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WiMUST: A cooperative marine robotic system for autonomous geotechnical surveys

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Abstract

This paper presents the main results of the European H2020 WiMUST project, whose aim was the development of a system of cooperative autonomous underwater vehicles and autonomous surface vehicles for geotechnical surveying. In particular, insights on the overall robotic technologies and methodologies employed, ranging from the communications and navigation framework to the cooperative and coordinated control solutions are given. The software architecture and the lessons learnt from the preliminary field test are also discussed. Finally, field results of the final survey campaign carried out in the Atlantic Ocean are presented, demonstrating how a team of seven robots could autonomously conduct a geotechnical survey, producing seismic images without artifacts.

KEYWORDS
autonomous underwater vehicles, autonomous surface vehicles, geotechnical exploration, marine robotics

1 | INTRODUCTION

Over the last few years, marine robotics has developed faster than ever, thanks to different breakthroughs in perception (Fairfield, Kantor, & Wettergreen, 2007; Ribas, Ridao, Tardós, & Neira, 2008), navigation (Leonard & Bahr, 2016; Webster, Eustice, Singh, & Whitcomb, 2012, 2013), communications (Cruz et al., 2013; Stojanovic & Freitag, 2013; Zeng, Fu, Zhang, Dong, & Cheng, 2017), control (Cui, Yang, Li, & Sharma, 2017; Simetti, Casalino, Wanderlingh, & Aicardi, 2018), and autonomy (Zhang, Marani, Smith, & Choi, 2015), enabling several new applications. In particular, the use of autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) has rapidly increased in the last decade. Major applications of marine robots include military (Ferri et al., 2017, 2018), environmental, and scientific missions (Leonard et al., 2010), as well as challenging tasks that arise in the oil industry and ocean mining (Birk et al., 2018; Camilli et al., 2010). In what concerns the latter application area, multistage seismic surveys employing AUVs for seafloor massive sulfide exploration were recently performed in Japan (Asakawa et al., 2018) and they share some similarities with this study. A number of survey articles (Bandyopadhyay, 2005; Rudnick, Davis, Eriksen, Fratantoni, & Perry, 2004; Yuh, 2000; Yuh, Marani, & Blidberg, 2011; Zereik, Bibuli, Miskovic, Ridao, & Pascoal, 2018) report the most common applications.

Among the possible new applications, geophysical and geotechnical exploration were the targets of the European Union Horizon 2020 funded WiMUST (Widely scalable Mobile Underwater Sonar Technology) project (Abreu, Antonelli, et al., 2016). Nowadays, traditional seismic surveys at sea are executed with a large manned vessel that carries acoustic sources and tows kilometers of streamers with hydrophones, such as the one depicted in Figure 1a. The acoustic waves generated by the sources bounce off subbottom formations, and the reflected waves are collected by the streamers' hydrophones. The data are then postprocessed to create the so-called seismic images, through which seismic experts can infer the contents of the layers underneath the seafloor. The disruptive concept introduced with the WiMUST project was to replace the manned vessel with autonomous marine robots. In particular, the vessel is replaced by ASVs that carry the acoustic sources and provide localization means to a fleet of AUVs, each of them towing a short streamer containing the hydrophones. This concept is shown

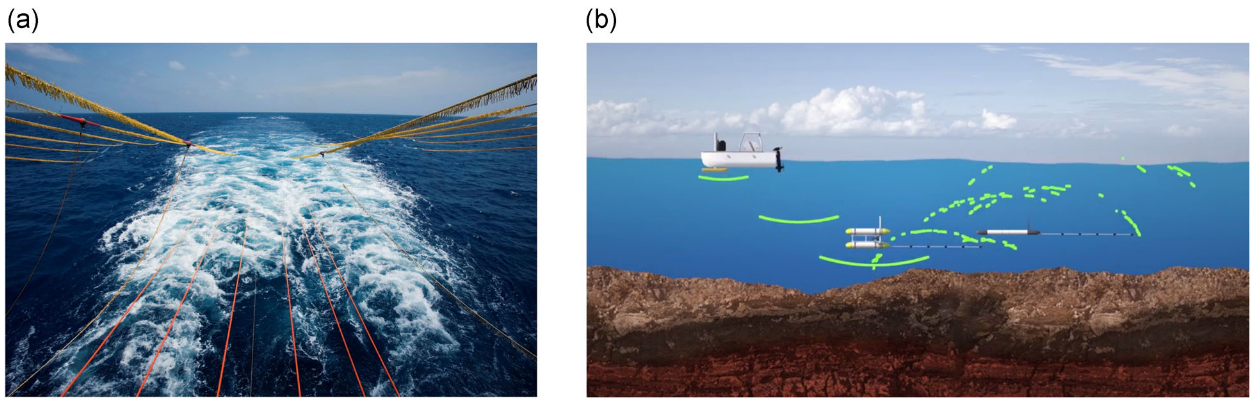

FIGURE 1 Geotechnical surveying approaches. (a) A conventional approach requires a large vessel towing both the acoustic sources and kms of streamers (photo courtesy of CGG). (b) The WiMUST concepts remove the connection between the seismic source and the streamers, employing autonomous underwater vehicles to tow streamers and autonomous surface vehicles to carry the acoustic sources

schematically in Figure 1. Given the different scales of geophysical and geotechnical exploration, it should be noticed that WiMUST focused on the latter.

The novel approach described above has several advantages with respect to state-of-the-art seismic surveys:

- A_1 The need of a large, expensive, manned vessel capable of towing multiple streamers is removed. Only a support ship to deploy and recover the AUVs is needed.
- A_2 The array of acoustic receivers can be reconfigured by simply commanding the robots to change their mutual positioning.
- A_3 The sensing nodes can be submerged at virtually any depth, whereas traditional streamers are normally floating a few centimeters below the sea surface. This means that additional acoustic array topologies can be obtained since the nodes can be located at different depths. Furthermore, as the vehicles can tow their own streamers closer to the seabottom, the signal to noise ratio is enhanced with respect to the traditional solution where the streamers are near the surface.
- A_4 More elaborate surveying techniques can be developed since no physical ties exist anymore between the acoustic sources and the streamers.
- A_5 Shallow water surveys are possible due to the fact that the ASVs can navigate at places where large vessels cannot.
- A_6 In traditional surveys, the vessels tow all the equipment and if a component breaks down, the survey needs to be stopped. In this case, the risk is spread out across all the AUVs, which could be replaced "on the fly" without stopping the surveying activity.

In spite of these attractive features, the employment of autonomous vehicles meets with different technical challenges. First, underwater vehicles do not have access to Wi-Fi communications but can, at most, communicate acoustically limited amounts of information on a time-shared channel. Further, a nonconventional infrastructure for accurate underwater vehicle localization must be created, since underwater vehicles do not have access to global navigation satellite system (GNSS) data and equipping each of them with high-performance inertial navigation systems would be prohibitive. In the case of WiMUST, this was done through the use of surface vehicles acting as *navigation anchors* equipped with the necessary gear to transmit their GNSS positions to the AUVs, which, in turn, measure their distances to the ASVs using range-measuring devices. Due to the low acoustic communications bandwidth, the resulting AUV-positioning information will be available at a low-rate; hence the control of the AUVs must be able to cope with this constraint. Furthermore, the AUVs must also receive from the anchors high-level control-related information to keep them in the required positions in the formation. Therefore, a comprehensive acoustic communications framework to broadcast information for AUV localization and formation control must be established between the AUVs and the surface vessels (Kebkal, Kebkal, Kebkal, et al., 2017). Finally, the acoustic sources and the streamers are not any more physically connected, hence synchronized. Therefore, suitable synchronization mechanisms need to be developed, as the hydrophones' data, during the offline processing, need to be put in correlation with the acoustic source positions when the signal was emitted.

While the final WiMUST survey results were previously presented in a conference publication (Indiveri, 2018), this paper contributes to significant additions. First, a detailed description of the acoustic and seismic acquisition systems employed is given, together with the solutions adopted for their mechatronic integration within the robots' architecture. Furthermore, the paper presents the main communication, navigation, and control solutions, including the coordinated control of the AUVs and ASVs, put into perspective in relation to recent advances published in the literature. Further original contributions lie in the presentation of the final WiMUST software architecture and in the lessons learnt during the several integration campaigns held before the final survey. Finally, the paper presents the WiMUST final survey field results, showing how the overall WiMUST system successfully completed a geotechnical survey of approximately 20000 m^2 area, acquiring seismic images, which allowed for the identification of relevant geological features, without signs of artifacts.

With the above objectives in mind, the paper is structured as follows. Section 2 provides details on the types of vehicles used, along with their WiMUST-related equipment and mechatronic integration. Section 3 introduces the communication and navigation framework that has been developed to allow the AUVs to navigate, receive control-related data, and communicate quality control data to a command and control (C2) console. Section 4 outlines the control algorithms that were developed to maintain the robot formation. Section 5 presents the software architecture supporting the WiMUST system, while Section 6 discusses the lessons learnt during the field integration campaigns. Section 7 details the main results of the open sea survey that was executed, and that demonstrated the effectiveness of the overall WiMUST approach. Finally, conclusions are given in Section 8.

2 | THE WiMUST SYSTEM

This section describes the role of each of the autonomous vehicles as well as their main equipment necessary to execute a WiMUST mission. As done in traditional seismic surveys, two acoustic sources are used to collect the necessary subbottom acoustic data. However, in the WiMUST setup, each source is carried by an ASV. Moreover, additional ASVs may be employed as navigation nodes. In particular, as described in the following sections, surface navigation nodes carry medium frequency (MF) modems to support the AUVs navigation through a specifically designed architecture that is scalable with respect to the number of AUVs used. Figure 2 depicts the developed and experimentally validated WiMUST system: two catamarans at the surface carry the acoustic sources, and an additional ASV aids the navigation of the four submerged AUVs, which keep the desired formation while tracking the motion of one of the catamarans.

2.1 | AUVs

The use of AUVs is one of the key technological aspects of the WiMUST project. Two different kinds of AUVs were used, namely the Folaga (Alvarez et al., 2009) and the Medusa (Abreu, Botelho, et al., 2016) vehicles.

All the AUVs were equipped with two modems, provided by the partner EvoLogics. A so-called MF modem (S2CR18/34), with a frequency band between 18 and 34 kHz, was used by the AUVs to receive localization and control information from the ASVs. Since these surface robots act as moving nodes of a long-baseline system (LBL), we will refer to them as "navigation/localization anchors". All the MF modems include a Chip Scale Atomic Clock (CSAC) to enable precise synchronization and the use of one-way ranging techniques (Eustice, Singh, & Whitcomb, 2011; Kebkal, Kebkal, Glushko, et al., 2017), as detailed in Section 3.1. The second kind of modem installed in all the AUVs is a so-called high-frequency (HF) modem (S2CR42/65), characterized by a frequency band between 42 and 65 kHz. Such a modem is interrogated by the ASVs and is used to deliver quality control data and to monitor information from the AUVs to the surface (as explained in Section 3.2).

In what concerns the seismic equipment, each AUV tows an 8 m long streamer containing 8 hydrophones, which collect the acoustic waves that bounce off sub-bottom formations. The data are then acquired and recorded by an acquisition board provided by the partner Geo Marine Survey Systems.

Finally, each AUV was also equipped with a buoy. The buoy is not an integral part of the final envisaged WiMUST system, but it was a very convenient way to monitor the AUVs underwater and act as a tool to recover the vehicles. Folagas and Medusa had different kinds of buoys. While the Folagas had a simple buoy with no electronics, Medusas had a Wi-Fi antenna directly connected to the robot. The use of this antenna was strictly for monitoring the navigation and control algorithms' performance for debugging purposes.

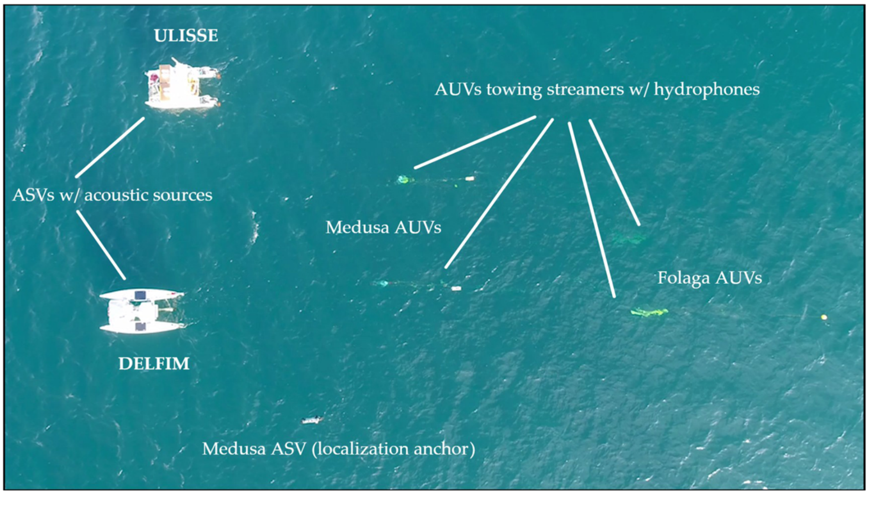

FIGURE 2 The WiMUST system during ocean trials in Sines, Portugal (aerial view taken by a drone)

2.1.1 | Mechatronic integration on the AUVs

A key step in the WiMUST project was to integrate on the AUVs the Multitrace system for streamer/hydrophone data acquisition provided by the partner Geo Marine Survey Systems.

Due to a lack of available space, the Multitrace system was not installed inside the main body of the Medusa robots. This is because each Medusa already housed two acoustic modems required for the WiMUST system, which took up almost all of the available payload volume. Hence, it was decided to completely encapsulate the Multitrace hardware on the outside of the main vehicle hull in a special type of potting resin for electrical components. Special care was taken to avoid mechanical stress that, in some cases, occurs due to the contraction of the epoxy resin. Two cables were also encapsulated: a small cable connecting the Multitrace system to the vehicle and the bigger streamer cable. This solution allowed us to easily connect and disconnect the streamer and Multitrace system from the vehicles. Regarding the integration on the Folaga AUVs, a WiMUST payload module was conceived, integrating the equipment required to perform the WiMUST mission. Namely, the payload contained the two acoustic modems and the Multitrace acquisition board that was connected to the streamer. As per Folaga's design, payload modules can be inserted in the middle of the vehicle, making it longer, but adding the required functionalities. The Folaga payload module was designed to be neutrally buoyant. The final mechatronic solutions are illustrated in Figure 3.

2.2 | ASVs

The use of surface vehicles is another key aspect of the WiMUST system. Depending on the actual hardware installed, each ASV can cover (multiple) different roles. First, ASVs can carry the acoustic sources, for example, a sparker that can generate a powerful broadband (50 Hz–4 kHz) omnidirectional pulse sound through the controlled discharge of electrical arcs. The necessity of having ASVs carrying the acoustic sources in the WiMUST project arose in part from the difference in speed of operation between small AUVs and large vessels (used in traditional seismic surveys), as detailed in Section 6. In fact, the available AUVs could operate at speeds between 0.5 and 1 m/s, at which most manned boats and vessels cannot maneuver accurately. Therefore, the solution was to adopt small (3–4 m long) more maneuverable ASVs (catamarans) capable of carrying acoustic sources, namely the ULISSE and DELFIM catamarans, developed by the interuniversity research center on Integrated Systems for Marine Environment (ISME, by its University of Genova node) and Instituto Superior Tecnico for Research and Development (IST-ID), respectively. In hindsight, this decision paved the way for the use of ASVs equipped with acoustic sources in a number of applications.

The second fundamental role of the ASVs is to act as anchors. If an ASV fulfills this role, then it is equipped with an MF modem and periodically broadcasts its position using the acoustic channel to allow the AUVs to localize themselves, along with other control-oriented information as detailed in Section 3.1. An ASV can also be equipped with an HF modem to receive the quality control information from the AUVs. The HF modems adopted for the project may also include an ultra-short baseline (USBL) receiver, which provides the position of the AUV being interrogated. This extra information was used during the project experiments to monitor and log the AUVs positions. The latter served as ground-truth against which to compare the AUVs' own position estimates for performance assessment purposes. Note that the USBL receiver on the ASVs does not represent the necessary equipment of the WiMUST system.

Finally, one of the ASVs was selected to be the leader of the WiMUST robotic fleet. This is a key role, as the AUVs, plus some of the other ASVs, track the position of the leader with appropriate offsets, to maintain their mutual positioning (called formation, see Section 4.2) during a WiMUST mission. Hence, its motion behavior impacts on the motion of all the follower AUVs and ASVs.

In what concerns the geometry of the formation, the ASVs might exhibit different constraints, depending on their (multiple) roles. The positioning of the ASVs carrying sparkers must meet stringent seismic acquisition requirements. If an ASV is acting as an anchor, then its position needs to account for the geometry of the moving LBL system. Finally, the high directionality of the HF modem transducers imposes further constraints on the relative position of each of the ASVs in the overall vehicle formation. These considerations have been used to define the WiMUST final survey formation, as described in Section 7.1.

(a) (b)

FIGURE 3 Integration of the WiMUST payloads on the autonomous underwater vehicles (AUVs). (a) The Medusa vehicle with the acquisition board in between the two main hulls, with the streamer cable going toward the back. (b) The WiMUST payload module designed for the Folaga AUV

2.2.1 | Mechatronic integration on the ASVs

The mechatronic integration required to make the two catamarans available for the project capable of carrying the acoustic sources presented several challenges. First, both DELFIM and ULISSE had no solution available on board to satisfy the energy needs of the seismic survey equipment (the power supply power consumption can reach 2 kW). The Honda EU20i Inverter generators (gasoline-powered, rated to 2 kW of peak power output, at 230 Vac) presented themselves as a very good compromise between cost, performance, size, and flexibility. They are lightweight and compact and allow for parallel operation, which was a key feature to scale to the energy needs of this installation by using two units, instead of resorting to a bigger (bulkier and heavier) generator. However, the internal gasoline tank of the Honda EU20i generators does not allow for a full day of operations (even for a low energy shot configuration). To mitigate this limitation and avoid at sea refueling, an external gasoline tank that feeds both generators was installed on both the catamarans.

Since both catamarans are supposed to operate in harsh sea conditions, and considering their small size, the design solutions had to make all the assembly resistant to water splashes. Especially during hot days in the summertime, thermal issues may arise. Hence, both the power supply box (the tall box at the stern of DELFIM and the orange box at the stern of ULISSE) and the gasoline generators box (the box at the DELFIM bow and the two white boxes at the ULISSE bow side) had to be designed carefully so that enough heat extraction could be achieved. The final design of the boxes, including the dimensioning of the venting fans, of the air conducts and of the overall geometry, was good enough to maintain the temperature under a safety threshold, allowing for the proper operation of the hardware.

In what concerns the mechatronic integration on ULISSE, two decks have been manufactured for the WiMUST project. One, installed near the stern under the roll-bar, is dedicated to hosting the sparker's power supply. The second one, installed near the bow, hosts the movable pole to lower down the modems' transducers needed to communicate with the WiMUST AUVs, an additional waterproof case hosting the modems electronics, and the two Honda EU20i portable power generators. A similar solution was adopted for DELFIM, where the sparker is rigidly fixed to the DELFIM movable pole together with the MF modem and the HF USBL. Two boxes were manufactured by IST-ID to contain the sparker power supply and the two Honda generators. Figure 4 shows some details of these integration solutions on both catamarans.

3 | THE WIMUST COMMUNICATION AND NAVIGATION FRAMEWORK

The communication and navigation framework developed for the WiMUST systems serves two main purposes. On the one hand, it provides the infrastructure for localizing the AUVs and sending control-related data to them; on the other, it affords the user the means to monitor the process of acoustic data acquisition in run-time. These two main goals are outlined in the following two subsections. The final subsection discusses the impact of seismic data processing requirements on the communication and navigation framework.

3.1 | Underwater acoustic distributed localization and navigation

The acoustic communication solution implemented in the WiMUST project builds upon a time-division interrogation loop between the anchors at the surface that relies on the time synchronization guaranteed by the GNSS pulse-per-second signal. Each anchor, at its turn, sends the AUVs its GNSS position and the position of the formation leader, together with a number of possible commands such as start or stop the mission. This loop is schematically represented in Figure 5. The information is sent in broadcast mode to all underwater vehicles using small (32 bytes) acoustic packets. Upon receiving one of these messages, each AUV computes its range to the corresponding anchor, using a simple one-way travel time technique; this is possible because the CSAC inside the MF modem allows the AUVs to be time-synchronized with the surface vehicles, with a very low drift (Kebkal, kebkal, Glushko, et al., 2017). With the above solution, the AUV localization cycle time is proportional to the number of anchor ASVs. Since the AUVs do not transmit using the MF modem and the number of anchors needed is very small in comparison with the number of AUVs used for collecting seismic data, this approach scales very well with the number of underwater vehicles.

Navigation of the ASVs and AUVs, that is, estimation of their linear position and velocity vectors, is quite different for these two classes of robots. At the surface, navigation is relatively simple to perform, due to the availability of GNSS data, provided by receivers at the rate of 10 Hz. However, underwater navigation is a far more complex task. A proper fusion of the information available from a variety of sensors is usually needed. For example, Doppler Velocity Logs (DVL) measure the velocity vector of a vehicle with respect to the water (and with respect to the bottom, when sufficiently close), but are quite costly. In some applications, this problem can be partially overcome by measuring the vehicle thruster RPMs (revolutions per minute) and estimating the longitudinal speed of the vehicle with respect to the water by using a quasi-steady-state calibration curve relating the two variables. The price to be paid is the obvious decrease in the accuracy of the linear speed estimate. In what concerns the vehicles' orientation, the latter is provided by attitude and heading reference systems. In the setup adopted, all vehicles are usually equipped with depth sensors. Their positions in the horizontal plane can then be estimated by measuring their distances to the anchor ASVs at the surface, the absolute positions of which are transmitted to the AUVs using the acoustic modems described before. Distances, in

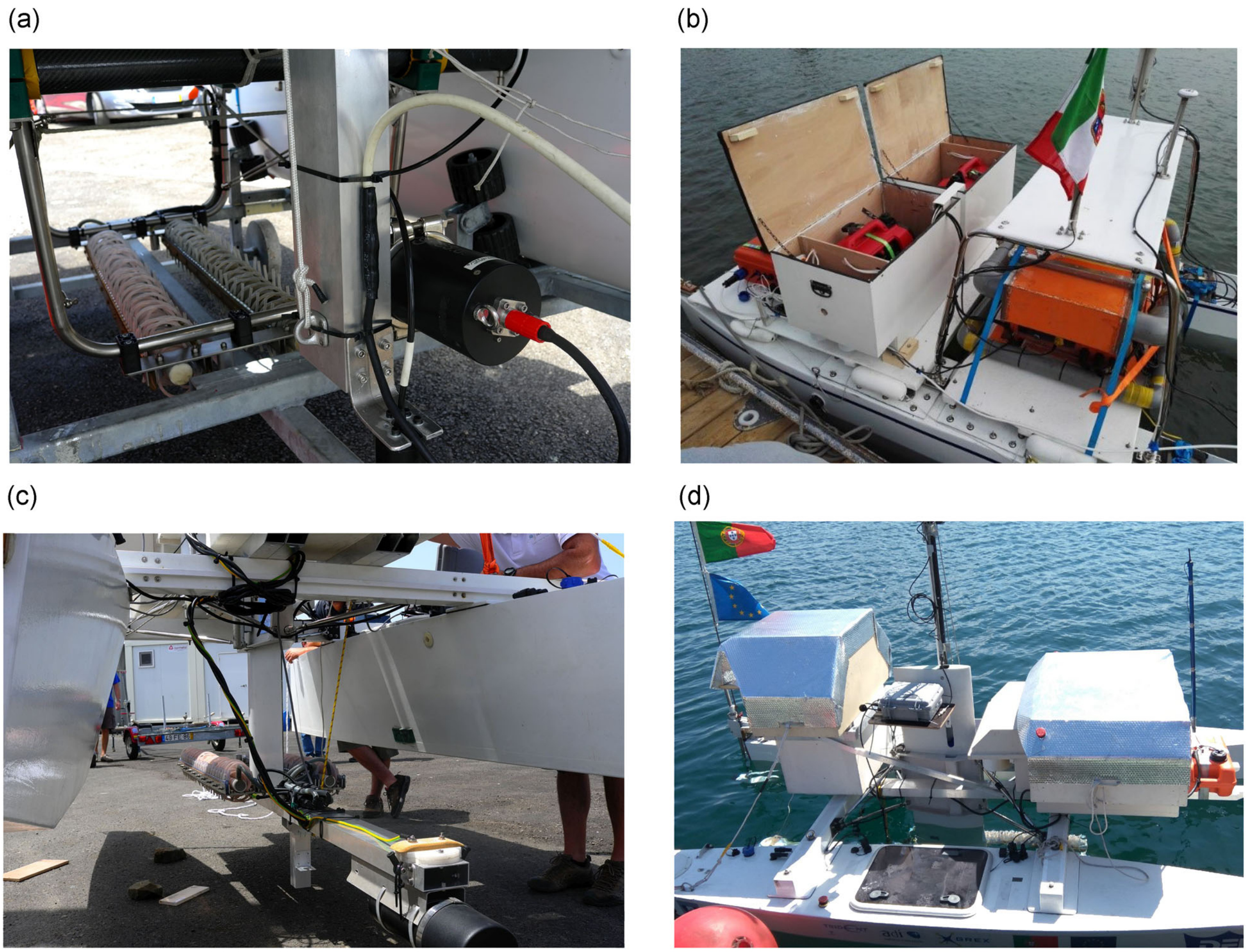

FIGURE 4 Mechatronic integration on the autonomous surface vehicles. (a) The sparker is fixed with a clamp system to the ULISSE's carbon fiber bars, and the two acoustic modem transducers are fixed to the movable pole. (b) The main deck of ULISSE, showing the boxes manufactured to contain the power generators on the left, and the sparker's power supply installed beneath the roll bar on the right side of the picture. (c) The sparker is rigidly fixed to the DELFIM movable pole, with the medium frequency modem in the middle; the high-frequency USBL can be seen at the bottom of the image. (d) The main deck of DELFIM, showing the boxes manufactured to house the power generators on the left, and the sparker's power supply on the right side of the picture

turn, are estimated using acoustic-ranging devices, by resorting to a one-way travel time technique or a two-way travel time technique. While the former requires time synchronization, as provided in the WiMUST system by the CSAC, the latter is cheaper but does not scale well with the number of AUVs.

Once the sensors are selected, and the localization infrastructure is designed, several solutions for their integration in an underwater navigation solution are already available in the literature. The following subsection briefly describes the navigation solution (based on the extended Kalman filter [EKF]) implemented on board each AUV of the WiMUST fleet.

3.1.1 | AUV EKF filter design

Classical seismic surveys are usually performed by having the surface vessel (carrying the acoustic sources) maneuver at an approximately constant speed over long periods of time. In line with this strategy, it was assumed from the outset that all the vehicles involved in the WiMUST system would also move at almost constant, possibly slowly changing speeds. For this reason, a pragmatic decision was made to develop a WiMUST navigation solution for the underwater segment using a simple, constant velocity EKF filter. Furthermore, since all the vehicles have a depth sensor and the seismic surveys are also usually done at a fixed depth, the filter was designed on the horizontal plane only, under the assumption that minor adjustments on the vertical plane would be negligible with respect to the motion on the horizontal one.

In accordance with the above, the state of the filter was defined as $\mathbf{x} = [\mathbf{p}^\top, \mathbf{v}^\top, \mathbf{v}_c^\top, \mathbf{p}_1^\top, \mathbf{v}_1^\top, \ldots, \mathbf{p}_n^\top, \mathbf{v}_n^\top]^\top$, where each of these entries is a two-dimensional (2D) vector. In particular, $\mathbf{p}$ is the estimated global position (x, y) of the AUV, $\mathbf{v}$ is its inertial velocity, $\mathbf{v}_c$ the velocity of the ocean current (assumed irrotational), while $\mathbf{p}_i$, $\mathbf{v}_i$, are the anchors'

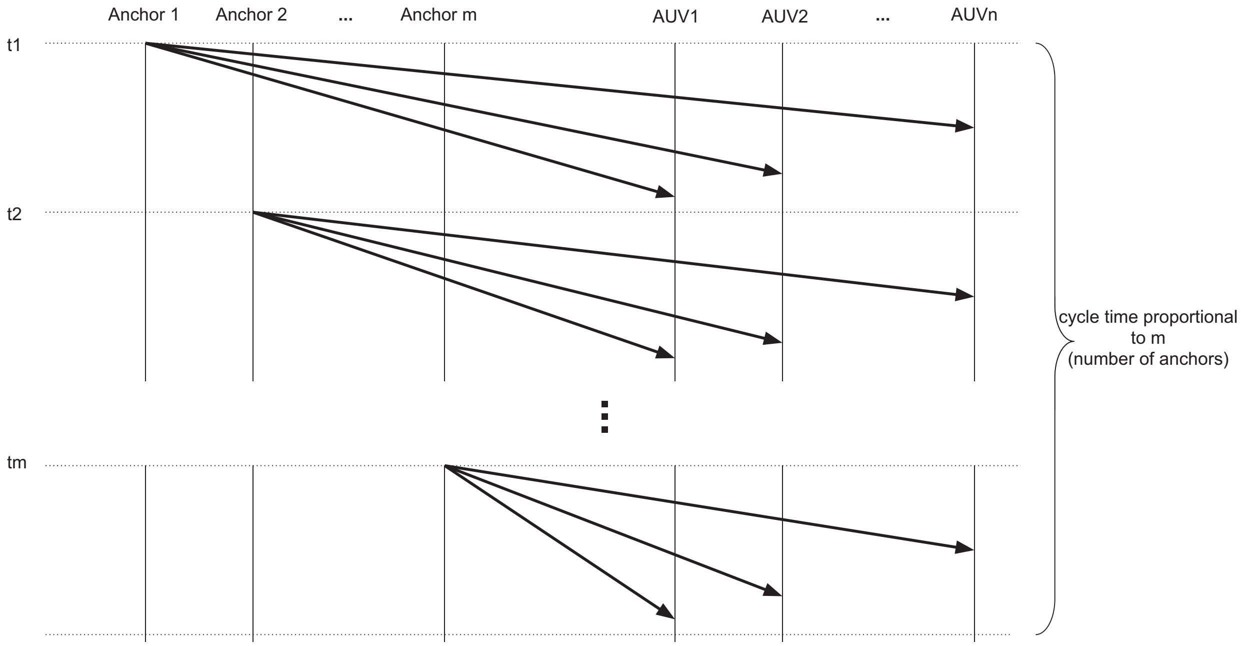

FIGURE 5 Localization loop of the autonomous underwater vehicles (AUVs) using medium frequency modems. Each surface anchor periodically broadcasts its position together with the leader of the formation's one to the AUVs

position and velocity estimates. The state transition model is shown hereafter:

$$\begin{bmatrix} \dot{\mathbf{p}} \\ \dot{\mathbf{v}} \\ \dot{\mathbf{v}}_c \\ \dot{\mathbf{p}}_1 \\ \dot{\mathbf{v}}_1 \\ \vdots \\ \dot{\mathbf{p}}_n \\ \dot{\mathbf{v}}_n \end{bmatrix} = \begin{bmatrix} \mathbf{v} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{v}_1 \\ \mathbf{0} \\ \vdots \\ \mathbf{v}_n \\ \mathbf{0} \end{bmatrix}. \tag{1}$$

The EKF can incorporate a different kind of measurements $\mathbf{y}_i$, as explained below:

1. $\mathbf{y}_1 = \mathbf{v}$, velocity with respect to the bottom given by a DVL sensor (not used in WiMUST).
2. $\mathbf{y}_2 = \mathbf{v} - \mathbf{v}_c$, velocity with respect to the water estimated by a model based on the thruster RPMs and/or measured by a DVL sensor (not used in WiMUST).
3. $\mathbf{y}_3 = \mathbf{p}$, position given by the GNSS.
4. $\mathbf{y}_4 = \mathbf{p}_i$, position of anchor i, broadcasted using acoustic communications.
5. $\mathbf{y}_5 = \mathbf{v}_i$, velocity of anchor i, broadcasted using acoustic communications.
6. $\mathbf{y}_6 = \|\mathbf{p}_i - \mathbf{p}\|$, range to anchor i, obtained by an acoustic device and transformed to the horizontal plane using information about the depth of the AUV.

Notice that to estimate the position $\mathbf{p}$, only a subset of these measurements is needed. Obviously, while at the surface, GNSS data is sufficient. Underwater, the WiMUST AUVs used the information on the position of at least two anchors and the ranges to them. However, since these ranges are obtained at a relatively low rate, velocity information estimated from the thruster RPMs was also integrated to improve the position estimate and to allow for the estimation of the velocity of the ocean current (notice that DVLs were not used as too costly for the application). As a final remark, ranges were computed from the time of flight using a constant sound speed. Considering the short distances between the sources and the receivers (order of tens of meters), the effect of sound ray distortion is quite limited. If longer distances between vehicles were needed, and the sound speed profile was available, then advanced ray-tracing-based techniques could be employed to improve the range computation (Casalino, Caiti, Turetta, & Simetti, 2011).

3.2 | Quality control and monitoring

As explained in Section 3.1, MF modems are used, in a time-division fashion, to send data necessary for tracking the leader and to allow for the navigation of the AUVs. To allow for a quick loop, anchors send their information in broadcast, and AUVs do not send any information through the MF modem.

Therefore, for the purpose of monitoring the quality of the seismic data acquired and following the state of progress of a mission, AUVs are interrogated, one by one, by the ASVs at the surface using the HF modem. Once interrogated, each AUV replies with the quality control data extracted from the seismic data and its estimated position. The resulting cycle time, i.e. the time it takes before an AUV can be queried again, is proportional to the number of AUVs. Hence, the quality control cycle time does not scale as well as the localization cycle time as the

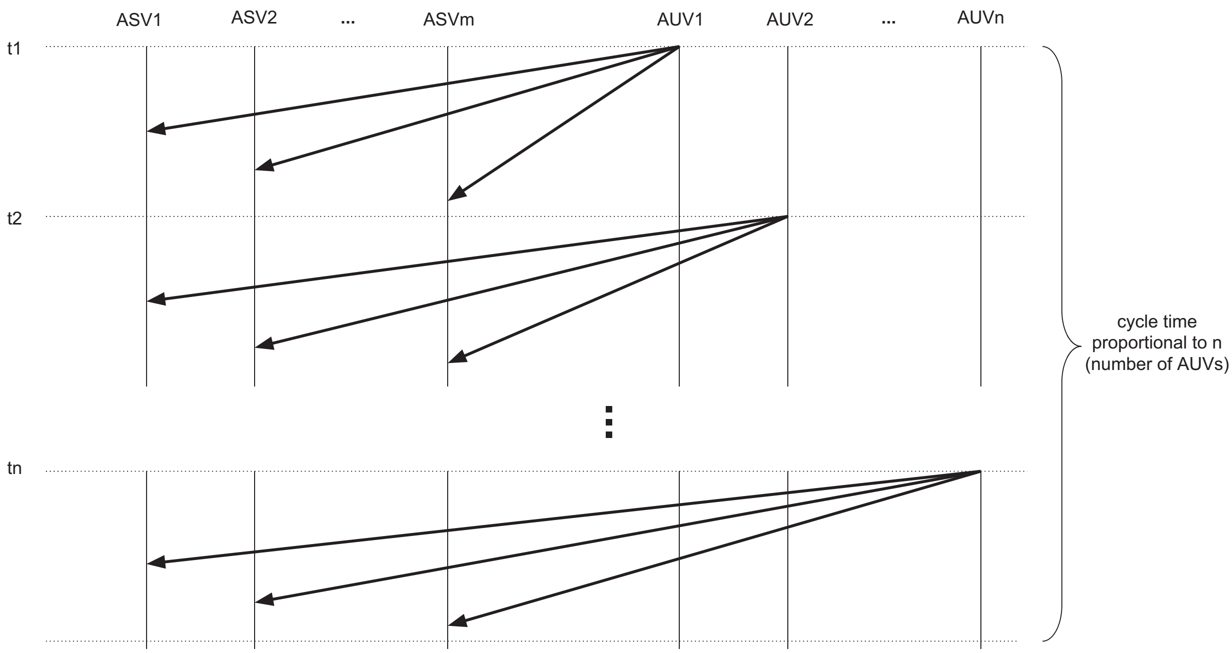

FIGURE 6 High-frequency (HF) modem interrogation scheme between the surface and underwater vehicles. Once one of the autonomous surface vehicles (ASVs) interrogate an autonomous underwater vehicle (AUV), the latter replies with quality control information. Considering the size of the WiMUST quality control data and the available communications bandwidth with the HF modem, a single interrogation takes approximately 3 s

number of AUVs increases. This interrogation scheme is graphically depicted in Figure 6.

3.3 | Seismic data processing requirements

To allow correct seismic data processing, two main requirements were individuated during the early phase of the project. First, the time base of the seismic recording needs to be accurate to less than half of the seismic sampling interval after 12 h. For a 10 kHz sample rate, this implies a clock drift of less than 50 μs after 12 h. Second, after data processing, each node's horizontal position must be known with submeter accuracy, while its vertical position must be known with decimeter accuracy.

As it concerns the first requirement, laboratory experiments allowed to develop practical recommendations for protocol maintenance and preparing the atomic clock for autonomous missions. In particular, when the atomic clock is disciplined every 3 weeks (without intermittent powering on and off), a short-term disciplining for 300–600 s is enough to refine the aging clock parameters. Subsequent tests showed an approximate clock drift of 2.5 μs/h.

For the second requirement, dedicated sea trials were conducted comparing the AUV estimated position with a real-time kinematic GNSS solution. The experiments demonstrated that the position of each node could be determined with centimeter-grade accuracy, thanks to the low drift of the integrated CSAC, hence meeting the desired positioning requirement.

Hence, these results show that the proposed communication and navigation framework meets the requirements of the WiMUST system. A detailed discussion of the synchronization issues and networking capabilities of the modems is beyond the scope of the current paper; see (Kebkal et al., 2019) for further details.

4 | THE WIMUST CONTROL FRAMEWORK

The three main control phases of a typical WiMUST mission unfold as follows. First, all the vehicles are deployed in the area, and the "Go To Formation" (GTF) algorithm is used to generate reference trajectories to be tracked by the fleet of vehicles so as to steer them to desired target positions and velocities (defining a so-called initial multiple vehicle formation), at the same terminal time, avoiding mutual collisions and streamer entanglement. Once the initial formation has been reached, the AUVs start diving and the ASVs (two of which carry acoustic sources) maneuver cooperatively at the surface, to act as anchors for the AUVs. The ASVs carrying the sources execute a "Cooperative Path Following" (CFP) maneuver, ensuring that a desired race-track path is followed by two sources in a cooperative manner, satisfying the stringent seismic surveying requirements. At the same time, an auxiliary anchor ASV and the AUVs, while underwater, track the leader of the surface formation using a "Coordinated Trajectory Tracking" (CTT) algorithm, while adopting a desired multiple vehicle geometric pattern.

The following paragraphs will present a brief description of the CPF, CTT, and GTF motion control approaches.

4.1 | Cooperative path following

In its simplest form, a path following algorithm (Bibuli, Bruzzone, Caccia, & Lapierre, 2009) is responsible for making a vehicle converge to and move along a desired spatial path adopting a speed profile that may be path-dependent. In this setup, a path Γ is parameterized by a parameter γ (not necessarily the length), and the speed profile v is given as $v = v(\gamma)$, where $v(\cdot)$ is the desired function, see Figure 7. Notice that it is not required for a vehicle to be at the desired position at the desired time. Instead, the vehicle is simply required to move along a path at the desired speed that may be path-dependent. Typically, the outputs of a path following algorithm are desired speed and heading references that are sent to the low level control of the vehicle (Aicardi et al., 2001; Fossen, Breivik, & Skjetne, 2003).

If multiple vehicles are employed, and each of them is commanded using a separate path following algorithm, no guarantee about formation holding can be given, even if the paths are conveniently parametrized. Instead, the CPF algorithm is responsible for making a group of N vehicles converge to and follow N assigned paths and adjust their motions so as move along the paths at a common, desired normalized speed while adopting a given geometric pattern. In this setup, the paths are conveniently parameterized by parameters γ_i with $i = 1, 2, \ldots, N$ so that cooperative path following is achieved when all γ_i are equal (i.e., when consensus is reached on the γ_i variables), see the illustration in Figure 7b. The reader is referred to (Aguiar & Pascoal, 2007; Vanni, Aguiar, & Pascoal, 2008; Fernandes Castro Rego, Aguar, & Pascoal, 2013) for detailed descriptions of the algorithms.

4.2 | Coordinated trajectory tracking

The CTT algorithm is responsible for making a group of N vehicles track N assigned trajectories. In the specific case of WiMUST, this system is in charge of making the four submerged AUVs track four trajectories that are shifted-in-space replicas of the estimated trajectory of the leader ASV, thus the name coordinated trajectory tracking. In sharp contrast with CPF, the curves to be followed are parametrized by time t, that is, each trajectory is a set of points $\mathbf{p}(t)$ defined in the inertial reference frame. Figure 8a shows the basic maneuver upon which CTT is rooted: trajectory tracking for a single vehicle, whereby the latter computes the commanded velocity vector $\boldsymbol{V}$ required to "point" the vehicle from its own inertial position to the desired position $\mathbf{p}(t)$ in the trajectory (the figures illustrates the computation of that vector for a number of discrete time points $\mathbf{p}(t_i)$ with $i = 1, 2, \ldots$). Because the speed is naturally set by $\dot{\mathbf{p}}(t)$, the strategy for trajectory tracking amounts to specifying the desired heading for the vehicle, so that its velocity will match $\boldsymbol{V}$.

Figure 8b illustrates the obvious extension to the case of two vehicles required to track trajectories $\mathbf{p}_1(t)$ and $\mathbf{p}_2(t)$, where the latter is a spatially shifted version of the first, that is, $\mathbf{p}_2(t) = \mathbf{p}_1(t) + \delta$, where δ is the required offset. Clearly, the methodology can be extended to an arbitrary number of vehicles. In the case of the WiMUST project, the CTT maneuver affords the four submerged AUVs the capability to track spatially shifted versions of the trajectory of the leader ASV, thus achieving the desired vehicle formation.

In what concerns the particular implementation of the WiMUST project, the leader ASV transmits periodically to all AUVs its own position in the inertial frame. The AUVs, in turn, build a sliding buffer of constant size with the points thus received (using a last-in, first-out procedure), fit smooth trajectories to them, and track the resulting trajectories in space and time.

4.3 | Go to formation

One of the practical problems in using autonomous vehicles is their launch, orderly deployment, and recovery procedures. In fact, especially for AUVs towing streamers several meters long, possible mutual collisions and entanglements between streamers make launch and recovery awkward even with a few vehicles only, more so as the number of vehicles increases. Because the vehicle formations for seismic surveys can be quite tight, it becomes impractical to deploy the vehicles close to their (initial) starting positions. While the vehicles are being deployed, the ones already in the water start drifting, making the whole process quite troublesome. Hence, the idea developed within the WiMUST project was to deploy the vehicles far

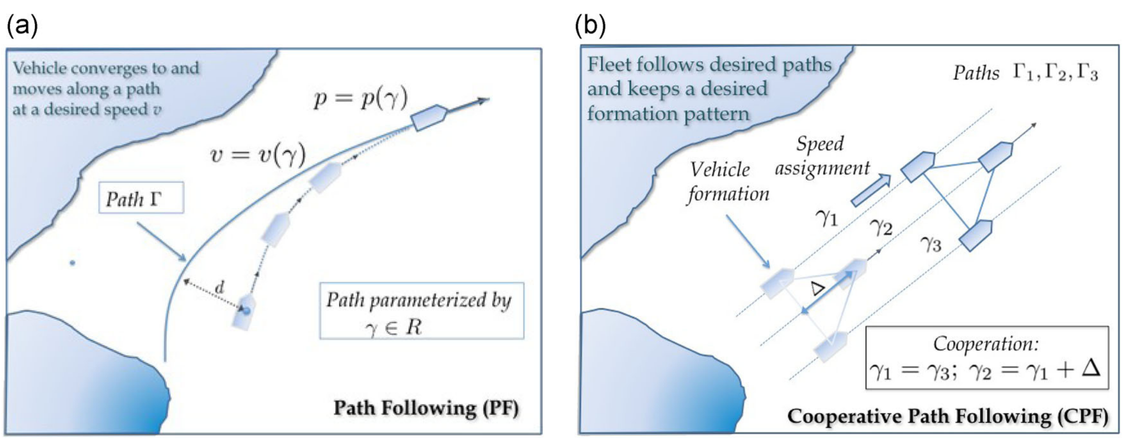

FIGURE 7 Main concepts and variables of (a) path following and (b) cooperative path following

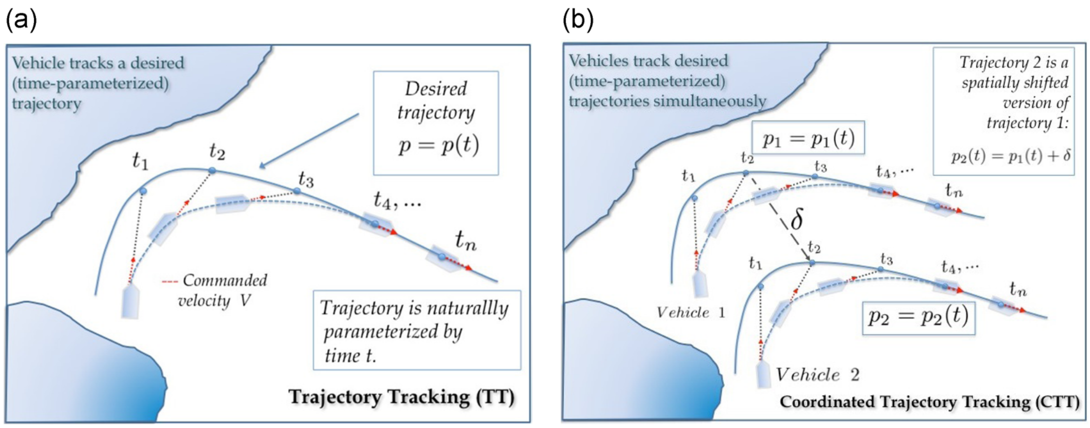

FIGURE 8 Main concepts and variables of (a) trajectory tracking and (b) coordinated trajectory tracking

away from each other, launching them along planned trajectories, optimally designed to avoid collisions and streamer entanglement and steering the fleet of vehicles to be at desired poses at the same time, from which the actual CPF and CTT algorithms could be safely started. In particular, regarding the trajectory planning solution, the main idea was to employ a decoupled prioritized motion-planning strategy (Van Den Berg & Overmars, 2005) where the global plan is constructed iteratively, starting from the highest priority vehicle. Lower priority ones will take the plan of higher priority ones into account, as moving obstacles. Further technical details about the multivehicle decentralized motion planning procedure adopted are reported in Volpi et al. (2018).

5 | THE WIMUST SOFTWARE ARCHITECTURE

This section presents the structure of the WiMUST software architecture based on the Robot Operating System (ROS) (Quigley et al., 2009). The first architectural decision was to run separate ROS masters on each robot, and one on the C2 console side. Indeed, if only a single ROS master on the console were employed, the AUVs would lose connection immediately once underwater. Furthermore, having a single master even between just the surface vehicles is impractical. In fact, ROS uses the Transmission Control Protocol (TCP) for its message exchange system, which guarantees the delivery of every packet in order of transmission. Hence, received packets are delayed until the previous ones have been successfully delivered and acknowledged. While the guarantee of delivery, despite the delay, could be useful for a message containing commands such as "start mission," it would be definitively a drawback for feedback messages, where only the latest one is important, and its delay should be kept small. Hence, the decision was to develop custom-made ROS bridges, one on each robot, exchanging data over User Data Protocol (UDP) sockets, which provide connectionless communication channels with no guarantee of delivery, but also without delaying packets that are received.

To further improve the reusability of the software among the heterogeneous fleet of robots, a key decision was to develop the so-called "Vehicle Wrappers" nodes. These ROS nodes deal with the pre-existing software of the robots, which is, of course, quite different for the Medusa, Folaga, Delfim, and ULISSE vehicles. However, by exposing a common interface, agreed between all the vehicle providers, all the other ROS nodes could be developed once, reducing drastically the development time of the WiMUST software architecture. Only tuning parameters needed to be adjusted depending on the particular vehicle.

Following these general design philosophies, the following sections first outline the acoustic software architecture in charge of managing the data exchange between the surface and underwater vehicles. Then, the Guidance, Navigation, and Control (GNC) architectures of the ASVs and AUVs are detailed. Finally, the C2 console is described.

5.1 | Acoustic software architecture

Figure 9 shows the main modules composing the acoustic software architecture in the anchor ASVs and in the AUVs. Starting from the architecture of the anchor ASVs, the "Vehicle Wrapper" periodically outputs the current position, speed, and heading of the platform. The "Acoustic Bridge" is instead a simple ROS node in charge of taking the data from the ROS network and creating an acoustic message, serializing and compressing data to fit the 32 bytes allowed for the acoustic packet. The "Interrogation" module is the one in charge of deciding when a message should be sent by a particular anchor, at fixed slots in time, since all surface vehicles are synchronized. In addition to the anchor's position, the serialized data contains the leader's position (for tracking) and some basic commands (such as start/abort mission), whenever they are received from the C2 console through the ROS Wi-Fi Bridge.

If the anchor is also equipped with an HF modem, then it will receive feedback from the interrogated vehicles, namely their estimated position and some qualitative indicators of the seismic data being collected. Once received through the HF modem, such information is decoded by the Acoustic Bridge and forwarded for diagnostics to the C2 console through the "ROS-WiFi bridge" node.

The architecture on the AUVs is basically the dual of that on the anchor vehicles. We highlight the fact that the "Driver" will also publish

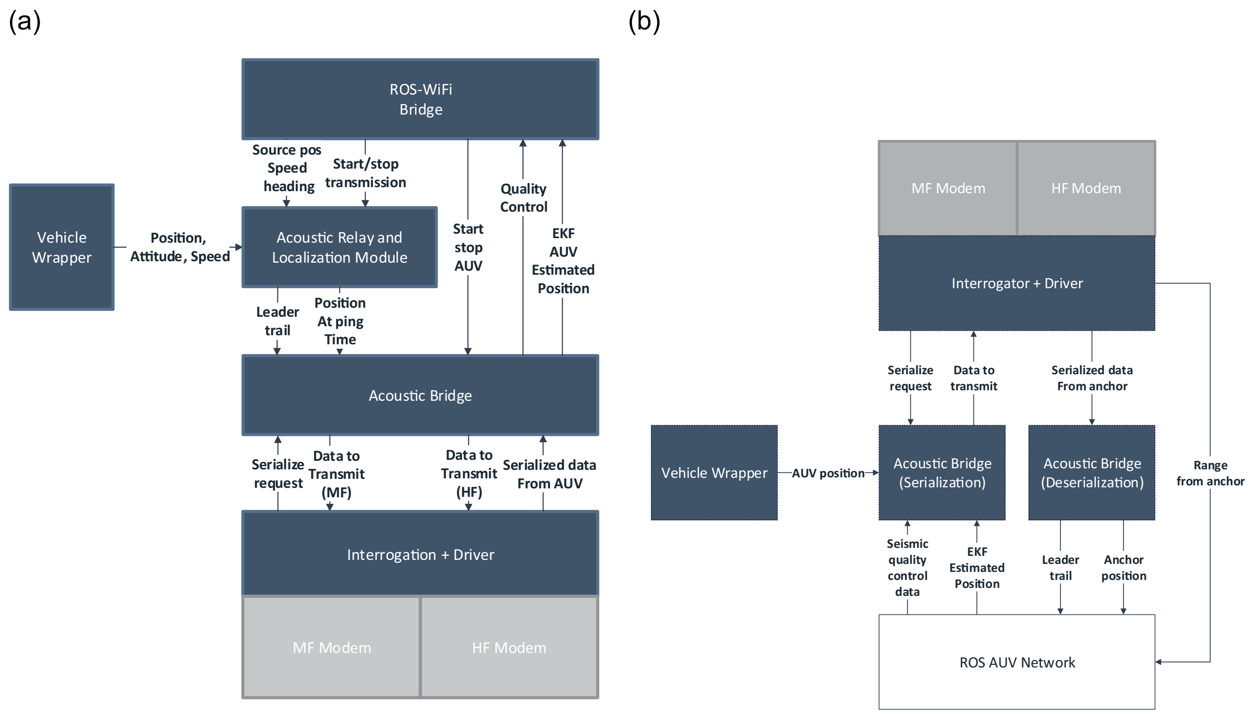

FIGURE 9 Acoustic communications software architecture running on (a) anchor autonomous surface vehicles (ASVs) and (b) autonomous underwater vehicles (AUVs). The "Acoustic Bridge" module takes care of serializing and compressing the data toward the acoustic channel and vice versa. The "Interrogation" module is instead in charge of deciding when an anchor ASV should broadcast its information to the AUVs

the range from the anchor and make this important data available in the ROS network, to be used by the EKF filter for estimating the AUV position. Furthermore, once interrogated through the HF modem, the "Interrogator" module will respond with the most recent quality control data and EKF-estimated position, as mentioned above.

5.2 | GNC software architecture of the ASVs

The main elements of the GNC architecture of each surface vehicle carrying the acoustic sources are outlined in Figure 10. In particular, the "Vehicle Wrapper" accepts as inputs surge and heading references. This interface is exploited by two external guidance controllers. The first, called "Goto Formation Controller," implements a trajectory controller to track the desired trajectory output of the GTF planning module described in Section 4.3 and received through the "ROS Wi-Fi Bridge." The second one, called "Cooperative Path Following controller," implements the CPF algorithm. The surface vehicles coordinate themselves through an exchange of data that goes through the "ROS Wi-Fi Bridge," to follow desired paths in a coordinated manner and complying with the stringent seismic surveying requirements.

5.3 | GNC software architecture of the AUVs

The structure of the GNC onboard the AUVs is composed of several modules and is presented in Figure 11. The "Vehicle Wrapper" receives the thruster commands, computed by vehicle-specific "Inner Control Loops" modules. These modules, similar to those on the ASVs, receive as reference inputs the desired values of depth (predefined), desired heading, and surge speed, computed by two external guidance controllers, named the "Tracking Controller" and the "Goto Formation Controller." The former implements the CTT algorithm described in Section 4.2, and takes as input the leader trajectory fitted by the "Formation Leader Navigation & Buffer module" based on the leader's positions received through the acoustic communications. The "Goto Formation Controller" is the same as that on the ASVs, and is only used on the surface during the vehicle's deployment to reach the initial formation position. Finally, the controllers and inner loops exploit the navigation data coming from the EKF described in Section 3.1.1. A similar GNC architecture is used by all the additional anchor ASVs, which track the leader of the formation while at the surface.

5.4 | Command and control console

An additional software block composing the overall WiMUST architecture is the Command and Control Console. In particular, the Console node receives the position from all the robots and displays the information in the Graphical User Interface (GUI), shown in Figure 12. The GUI is able to relay to the "Mission Planner" module the command to compute the GTF trajectories,

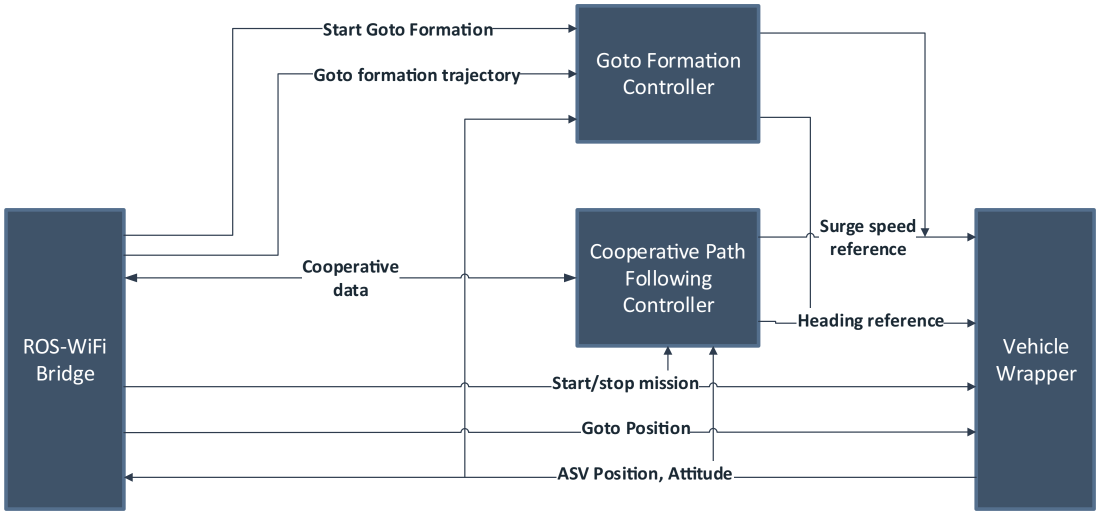

FIGURE 10 Main modules composing the GNC software architecture of the WiMUST autonomous surface vehicles (ASVs). Once deployed in the field, the "Goto Formation Controller" is used to simultaneously drive all the robots to the initial formation, and then the "Cooperative Path Following Controller" is used to maintain the ASVs in formation

to generate start/stop mission commands for the fleet of robots, and to command the vehicles to specific positions (waypoints). Once the GTF trajectories have been generated, they are sent through the "ROS Wi-Fi Bridge" to each vehicle and displayed on the GUI. Finally, the "ROS Wi-Fi Bridge" receives the position of the ASVs, of the AUVs (from the anchors), and the seismic quality control data (from the ASVs with the HF modem), which are logged, on a per mission basis, by the Multitrace software.

6 | PRELIMINARY FIELD CAMPAIGNS: INTEGRATION EFFORTS AND LESSONS LEARNT

This section describes the preliminary field campaigns that were held during the WiMUST project, with the focus of showing the lessons learnt, leading to the final system design, as presented in the previous sections.

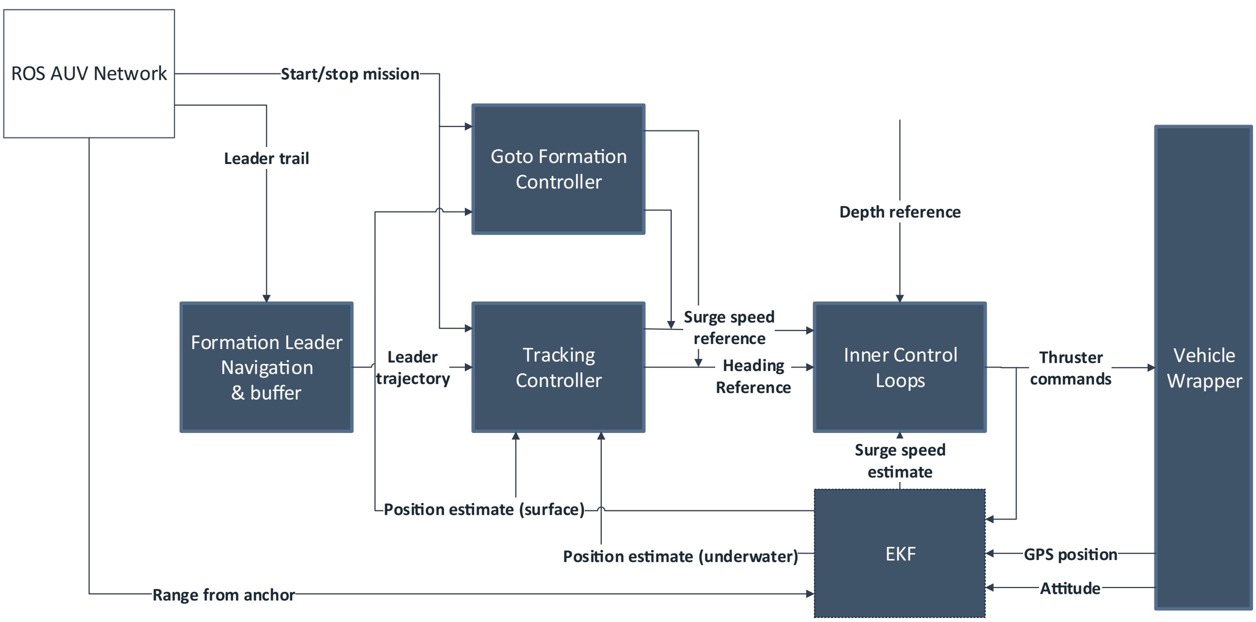

FIGURE 11 Main modules composing the GNC software architecture of the WiMUST autonomous underwater vehicles (AUVs). Once deployed on the field, the "Goto Formation Controller" is used to simultaneously drive all the robots to the initial formation. Then, the AUVs dive and the "Tracking Controller" is used to maintaining the AUVs in formation, following the leader's trajectory estimated by the "Formation Leader Navigation & Buffer" module

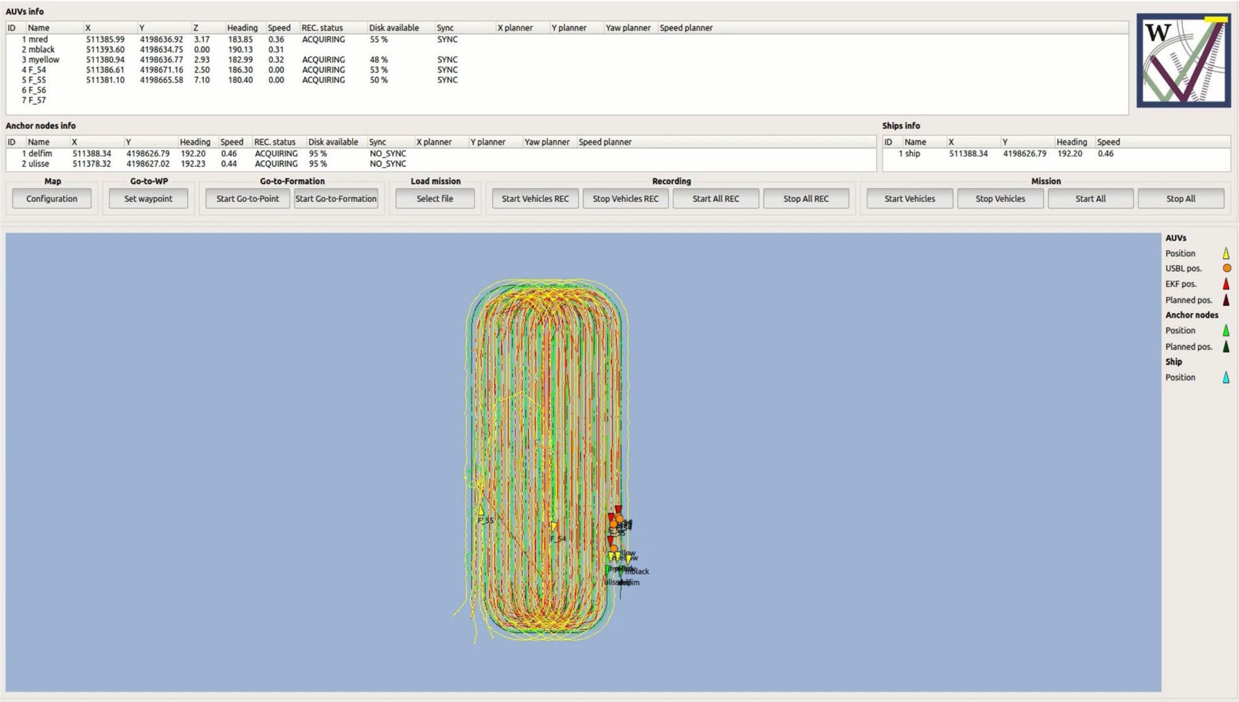

FIGURE 12 The WiMUST Command and Control Console. The screenshot shows the data as displayed during the WiMUST Sines 2018 survey

6.1 | First integration campaign: November 2016

A first, week-long, full-scale integration campaign was held in November 2016, in Sines, Portugal. In the campaign, one acoustic sparker was either moored in the operating area or towed by a manned boat, and the ASVs were acting as anchor nodes only.

The first lesson learnt was that it is very difficult to coordinate a manned boat towing a sparker with the AUVs and ASVs. As a preliminary observation, it should be noticed that to mimic traditional survey methods, the ship towed source and the AUVs should be accurately time-synchronized and have the same speed for spatial synchronization. This second requirement turned out to be a problem since the maximum speed of the WiMUST AUVs was too small for a medium-sized manned vessel. The ship used in these experiments, shown in Figure 13, was not very maneuverable at low speeds, and as a consequence, it could not perform accurate path following. To solve this problem, we first have investigated alternative survey patterns that would not require the AUVs and the ship to move at the same speed. Circling and looming strategies were investigated, but were deemed unfeasible as the resulting paths for the ship would have been geometrically complex and required the execution of path following maneuver at possibly varying speed. Based on the experience of the partners, it was concluded that the pilots in charge of performing seismic acquisition missions would not have considered such paths acceptable. In addition, notice that the coordination of the man-piloted ship with the AUVs would have imposed nontrivial control and human–machine interface issues to be tackled. Therefore, the final solution was to develop ASVs capable of carrying the acoustic sources, removing the need of a manned ship during the seismic survey. In hindsight, this turned out to be one of

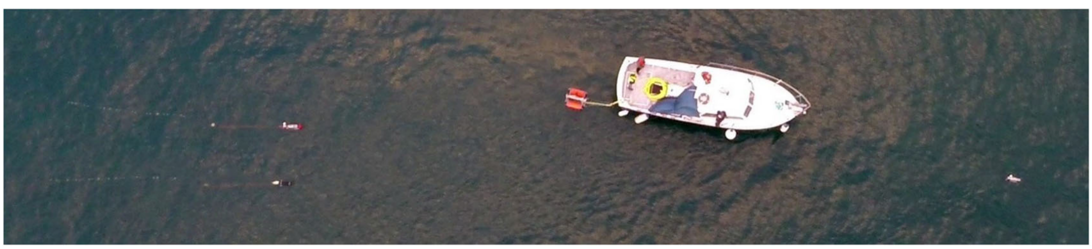

FIGURE 13 A manned boat towing a sparker in coordination with the autonomous underwater vehicles (AUVs) during the first full-scale integration campaign. These tests were instrumental to the decision of substituting the manned boat with autonomous surface vehicles due to the difficulty in coordinating manned vehicles with the AUVs

the key contributions of the project, for it paves the way for the replacement of expensive surface vessels by cost-effective marine robots.

The second lesson learnt was that the streamers' original length of 16 m was too big for the AUVs available for the project. Indeed, Figure 14 shows that the streamer shape was far from ideal during the trials. In fact, due to the relatively low speed achieved by the vehicles (0.6 m/s nominal), the drag caused by the cloth placed at the end of the streamer (to augment drag locally) did not impart enough tension on the streamer as it would be required to straighten the streamers. The fact that the streamer shape was far from a straight line could negatively impact on the quality of the data acquired by the seismic system. Hence, it was decided to reduce the length of the streamers to 8 m.

6.2 | Second integration campaign: July 2017

A second, 2 weeks long integration campaign was held in Sines, Portugal, in July 2017. The major result of this integration campaign was that the acoustic sources were successfully installed, along with their power supplies and generators, on top of the two ASVs used in the project. To the best of our knowledge, this was the first time where a small-scale seismic survey was carried with acoustic sources carried by autonomous vessels (Figure 15).

6.3 | Further integration campaigns

Three further major field campaigns were necessary to complete the WiMUST system integration. The third campaign was held at the SeaLAB joint laboratory of ISME and the naval experimentation and support center CSSN of the Italian Navy in La Spezia (Italy) from 25th to 29th September 2017. During this campaign, the GTF and navigation subsystems were integrated and tested in the Folaga AUVs. Moreover, HF modems and their software interface were preliminarily tested. The fourth campaign was held at the Lisbon Expo Dock, from 16th to 27th October 2017. In this campaign, the CPF algorithm between the catamarans was implemented and successfully tested. Furthermore, a complete mission (lasting around 2 h) with five vehicles was performed. Finally, the GTF algorithm was employed and tested with multiple vehicles. A final integration campaign was held again in Lisbon Expo Dock, from December 4 to 13, 2017. This campaign was dedicated to the integration of commands within the acoustic communications architecture, in both the MF and HF modems.

7 | AUTONOMOUS GEOTECHNICAL SURVEY IN OPEN SEA: FIELD RESULTS

This section presents the final survey experiment that was done in the scope of the WiMUST project in Sines, Portugal. A summary of these results was anticipated in Indiveri (2018). The final experiment

FIGURE 14 Images of 16 m long streamers towed by the autonomous underwater vehicles (AUVs) during the first integration campaign: aerial (bottom) and underwater (top) views. As in images shown, the streamer shape while being towed was far from ideal due to the low speed of the AUVs. After these trials, it was decided to reduce the streamer length to 8 m

FIGURE 15 An image captured during the second integration campaign held in July 2017 trials, showing a major milestone of the WiMUST project: the first small survey where two acoustic sources were successfully installed on the autonomous surface vehicles

consisted of a 2 h and 15 min long survey in the open sea, covering an area of approximately 100 ×200 m just outside the Sines harbor. The fleet of robots that was employed in the experiment was the following one:

- DELFIM (ASV) (Alves et al., 2006), acting as a formation leader, carrying a sparker, and acting as a navigation anchor, performing CPF with ULISSE.
- ULISSE (ASV) (Antonelli et al., 2018), carrying a sparker and performing CPF with DELFIM.
- MBLACK (Medusa ASV Abreu, Botelho, et al., 2016), acting as a navigation anchor, tracking the formation leader.
- MRED and MYELLOW (Medusa AUVs), F1 and F2 (Folaga AUVs Alvarez et al., 2009), each of them tracking the formation leader, towing streamers, and acquiring seismic data.

7.1 | Design of a WiMUST survey

The design of a survey mission required the execution of the following steps:

- A suitable area outside the Sines harbor was selected for the open sea survey. The rationale behind the choice of the area was the existence of some identifiable underwater geological feature, to check if the acquired seismic images were correct. To this purpose, a *scout survey* was conducted during late 2016 with traditional methods, and a suitable area was identified. More in detail, the geology of the survey area consists of a thin veneer of Holocene marine sands up to 5 m thick covering the Sines subvolcanic massif basement, part of the “Late Cretaceous Iberian Alkaline Province” (Macintyre & Berger, 1982; Rock, 1982) that is found in the West Iberia Margin, in northern Spain, and in the Pyrenees. The crystalline basement rocks are believed to be gabbros, diorites, and syenites in varying states of weathering. Given that the sparker source is not suitable to image crystalline rocks, the imaging goal of the test was to resolve the morphology of the subcropping basement and thickness of the sediment cover.
- A *race track* path, as depicted in Figure 16, was defined to cover the target area. This reference path was followed by the DELFIM and ULISSE using the CPF algorithm explained in the previous section. The Medusa MBLACK (anchor) and the AUVs were tracking DELFIM, hence following this path indirectly.

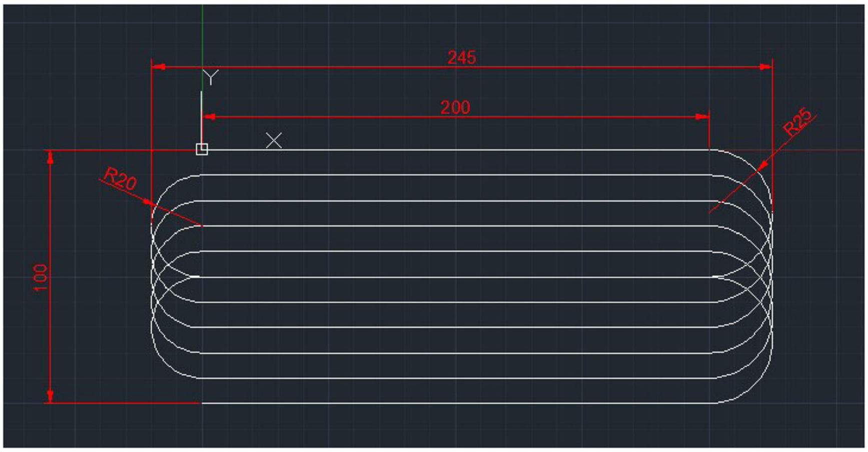

FIGURE 16 The “race-track” path to be executed by the vehicle formation during the Sines 2018 WiMUST survey

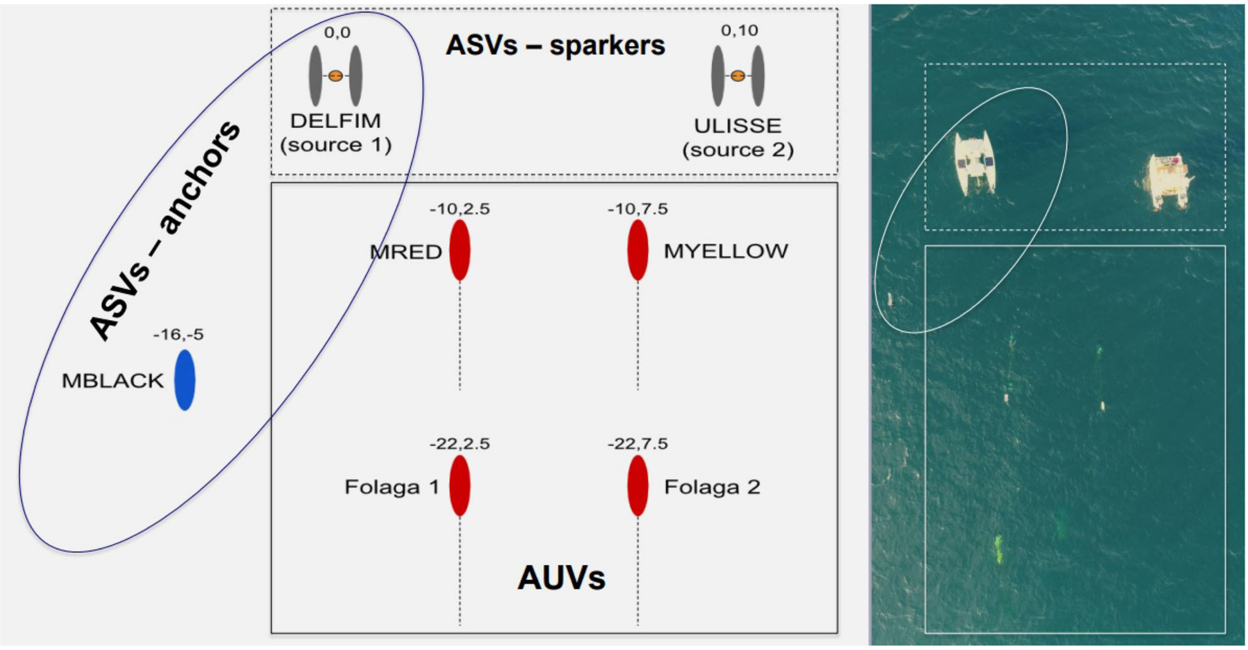

FIGURE 17 The geometry of the formation of the Sines 2018 WiMUST survey. The numbers near the vehicles indicate their position (in meters) with respect to DELFIM, that is, the formation leader. ASV, autonomous surface vehicle; AUV, autonomous underwater vehicle

- The desired formation was specified, as shown in Figure 17. The relative positions of the ASVs carrying the sparkers and the AUVs were dictated by seismic imaging considerations. This posed constraints on the position of the HF modems on both ASVs and AUVs, due to their high directivity. Indeed, HF modems were installed to point toward the back of the ASVs, while they were positioned in the front part of the AUVs. The positioning of anchors ASVs is instead related only to having a good geometry for the localization.
- Finally, the survey speed was designed to be 0.4 m/s with respect to the ground during straight lines. The speed limit was mainly due to the limited towing capacity of the vehicles and the maximum velocity of the vehicles on the outer parts of the curves joining the straight legs of the survey. Considering the length of the path and the nominal speed, it was expected that the survey would last approximately 2 h and 15 min.

Table 1 summarizes the main parameters used for the Sines 2018 survey, divided into three main blocks: survey area and mission parameters, formation, and seismic data acquisition parameters.

7.2 | Mission execution

The survey was executed on January 24, 2018. The vehicles were deployed in different positions and sent to reasonable starting points near the beginning of the race-track path. Each of the vehicles was sent to GNSS coordinates compatible with its relative position in the formation to prevent vehicles crossing each other to reach the desired

TABLE 1 Key parameters for the Sines 2018 final survey

Parameter	Value
Nominal forward speed	0.4 m/s
Distance between legs	5 m
Area to be surveyed	200 × 100 m
Average operational area depth	30 m
Formation (*x*, *y*, *z* offset in meters from the leader)	DELFIM (leader): 0, 0, 0
	ULISSE: 0, 10, 0
	MBLACK: −16, −5, 0
	MRED: −10, 2.5, 3
	MYELLOW: −10, 7.5, 3
	F1: −22, 2.5, 5
	F2: −22, 7.5, 8
Hydrophones number	24 in total, as follows: 4 AUVs, 1 streamer per AUV, 8 hydrophones per streamer
Hydrophones spacing	1 m along the streamer
Shot interval and pattern	Each source firing every 500 ms alternated every 250 ms
Sparker voltage	5 kV
Sampling rate	10 kHz

Abbreviation: AUV, autonomous underwater vehicle.

formation geometry. Every time a vehicle was reaching its commanded position, it entered a "hold" position control mode. In particular, ULISSE, DELFIM, and Medusa vehicles were estimating the current direction and placed themselves against the current. Folaga vehicles were instead keeping the desired heading, returning to the desired position if they were drifting away above a certain distance, with a hysteresis zone to prevent chattering around the threshold.

Once all the vehicles were in the required positions, the two catamarans were started. Once they were correctly executing the CPF maneuver, the Medusa vehicles were started. Shortly afterward, the two Folaga vehicles were started as well. Once the vehicles were all correctly proceeding in formation, a manual command to dive was given to the AUVs. Medusa vehicles were commanded to dive to 3 m, Folaga F1 to 5 m and Folaga F2 to 8 m. The reason for the different desired depths is twofold. First, the Medusa was towing a small buoy with a wireless communication antenna. The cable connecting the buoy with the antenna to the robot was limited to about 3 m in length. The second reason is that, given the relatively short distances between the vehicles, different desired depths were substantially decreasing the possibility of mutual collision or entanglements between the streamers if anything had gone wrong. However, before the start of the mission, as the Folaga F1 was holding its position, the rope tying its buoy got progressively entangled with its antenna, becoming shorter than expected. Hence, once submerged, Folaga F1 could not reach its prescribed depth, since the rope was too short and the buoy was remaining on the surface, slowing the AUV down and letting it fall behind the formation. Therefore, a "stop mission" command was issued with the WiMUST C2 console and this message was routed to Folaga F1 through the MF modems of the anchors. Once Folaga F1 resurfaced, it was manually sent to the back of the formation. Once in a safe position, a new "start mission" command was issued, with a lower depth setpoint, and sent through wireless communications.

Figure 18 shows the different AUV positions in East, North coordinates. These positions were estimated internally by the navigation system of each AUV. Looking at Figure 18, the resurfacing and rejoining maneuver that Folaga F1 performed at the very beginning of the survey is very evident. Figure 19 shows the norm of the tracking error computed by the CTT controller. It shows the belief of each AUV on its error with respect to the desired positions. Notice how Folaga F1 has higher peaks of error during the arcs of the trajectory with respect to its twin Folaga F2. While this may be caused by slightly different performances and the wearing of the actuators, it is very likely that the true reason is the position of Folaga F1 on the external part of the formation, which implies a higher requested surge speed, possibly above the actual limits of the Folagas with the streamer. Hence, in a future implementation of the WiMUST concept, this could be certainly tackled by having more powerful actuators to guarantee that vehicles on the external part of the arcs can satisfy their speed requirements.

In what regards the performance of the complete ensemble of robotic vehicles, one of the requirements that were set forth at the initial stage of the project by seismic experts was that each vehicle, and therefore its streamer, was required to stay within 4 m of their nominal relative position in the group. As can be seen in the figure, the error is almost everywhere below 4 m, except for a few moments during the curves. This allows us to conclude that the systems developed met this important requirement.

Another requirement that was specified at the start of the project was to always have a minimum distance of at least 4 m between the vehicles, to ensure the safety of the robots. Figure 20 depicts the distance between AUVs on the same rows, that is, the distance between Folaga F1 and Folaga F2 and the one between Medusa MRED and Medusa MYELLOW. Looking at the desired formation presented in Section 7.1, the nominal distance should be 5 m. The figure shows how the distance falls below the threshold of 4 m only for a few time instants during the trajectory arcs. The explanation of this phenomenon is likely the same one that was given above, namely a surge request exceeding the actuation limits during curves. Overall, we can conclude that the requirement of minimum inter-vehicle distance was met with success.

Finally, in terms of the MF acoustic communication performances, the chosen metric was the probability of first-attempt

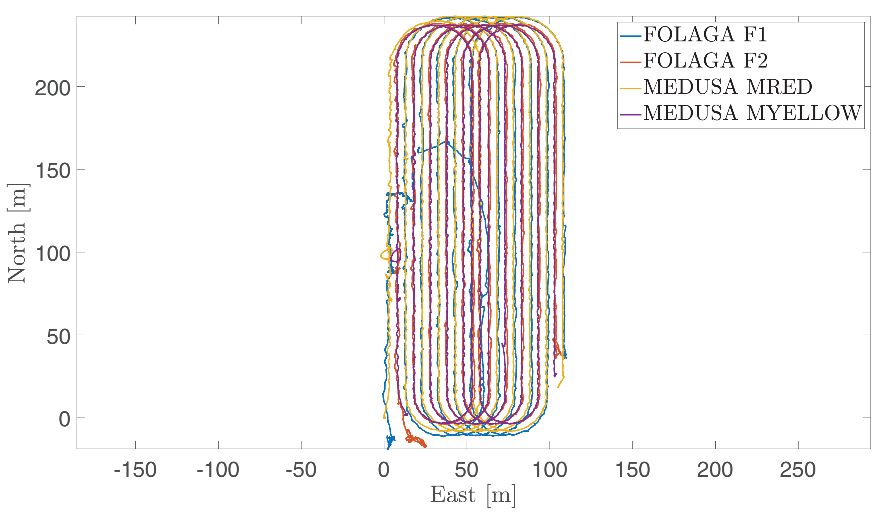

FIGURE 18 Final robotics-based survey; navigation performance. Estimated (EKF) positions of the autonomous underwater vehicles during the survey. It can be noticed how Folaga F1 stops following the formation during the initial leg due to the short rope problem and later rejoins it during the second leg

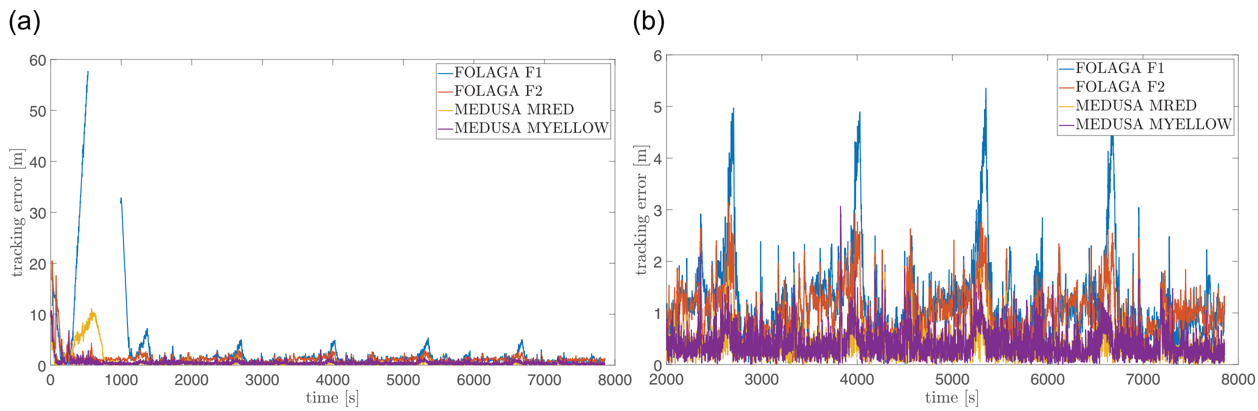

FIGURE 19 Final robotics-based survey; tracking error performance. Estimated autonomous underwater vehicle (AUV) tracking error norm during the survey. (a) Time history of the whole survey and (b) zoom after F1 rejoined formation correctly. The peaks of the tracking error are in correspondence of the curves of the survey, where the AUV on the outer part of the curve completely saturates its actuation limits

delivery of a packet of up to 512 bits of data, which was between 0.9 and 1.0, when the emitted signals level of the MF and HF modems were comparable. If the HF signal levels were 12 dB higher than the MF ones, the probability of successful first-attempt data delivery dropped to 0.7. With comparable signal levels, the demonstrated values of effective HF modem bitrate were between 2.3 and 5.2 kbit/s (with an average value above 3.5 kbit/s), allowing the AUVs to send quality control information (estimated in 10 kbit size) on average within 3 s (Kebkal et al., 2019).

7.3 | Seismic acquisition results

From a seismic user point of view, the main results are the seismic images reported in Figure 21, which cover the survey area of approximately 20,000 m^2 and have a 1-m bin size and up to 10 ms two-way time penetration below the seabed (as expected for the site conditions). Data processing was carried out with RadexPro from Decogeophysical following GeoSurveys industry standards for 3D ultrahigh-resolution (UHR) seismic data. The typical flow consists of signature deconvolution, frequency band-pass filtering and F-K filtering, normal moveout (NMO) correction, heave corrections and tidal corrections, common-depth-point (CDP) stack, K-K filtering to remove acquisition footprint effects, and Kirchhoff migration. The images allow for the identification of two relevant geological features present on-site at the imaged depths, that is, a soft sediment cover with a semitransparent low amplitude reflections facies overlaying a chaotic facies corresponding to an igneous basement. Furthermore, the images show no sign of hardware/positioning artifacts.

The images produced from the data acquired by the WiMUST system are clear proof that the essential requirements for imaging were met by the WiMUST system. Indeed, any major problem in the time synchronization of systems, formation stability, navigation plan compliance, or in the operation of the seismic apparatuses would have clearly compromised the image in an unambiguous manner.

8 | CONCLUSIONS

The paper presented the main robotic technologies and methodologies employed in the scope of the successful H2020 WiMUST project. Two catamarans were used to autonomously carry the

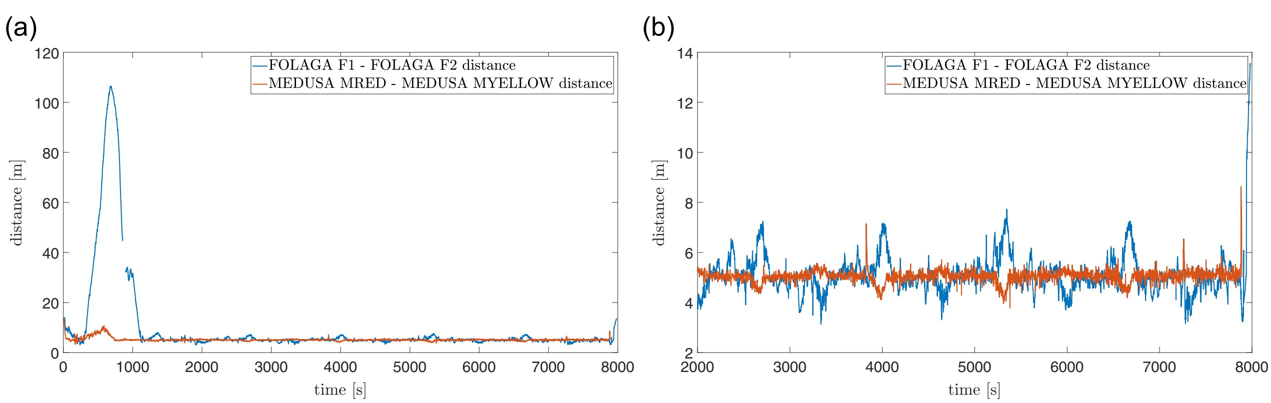

FIGURE 20 Final robotics-based survey; distance between vehicles. The plot shows the distance between AUVs in the same row, which should be 5 m. (a) Time history of the whole survey and (b) zoom after F1 rejoined formation correctly. The peaks are in correspondence of the curves of the survey

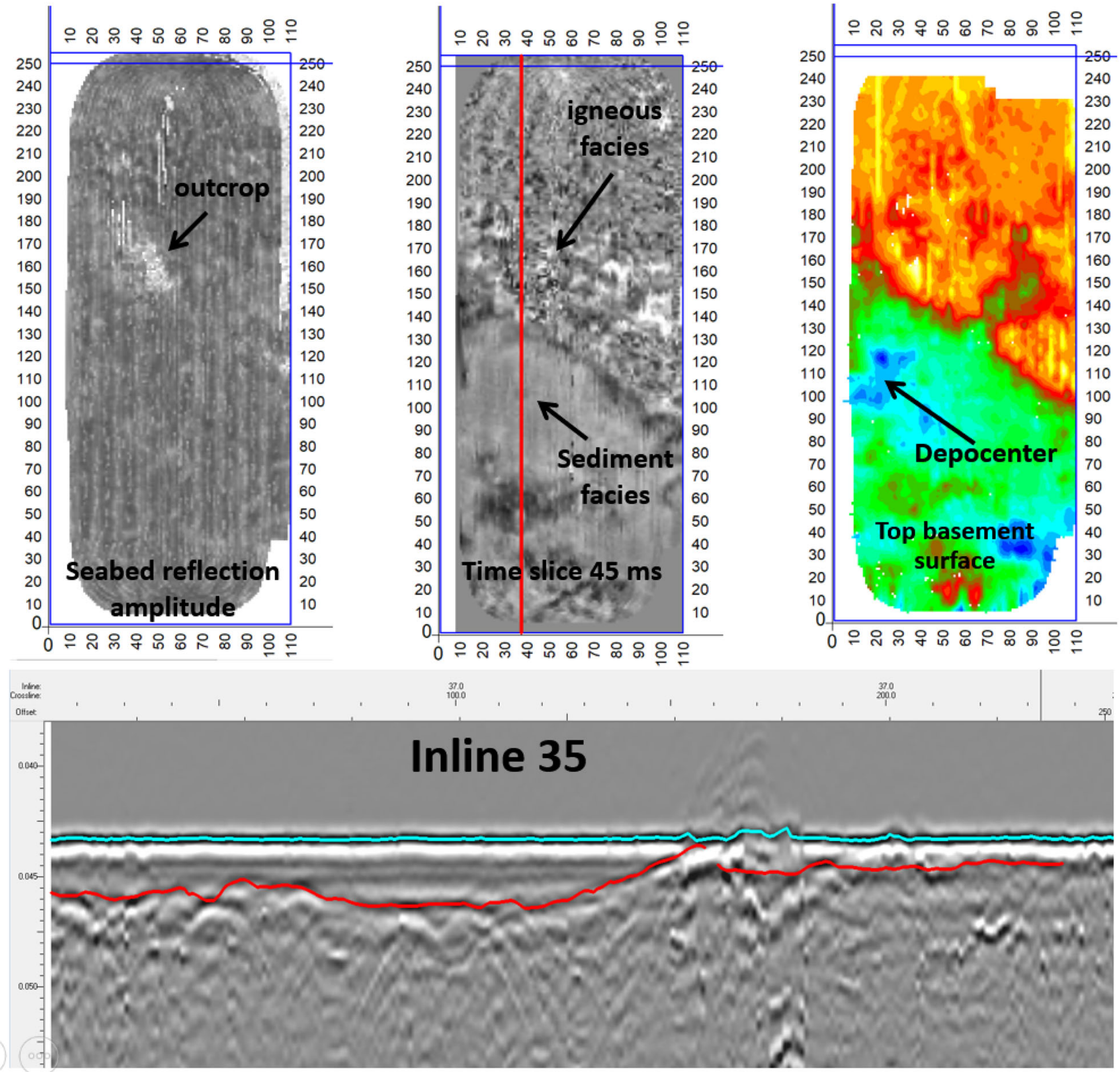

FIGURE 21 Seismic images acquired by the WIMUST spread on the project's final trials. Top left—seabed reflection amplitude. Top middle—time slice at 45 ms two-way time, showing the acoustic facies of sediments and of basaltic rocks. Top right—top basement surface representation (colors represent two-way time) showing the relevant sediment depocenters. Bottom—profile of inline 35 (images courtesy of Geo Surveys)

acoustic sources, executing a coordinated path following maneuver along a designed race-track pattern. Executing the CPF algorithm has ensured that the specifications of the seismic acquisition geometry were successfully met by the WiMUST system, and furthermore, has ensured that no collisions between the two catamarans occurred. A further surface vehicle was employed to aid the navigation of the four underwater vehicles. The latter was employed to tow short streamers, collecting the seismic data. Thanks to the atomic clocks embedded within each vehicle's acoustic modem, the data were synchronized within the timing thresholds necessary to reconstruct seismic images without artifacts, as shown in this paper. The final survey experiment consisted in a 2 h and 15 min long survey in the open sea, covering an area approximately of 100 × 200 m, in the Atlantic Ocean, just outside the Sines harbor. The experiment has shown all the potentialities of the WiMUST approach to autonomous seismic surveys. With such a setup, WiMUST paved the way for performing some specific geotechnical surveys (e.g., in shallow water and in encumbering environments) without the need to resort to very expensive manned vessels.

The results represent a major milestone in autonomous robotic geotechnical surveying. Future work, beyond the WiMUST project, might focus on extending this system to be multisensor, for example, by integrating ocean bottom nodes with geophones or AUVs towing magnetometers, which could allow for even better ocean bottom model reconstruction.

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REFERENCES

Abreu, P., Antonelli, G., Arrichiello, F., Caffaz, A., Caiti, A., Casalino, G., … Turetta, A. (2016). Widely scalable mobile underwater sonar technology: An overview of the H2020 WiMUST project. *Marine Technology Society Journal*, *50*(4), 42–53. http://dx.doi.org/10.4031/mtsj.50.4.3

Abreu, P. C., Botelho, J., Góis, P., Pascoal, A., Ribeiro, J., Ribeiro, M., & Silva, H. (2016). The MEDUSA class of autonomous marine vehicles and their role in EU projects. In *OCEANS 2016—Shanghai* (pp. 1–10). Shaghai, China: IEEE.

Aguiar, A. P., and Pascoal, A. M. (2007). Coordinated path-following control for nonlinear systems with logic-based communication. In *2007 46th IEEE Conference on Decision and Control*. New Orleans, LA, USA: IEEE.

Aicardi, M., Casalino, G., Indiveri, G., Aguiar, A., Encarnaçao, P., and Pascoal, A. (2001). A planar path following controller for underactuated marine vehicles. In *Ninth IEEE Mediterranean Conference on Control and Automation*. Dubrovnik: IEEE.

Alvarez, A., Caffaz, A., Caiti, A., Casalino, G., Gualdesi, L., Turetta, A., & Viviani, R. (2009). Fòlaga: A low-cost autonomous underwater vehicle combining glider and AUV capabilities. *Ocean Engineering*, *36*(1), 24–38. https://doi.org/10.1016/j.oceaneng.2008.08.014

Alves, J., Oliveira, P., Oliveira, R., Pascoal, A., Rufino, M., Sebastiao, L., and Silvestre, C. (2006). Vehicle and mission control of the DELFIM autonomous surface craft. In *2006 14th Mediterranean Conference on Control and Automation* (pp. 1–6). Ancona: IEEE.

Antonelli, G., Arrichiello, F., Caiti, A., Casalino, G., De Palma, D., Indiveri, G., … Simetti, E. (2018). ISME activity on the use of autonomous surface and underwater vehicles for acoustic surveys at sea. *ACTA IMEKO*, *7*(2), 24–31. https://doi.org/10.21014/acta_imeko.v7i2.539

Asakawa, E., Murakami, F., Tara, K., Saito, S., Tsukahara, H., and Lee, S. (2018). Multi-stage seismic survey for seafloor massive sulphide (SMS) exploration. In *2018 OCEANS—MTS/IEEE Kobe Techno-Oceans (OTO)* (pp. 1–4).

Bandyopadhyay, P. R. (2005). Trends in biorobotic autonomous undersea vehicles. *IEEE Journal of Oceanic Engineering*, *30*(1), 109–139. https://doi.org/10.1109/joe.2005.843748

Bibuli, M., Bruzzone, G., Caccia, M., & Lapierre, L. (2009). Path-following algorithms and experiments for an unmanned surface vehicle. *Journal of Field Robotics*, *26*(8), 669–688.

Birk, A., Doernbach, T., Mueller, C., Luczynski, T., Chavez, A. G., Koehntopp, D., … Letier, P. (2018). Dexterous underwater manipulation from onshore locations: Streamlining efficiencies for remotely operated underwater vehicles. *IEEE Robotics Automation Magazine*, *25*(4), 24–33.

Camilli, R., Reddy, C. M., Yoerger, D. R., Van Mooy, B. A., Jakuba, M. V., Kinsey, J. C., … Maloney, J. V. (2010). Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. *Science*, *330*(6001), 201–204.

Casalino, G., Caiti, A., Turetta, A., & Simetti, E. (2011). RT2: Real-time ray-tracing for underwater range evaluation. *Intelligent Service Robotics*, *4*(4), 259–270. https://doi.org/10.1007/s11370-011-0093-8

Cruz, N. A., Ferreira, B. M., Kebkal, O., Matos, A. C., Petrioli, C., Petroccia, R., & Spaccini, D. (2013). Investigation of underwater acoustic networking enabling the cooperative operation of multiple heterogeneous vehicles. *Marine Technology Society Journal*, *47*(2), 43–58.

Cui, R., Yang, C., Li, Y., & Sharma, S. (2017). Adaptive neural network control of AUVs with control input nonlinearities using reinforcement learning. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *47*(6), 1019–1029.

Eustice, R. M., Singh, H., & Whitcomb, L. L. (2011). Synchronous-clock, one-way-travel-time acoustic navigation for underwater vehicles. *Journal of Field Robotics*, *28*(1), 121–136.

Fairfield, N., Kantor, G., & Wettergreen, D. (2007). Real-time SLAM with octree evidence grids for exploration in underwater tunnels. *Journal of Field Robotics*, *24*(1-2), 03–21.

Fernandes Castro Rego, F., Aguar, A. P., and Pascoal, A. M. (2013). A packet loss compliant logic-based communication algorithm for cooperative path-following control.*IFAC Proceedings Volumes*, *46*(33), 262-267. 9th IFAC Conference on Control Applications in Marine Systems.

Ferri, G., Munafo, A., & LePage, K. D. (2018). An autonomous underwater vehicle data-driven control strategy for target tracking. *IEEE Journal of Oceanic Engineering*, *43*(2), 323–343.

Ferri, G., Munafò, A., Tesei, A., Braca, P., Meyer, F., Pelekanakis, K., … LePage, K. (2017). Cooperative robotic networks for underwater surveillance: an overview. *IET Radar, Sonar & Navigation*, *11*(12), 1740–1761.

Fossen, T. I., Breivik, M., & Skjetne, R. (2003). Line-of-sight path following of underactuated marine craft. *IFAC proceedings volumes*, 36(21), 211–216.

Indiveri, G. (2018). Geotechnical surveys with cooperative autonomous marine vehicles: the ec wimust project. *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*. IEEE, 1–6.

Kebkal, K., Kebkal, O., Glushko, E., Kebkal, V., Sebastiao, L., Pascoal, A., … Indiveri, G. (2017). Underwater acoustic modems with integrated atomic clocks for one-way traveltime underwater vehicle positioning. In *Proceedings of the Underwater Acoustics Conference and Exhibition (UACE)*, 315–324.

Kebkal, K., Kebkal, O., Kebkal, V., Glushko, I., Pascoal, A., Ribeiro, M., & Simetti, E. (2019). Hydro-acoustic communications and networking in contemporary underwater robotics: Instruments and case studies. In F. Elhers (Ed.), *Navigation and control of autonomous marine vehicles*, Transport (pp. 263–300). Institution of Engineering and Technology. https://doi.org/10.1049/PBTR011E_ch10

Kebkal, K., Kebkal, O., Kebkal, V., Sebastiao, L., Pascoal, A., Ribeiro, J., … Mantouka, A. (2017). Performance assessment of underwater acoustic modems operating simultaneously at different frequencies in the presence of background impulsive noise emitted by a sparker. In *Proceedings of the Underwater Acoustics Conference and Exhibition (UACE)*, 325–334.

Leonard, J. J., & Bahr, A. (2016). Autonomous underwater vehicle navigation. In M. R. Dhanak & N. I. Xiros (Eds.), *Springer Handbook of Ocean Engineering* (pp. 341–358). Cham: Springer.

Leonard, N. E., Paley, D. A., Davis, R. E., Fratantoni, D. M., Lekien, F., & Zhang, F. (2010). Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in monterey bay. *Journal of Field Robotics*, *27*(6), 718–740.

Macintyre, R., & Berger, G. (1982). A note on the geochronology of the iberian alkaline province. *Lithos*, *15*(2), 133–136.

Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., … Ng, A. Y. (2009). *Ros: An open-source robot operating system*. ICRA workshop on open source software, Vol. 3, p. 5, Kobe.

Ribas, D., Ridao, P., Tardós, J. D., & Neira, J. (2008). Underwater SLAM in man-made structured environments. *Journal of Field Robotics*, *25*(11–12), 898–921.

Rock, N. (1982). The late cretaceous alkaline igneous province in the Iberian peninsula, and its tectonic significance. *Lithos*, *15*(2), 111–131.

Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., & Perry, M. J. (2004). Underwater gliders for ocean research. *Marine Technology Society Journal*, *38*(2), 73–84.

Simetti, E., Casalino, G., Wanderlingh, F., & Aicardi, M. (2018). Task priority control of underwater intervention systems: Theory and applications. *Ocean Engineering*, *164*, 40–54. https://doi.org/10.1016/j.oceaneng.2018.06.026

Stojanovic, M., & Freitag, L. (2013). Recent trends in underwater acoustic communications. *Marine Technology Society Journal*, *47*(5), 45–50.

Van Den Berg, J. P. and Overmars, M. H. (2005). Prioritized motion planning for multiple robots. In *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 430–435). Edmonton, Alberta, Canada: IEEE.

Vanni, F., Aguiar, A. P., & Pascoal, A. M. (2008). Cooperative path-following of underactuated autonomous marine vehicles with logic-based communication. *IFAC Proceedings Volumes*, *41*(1), 107–112.

Volpi, N. C., Smith, S. C., Pascoal, A. M., Simetti, E., Turetta, A., Alibani, M., & Polani, D. (2018). Decoupled sampling-based motion planning for multiple autonomous marine vehicles. In *OCEANS 2018 MTS/IEEE Charleston* (pp. 1–7). Charleston, SC, USA: IEEE.

Webster, S. E., Eustice, R. M., Singh, H., & Whitcomb, L. L. (2012). Advances in single-beacon one-way-travel-time acoustic navigation for underwater vehicles. *The International Journal of Robotics Research*, *31*(8), 935–950.

Webster, S. E., Walls, J. M., Whitcomb, L. L., & Eustice, R. M. (2013). Decentralized extended information filter for single-beacon cooperative acoustic navigation: Theory and experiments. *IEEE Transactions on Robotics*, *29*(4), 957–974.

Yuh, J. (2000). Design and control of autonomous underwater robots: A survey. *Autonomous Robots*, *8*(1), 7–24.

Yuh, J., Marani, G., & Blidberg, D. R. (2011). Applications of marine robotic vehicles. *Intelligent Service Robotics*, *4*(4), 221–231.

Zeng, Z., Fu, S., Zhang, H., Dong, Y., & Cheng, J. (2017). A survey of underwater optical wireless communications. *IEEE Communications Surveys & Tutorials*, *19*(1), 204–238.

Zereik, E., Bibuli, M., Miskovic, N., Ridao, P., & Pascoal, A. (2018). Challenges and future trends in marine robotics. *Annual Reviews in Control*, *46*, 350–368.

Zhang, F., Marani, G., Smith, R. N., & Choi, H. T. (2015). Future trends in marine robotics [tc spotlight]. *IEEE Robotics & Automation Magazine*, *22*(1), 14–122.

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