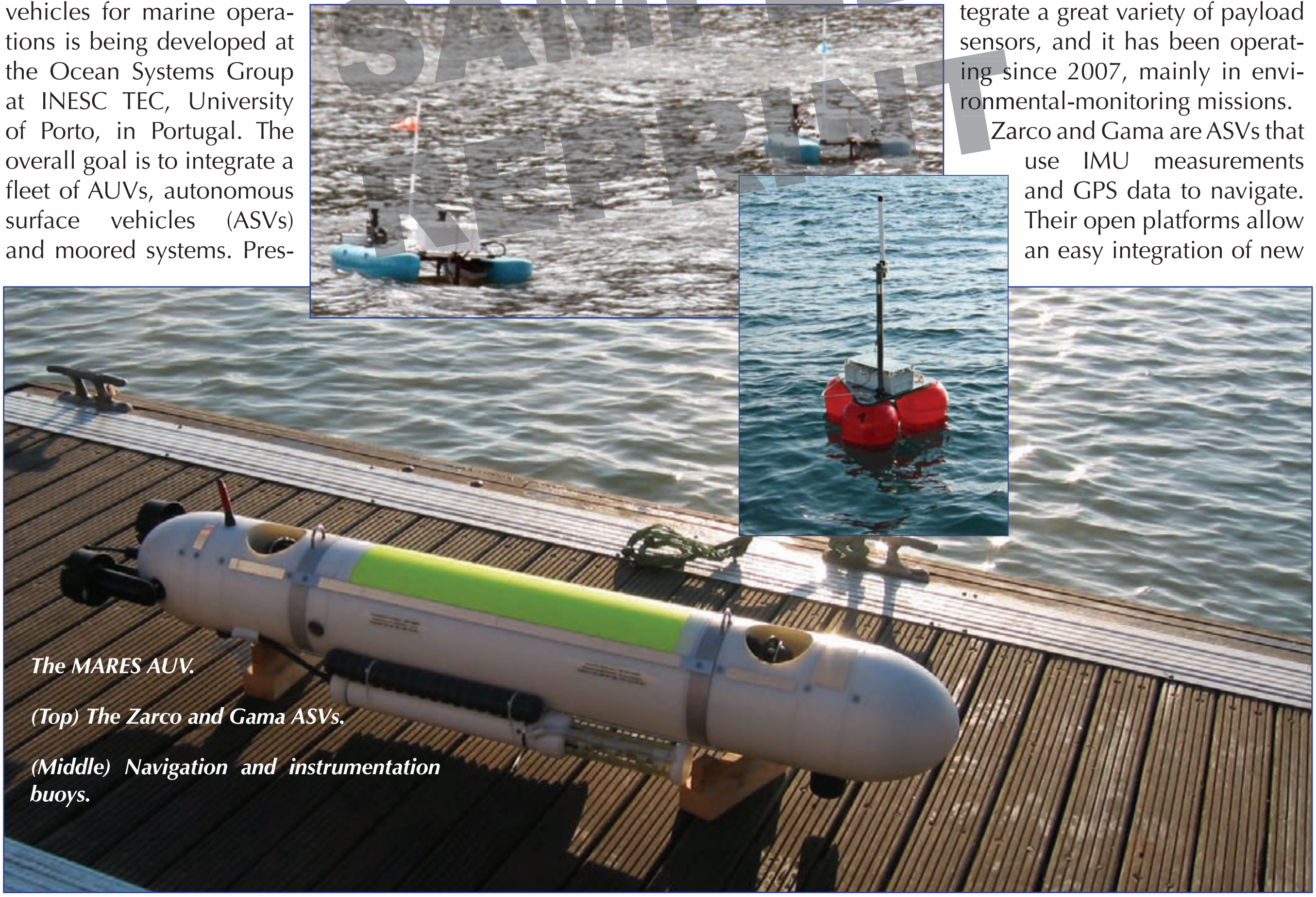
By Nuno A. Cruz • Bruno M. Ferreira • Aníbal C. Matos

The coordinated operation of marine vehicles has been a particularly active research topic during the last decade, with the realization that the new scenarios for underwater monitoring and intervention require new paradigms of operation, based on heterogeneous robotic assets. In order to exploit their complementary competencies in an efficient way, such operations require the development of robust formation-control strategies and a dependable communications infrastructure to exchange reliable information in a timely manner. When using AUVs, the communications channel is the water, and the formation-control strategy has to encompass the hindrances associated to underwater communications.

A long-term program for using multiple heterogeneous vehicles for marine operations is being developed at the Ocean Systems Group at INESC TEC, University of Porto, in Portugal. The overall goal is to integrate a fleet of AUVs, autonomous surface vehicles (ASVs) and moored systems. Present work involves use of the MARES AUV, Zarco and Gama ASVs, and navigation and instrumentation buoys (NIBs).

The MARES is a small, torpedo-shaped AUV 1.5 meters long and 32 kilograms in weight in the basic version. In a typical configuration, a PC/104 computational system manages the entire mission, including communications with other devices and a control station. Navigation is provided by the fusion of data from an inertial measurement unit (IMU) and an acoustic system for long baseline localization (LBL), complemented by a small GPS receiver, when the vehicle is at the surface. Four thrusters provide the capability to move as fast as 5 knots and to hover in the water column, with a set of lithium-ion batteries ensuring 10 hours of operation. MARES is a highly modular vehicle, with the ability to integrate a great variety of payload sensors, and it has been operating since 2007, mainly in environmental-monitoring missions.

Zarco and Gama are ASVs that use IMU measurements and GPS data to navigate. Their open platforms allow an easy integration of new



The MARES AUV.

(Top) The Zarco and Gama ASVs.

(Middle) Navigation and instrumentation buoys.

sensors, and all data can be stored onboard and transmitted in real time via radio. These vehicles operate with two independent thrusters, capable of holding position or navigating up to 4 knots. Zarco and Gama have been in operation since 2006, either independently (for bathymetry, for example) or coordinated, to provide a moving baseline for AUV navigation.

The NIBs are auxiliary equipment commonly used as static beacons responding to acoustic pings, using a two-way travel time scheme, or transmitting synchronized pings for one-way travel time positioning, therefore providing ranging capabilities to underwater vehicles. They are equipped with GPS receivers and radio-communication devices. Whenever communication with AUVs is available, the geolocation of the NIBs are fed into the vehicles for more precise localization.

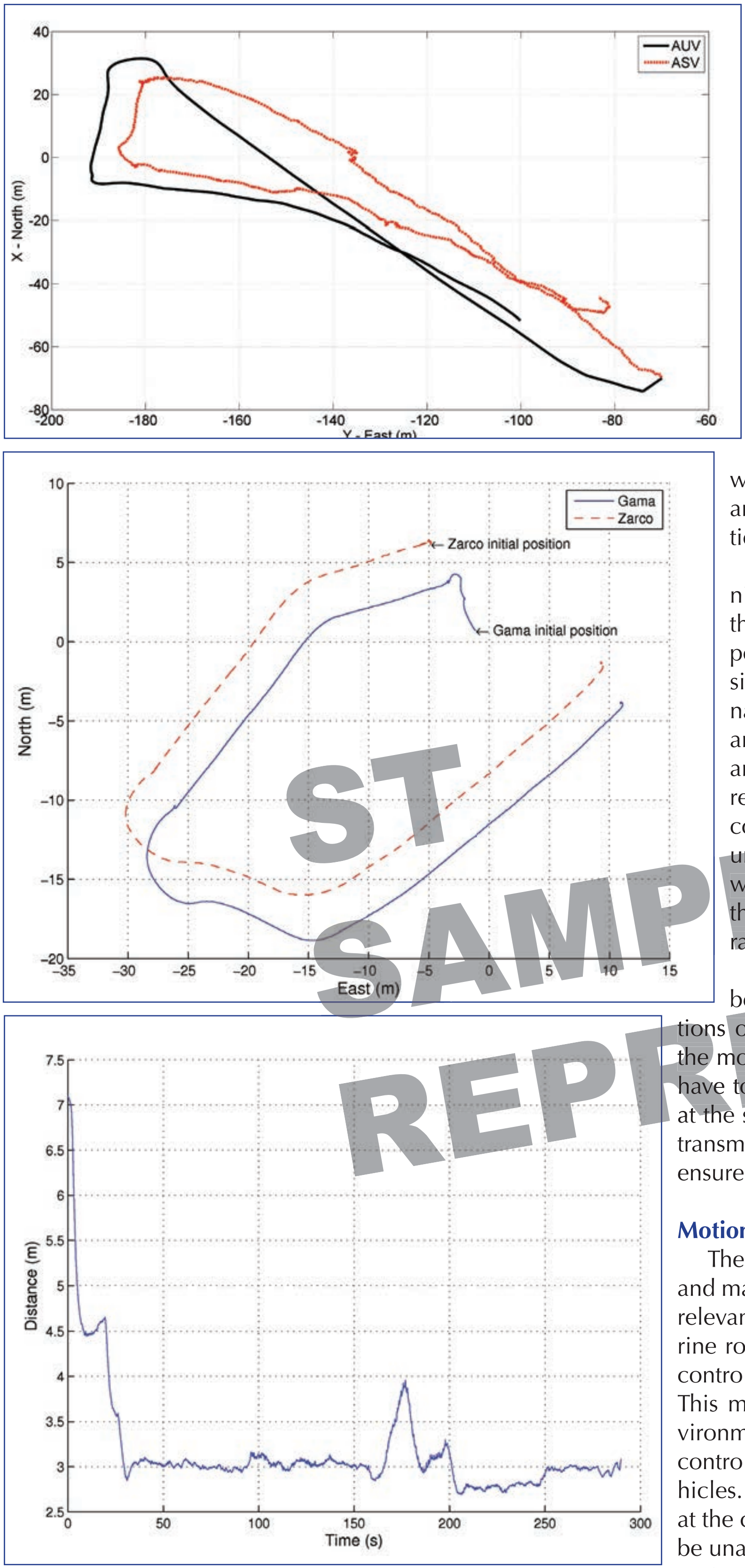
The Ocean Systems Group has tackled the technical challenges associated with the operation of these marine systems, such as relative and absolute positioning systems for multiple vehicles; sensor fusion for precise navigation, including underwater navigation in a moving acoustic network; and guidance and control of individual vehicles, both ASVs and AUVs. The current research builds upon earlier results to address the challenges associated with coordinated operations, mainly formation control under the constraints of communications and networking. These are particularly severe when using the underwater channel, with high latency, low data rate and high probability of transmission error.

The goal is for the communications network to be adaptive according to the instantaneous conditions of the acoustic channel and to the capabilities of the moving nodes. In particular, some of the nodes may have to move to increase the overall throughput, while, at the same time, the network routing will deal with the transmission conditions between the available nodes to ensure a proper transmission of information.

Motion Coordination

The capability of vehicles to follow a given trajectory and maintain reliable data exchange are among the most relevant topics when it comes to coordination of marine robots. First, the vehicles need robust and versatile controllers to allow coherent motion of the formation. This may be quite challenging in an unpredictable environment with dynamic disturbances. Therefore, robust control laws must ensure position stability for all the vehicles. Of course, control performances can be improved at the cost of more navigation sensors, although this may be unaffordable for a fleet of robots.

Second, data exchange via communications suffers from several constraints in marine environments. Robot formations should be flexible enough to accommodate intrinsic delays of radio or acoustic communications. Further to the delays, and mainly due to the compromise between frequency and range of operation, acoustic communications have very low data rates as compared to radio or optical communications. Gray areas originated by multipath, oc-



(Top) Trajectory of the Zarco ASV, following the position of the MARES AUV.

(Middle) Trajectories of the Zarco and Gama ASVs in a coordinated mission, three meters apart.

(Bottom) Relative distance of the vehicles.

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clusions or attenuation may also lead to intermittence in the communication links. All these constraints naturally impact on the formation control, but stable and robust formation is still possible.

In this case, the coordination of the vehicles is achieved through a centralized algorithm that considers two types of elements: a virtual leader, which coordinates the operations of the vehicles, and followers, which are instructed by the leader on the actions to perform and/or positions to track. The virtual leader generates the position references for each of the followers, and it can be coincident with any of the physical robots (and use the same computational system).

The evolution of the formation takes into account the tracking errors of each robot: the larger the individual errors, the slower the evolution of the formation. By construction, the control algorithm ensures that when any individual error is above a given threshold, the formation stops, i.e., the virtual leader and the communicating followers will hold their positions in the formation, waiting for the remaining vehicle(s) to recover its (their) position(s).

Complementarily, in the absence of a communication link with one of the robots for a long time, the formation will hold the position, waiting for status information exchange and position recovery of the missing vehicle(s). This is of special importance in the case of acoustic communications, which may suffer from intermittence due to occlusions or other forms of interference.

Although centralized, this approach is particularly well-suited for arbitrary trajectories of possibly time-varying formations. Moreover, the stability of the formation is unaffected by possible communication delays. Obviously, the latency of interaction among the robots degrades the overall performance of the coordinated system, but the algorithm still guarantees stability.

The coordination algorithm requires the vehicles to have local robust control laws that ensure each vehicle is able to track its reference with a bounded error. Therefore, MARES, Zarco and Gama integrate a set of methods that makes it possible to send high-level commands or references. This set includes line following, circle following and target tracking. Under static position reference, the target-tracking maneuver also allows station keeping.

Commands sent to the vehicles thus involve two main fields: the maneuver and the corresponding reference, which may dynamically change over time. This rather simple and limited set of elemental maneuvers provides a sufficiently versatile framework for any complex motion of marine vehicles. Furthermore, combinations of the maneuvers can approximate any type of trajectory.

For the coordinated motion of the vehicles, the centralized algorithm makes use of the target-tracking maneuver with dynamic reference points to drive the vehicles in a coherent manner. One of the main advantages of this implementation is that the vehicles do not require knowing their trajectory in advance, which opens the possibility for dynamic path generation and time-varying formation geometries.

Testing

Several tests carried out thus far have provided successful and encouraging results. As a first trial, conducted in 2008 in a large dam reservoir in the Douro river, about 25 kilometers east of Porto, the MARES AUV was tracked acoustically, and the tracking information was used to guide the Zarco ASV. Even with acoustic tracking errors in the order of 10 meters, the ASV was able to follow the AUV trajectory.

During the summer of 2012, testing was conducted in the same reservoir in the Douro, involving coordinated operation of two ASVs. A radio link provided communication capabilities to the vehicles and the central base station. Both ASVs reported their positions to this base station, which computed the formation position as well as the individual positions of the followers. A rate of 10 hertz was applied to both data exchange and control frequency. The followers were able to receive their references and to track them with relatively small errors, even in the presence of natural disturbances, including wind and currents. The currents were estimated to be about 0.2 meters per second.

The short mission involved the vehicles being required to move in formation 3 meters apart from each other, keeping the same relative positions. The data were directly collected from the GPS receivers on board. During the first instants of the mission, Zarco held its position, waiting for Gama to approach its desired position in the formation. When Gama joined the formation, relative error was reduced. The data showed that the vehicles remained very stable, with very small error in relative positioning. A noticeable error peak occurred at 170 seconds because of a desired stabilization (station keeping) in the face of environmental disturbances. But even in the presence of disturbances, relatively complex motions, including station keeping, were obtained with minimal error. Additionally, the asymmetries induced by different navigation sensors were well-accommodated.

Conclusions

The performances of the vehicles over their trajectories demonstrate the robustness of the two control levels. Both target tracking and coordination algorithms have proved to be robust enough to accommodate natural latencies and communication intermittences. The results show that even in the presence of such effects, the vehicles were able to keep in formation. Although the examples presented here consider only two vehicles, the control scheme can be extended to larger formations.

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