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ISME trends: Autonomous Surface and Underwater Vehicles for Geoseismic Survey

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I. ABSTRACT

The paper presents the recent and ongoing activities of the Italian Center named ISME on the use of Autonomous Surface Crafts (ASCs) and Autonomous Underwater Vehicles (AUVs) for geoseismic survey. In particular, the paper will focus on the technologies and the algorithms developed in the framework of the H2020 European Project WiMUST.

II. INTRODUCTION TO THE WIMUST PROJECT

The Interuniversity Center on Integrated Systems for the Marine Environment (ISME) is an Italian Institution that involves a set of Universities (ISME-Nodes) that actively work in the field of marine robotics and acoustic systems. Among the set of activities, ISME has been recently involved in different research projects were ASCs and/or AUVs have been used to acquire data for oceanographic missions as geoseismic survey or adaptive sampling.

Concerning the geoseismic survey, ISME is coordinating the ongoing H2020 Research and Innovation Action funded by the European Commission (Work Programme 2014 - 2015, LEIT- ICT, 5. Leadership in enabling and industrial technologies - Information and Communication Technologies) named Widely scalable Mobile Underwater Sonar Technology (WiMUST); in particular, prof. Giovanni Indiveri from ISME node Lecce is the coordinator of the project.

The project is a 36 months Research and Innovation Action (RIA) having as main objective to design and the test of a system of cooperating Autonomous Underwater Vehicles (AUVs) for geotechnical surveying operations, see [1-3]. To this aim, the WiMUST action involves four Academic Partners (ISME, IST, CINTAL, UH) and 5 Industrial Partners (Graaltech, EvoLogics, CGG, Geo Marine, Geosurveys). In particular, the main goal of the project is to develop robotic technologies exploiting Autonomous Underwater Vehicles for geotechnical surveying and geophysical exploration by means of seismic acoustic surveys. http://www.wimust.eu/

Seismic acoustic surveys at sea are methods for the exploration of the sea bottom and sea subsurface for applications that span from the geophysical domain (e.g. oil & gas) to the geotechnical domain (e.g. civil and commercial applications, underwater constructions). The survey is traditionally performed using a surface vessel carrying one or two powerful acoustic sources, named sparkers, and towing a set of surface streamers equipped with several hydrophones to record acoustic signals. The sparkers generate seismic waves by intermittently releasing electric pulses that produce low frequency sound waves. Such waves travel towards the sea floor and are reflected back to the streamer hydrophones. The speed with which waves return to the surface, registered with the hydrophones, provides valuable information about the properties of the Earths subsurface.

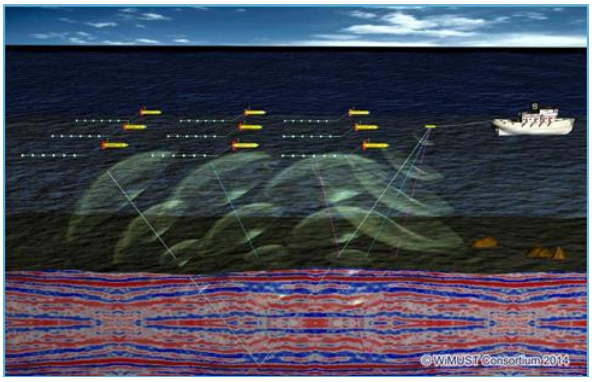

Fig. 1 Sketch of the WiMUST system.

The WiMUST project aims at expanding and improving the functionalities of current cooperative marine robotic systems by effectively enabling distributed acoustic array technologies for seismic surveying. Indeed, the WiMUST system is composed of two ASCs carrying a sparker each, and by a small fleet of AUVs towing streamers equipped with hydrophones to acquire sub-bottom profiling acoustic data. The AUVs towing the streamers can be envisioned as an acoustic array that, by means of the autonomous and coordinated motion among ASCs and

AUVs, can have an adaptive variable geometry. Indeed, by actively controlling the geometry of the robot formation, it becomes possible to change the shape of the acoustic array antenna, according to the needs of the considered application.

The resulting operational flexibility holds potential advantages, as it allows improving the seabed and sub-bottom resolution and obtaining sidelobe rejection at almost any frequency and for any plane. The availability of the proposed system, other than improving the quality of the acquired data, also greatly facilitates the operations at sea, thanks to the lack of physical ties between a surface ship and the acquisition equipment. On the other side, the loss of the towing system introduces high complexity due to the need of ad-hoc cooperative navigation and control architecture for the team of ASCs and AUVs, as well as the establishment of an acoustic communication network. Moreover, the hydrophones' positions, needed for acoustic data processing, can not be easily computed as in the case of surface surveys since the AUVs while diving can not rely on GPS.

III. ISME ACTIVITIES IN THE WIMUST PROJECT

The project is actually at the third year, where most of the hardware and software components have been developed, and where the focus of the project is on the system integration. Among the overall activities of the WiMUST project, the contributions of ISME (nodes of Lecce, Genova, Pisa and Cassino) can be identified in the following activities.

A. DEVELOPMENT OF AN AUTONOMOUS CATAMARAN

The ISME Genova node has designed and realized the ULISSE platform, i.e. the second generation of autonomous surface vehicles, following a previous design created for a private company in 2015. ULISSE is a 3 m long and 1.8 m wide catamaran, built in fiberglass (see. Fig.1). Two carbon fiber bars keep the two hulls together. The catamaran is propelled by two commercial electric motors, of 2 kW electrical power and about 50% propulsive efficiency. The catamaran has been designed capable to transport payloads up to 200 kg.

Both hulls have a dedicated compartment, accessible through a waterproof hatch, that hosts the necessary electronics for control, as well as the batteries. The rest of the hull space is used by a pump system that controls two ballast tanks, which can be used to regulate the pitch of the vehicle and its draft depending on the payload mounted on it.

The vehicle has been designed with the possibility of maximum reconfigurability. In fact, along both hulls there is an aluminum Bosch Rexroth profile, which can be used to fix custom decks hosting the necessary payload for the mission at hand.

In the stern side of the vehicle, two connector boxes allow to turn on and off the system and recharge the batteries. Furthermore, an additional power connector is available to power up payloads, with around 600 W available. Fig. 2 shows the vehicle "naked", without any payload or decks mounted.

Fig. 2. ULISSE with no payload mounted.

Communication with the base station goes through a standard 5 GHz communication system, which proved to be sufficient for the distances that were so far tested (around 300 m). The first engineering tests have shown that the vehicle was capable of a speed of around 4 m/s (about 8 knots) when the propeller were commanded at about 75%. It is therefore estimated that the maximum achievable speed is around 10 knots. Furthermore, the two motors allow for a differential control of the catamaran and thus the vessel can turn on the spot. The maximum rotational speed on the spot is around 25 deg/s.

Fig. 3. ULISSE during WiMUST deployment. The acoustic sparker can be seen in the middle part. The two acoustic modem transducers can be seen near the bow.

In the WiMUST project, ULISSE will carry one of the two acoustic sparkers. The sparker itself has been mounted with a clamp system, exploiting the two carbon fiber bars, in the middle part of the vehicle, in such a way to be at least 30 cm below the water level. The sparker can be seen in Fig. 3. The sparker is powered by a power supply, that charges high-voltage capacitors (4 kV) necessary to create the spark. The power supply has been mounted in a dedicated deck just under the roll bar hosting the antennas, in the stern side, as can be seen in Fig. 4.

Fig. 4 Ulisse ISME Autonomous Catamaran.

The power supply is in turn powered by two motogenerators, that have been fixed in a second deck in the bow side of ULISSE. This second deck also hosts a movable pole that is lowered manually to deploy the acoustic modems transducers. Still in Fig. 3., the two modems transducers can be seen near the vehicle's bow.

The bow deck also hosts an additional waterproof case, containing the modem electronics and an Ethernet switch, which connects the two modems and the sparker triggering electronics to the onboard network and to the outgoing 5 GHz connection.

The catamaran is capable of autonomously navigating on the base of information from onboard sensors, as GPS, IMU, compass, and of the information exchanged with other network nodes (using wi-fi for surface nodes and acoustic modems for communication with underwater nodes).

B. SYSTEM INTEGRATION AND MOTION CONTROL ALGORITHMS FOR CATAMARAN AND FOLAGA AUVS

ISME is responsible for the overall system integration of the WiMUST project, that involves software and hardware integration of the different components of the system, i.e. the different type of autonomous vehicles (Delfim Catamaran from IST, ULISSE catamaran from ISME, 4 Medusa AUVs from IST, 4 Folaga AUVs from ISME and Graaltech), the acoustic communication devices, the streamers with hydrophones and the sparkers. Thus, the system integration deals with issues as: mechatronic integration of the sensing payloads and the communication devices on board the AUVs; software integration of the modules concerning group navigation and coordination; software integration of communication protocols and strategies to manage two acoustic communication networks (medium frequency for acoustic localization and high frequency for seismic data quality control), and a wi-fi network for the communication on the sea surface; hardware and software integration of the sparkers with the ASC catamarans. The overall system will be validated through experimental tests at sea (two integration weeks have been already performed in Sines, Portugal in November 2016 and July 2017). For the final experiments, the autonomous vehicles constituting the WiMUST system will need to perform cooperative guidance, navigation-localization and control by implementing the solutions and methods derived in the action. In particular, the WiMUST vehicles will need to exhibit a sufficient degree of autonomy and intelligence in controlling the required formation while concurrently performing operational tasks related to the level of individual power supply, intra-vehicle distance, and quality of service of vehicle-to-vehicle communication.

To manage the fleet of AUVs and ASCs composing the WiMUST system, a range based localization strategy and a formation control algorithm have been developed by IST to make the system navigate in preassigned formation (see Fig. 5).

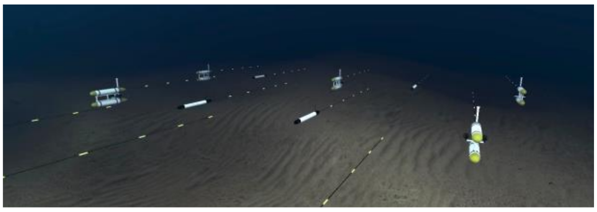

Fig. 5 Computer animation of a WiMUST mission towing streamers.

In this context, ISME activities has been focused on the development of low level motion control strategies for the ULISSE catamaran and for the Folaga AUVs towing streamers (see Fig.6). In particular, the Folagas are torpedo-like AUVs that, for the WiMUST purposes, have been equipped with a central payload to tow a streamer of hydrophones of a length of about 10 meters and to get online the acoustic data acquired with the hydrophones.

Fig. 6 Folaga AUVs towing streamers with hydrophones

The motion control software of both the ULISSE catamaran and the Folaga AUVs have been enhanced with a control mode, in the framework of the ROS-based (Robotic Operative System), that regulates the speed of advancement in a particular direction, taking into account the value of the current, being estimated with the observer proposed in [4].

C. AUV-STREAMER LOCALIZATION ALGORITHMS

For a proper post-processing of the WiMUST acquired acoustic data, there is the need to know the hydrophones' positioning; however, the absence of a localization infrastructure requires the development of a strategy to estimate the hydrophones' positioning from the available set of information.

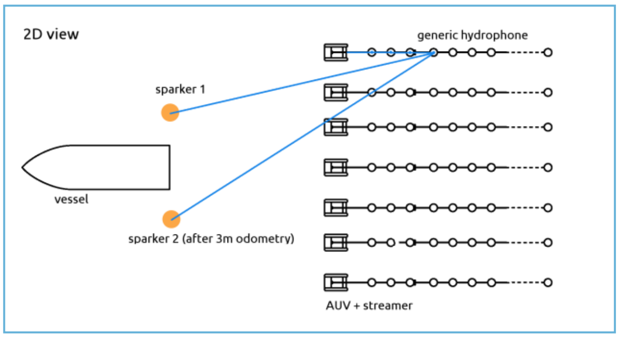

Fig. 7 Sketch of the localization problem

To the purpose, the ISME Cassino developed a localization strategy for the AUV-streamer system that, beyond using the data from navigation sensor of the AUV, as gyroscope, compass, Inertial Measurement Unit, USBL (as in [5]), it also makes use of information gathered from acoustic signals generated for the geoseismic survey. Indeed, considering that the sparkers and AUVs can be equipped with acoustic modems with atomic clocks that allow precise synchronization, it is possible to use the direct time of arrival of the acoustic signals from the sparker to the hydrophones to compute range measurements. In particular, in the proposed localization strategy, range measurements from sparker to each hydrophone (see Fig. 7) are collected and fused with AUV on board navigation sensors to estimate the overall system state using an Extended Kalman Filter.

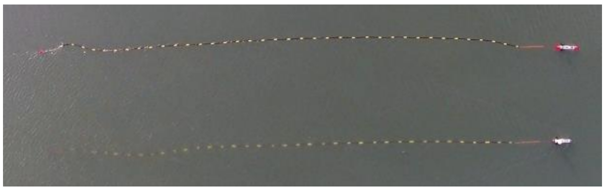

Fig. 8 Picture of Medusa AUVs towing a streamer with hydrophones

To the purpose, the dynamic model of the AUV-streamer system (see Fig. 8) has been firstly derived considering the AUV as a fully-actuated rigid body, and the streamer as a serial chain of rigid links with a spherical unacutated joints in correspondence of each hydrophone as [6].

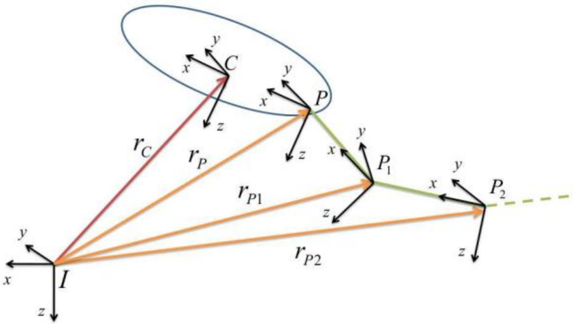

Fig. 9 Modeling of AUV-streamer system

The underwater dynamics of each rigid body has been modelled following the approach in [7]. In particular, the parameters of the dynamic model of the AUV have been defined on the basis of the Folaga Vehicles characteristics, i.e. a 2m-length torpedo shaped AUV, used for the WiMUST project purposes; the streamer, instead, has been modeled as a set of almost neutrally buoyant thin cylindrical elements connected via unactuated spherical joints. Hydrodynamic terms and drag coefficients have been chosen accordingly to the effective geometry of the system, and on the basis of the common velocity regimes of the WiMUST system (i.e. cruise velocity about 1 m/s). Given the large dimension of the overall system state, the direct and inverse dynamic functions, needed for both numerical simulations of the system dynamics and for the computation of the prediction terms of an Extended Kalman Filter (EKF), have been developed referring to the Newton-Euler recursive procedure used for industrial manipulators [8]. The overall localization has been extensively tested in numerical simulations in Matlab, considering the case of single and multiple sparkers, and considering the AUV equipped with different set of navigation sensors. Moreover, the localization algorithm has been tested using data gathered from the experimental tests performed in Sines, Portugal (Nov. 2016) for the WiMUST project purposes. A preliminary study on the feasibility of the localization strategy of the AUV-streamer system considering the availability of range measurement from the sparker has been investigated in [9]; however, that study was based on the use of an instantaneous set of sensor data, thus assuming the systems static. We then extend such work by considering the system dynamic [10] and then building the equation of the AUV-streamer dynamic model, by deriving the EKF equations for the considered system, by performing numerical validations on trajectories and not anymore on instantaneous configurations, and by integrating data

from experimental tests in the numerical validation.
The acoustic signals collected with the hydrophones were stored in the format of SEG-Y files, i.e. the standard format for storing geophysical data. Specifically, the SEG-Y file contains a set of traces for each hydrophone, where a trace represents the progress of the acoustic signal in a time slot of predefined length and time synchronized with the acoustic source. By post processing the SEG-Y file, beyond studying the sea subsurface from the signal reflections, it is also possible to extract the range measurements from the sparker to hydrophones by computing the direct time of arrival of the acoustic signals (i.e. the time to reach the hydrophone without reflection on the sea bottom). Fig. 10 illustrates an example of the range data extracted from the SEG-Y file and filtered out of a set of outliers following a threshold base approach.

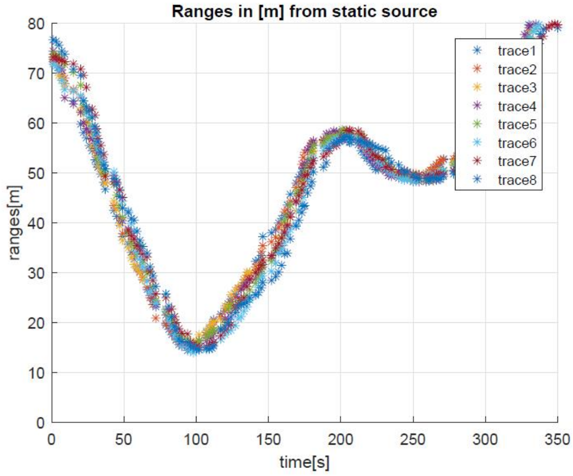

Fig. 10 Range measurements from the sparker to the hydrophones collected from geoseismic acoustic data

Such data have been used in the following case study, together with the AUV's GPS measurements, to perform a realistic simulations of the localization approach performance. The GPS readings of the experiment with the AUV have been used as desired trajectory for a simulated AUV, where a basic PI controller has been used as a low-level dynamic control law.
Fig. 11 shows the actual and the estimated position of the AUV and of the hydrophones while the AUV followed the desired path and the range measurements from the sparker were used. The norm of the positioning estimation error for each hydrophone is plotted in Fig.12. From the figure it can be noticed that, as can be expected, the estimation error decreases from the large initial error value, it keeps relatively low values with oscillations due to the process and measurement noise, and it keeps highest values for the farthest hydrophone from the AUV.

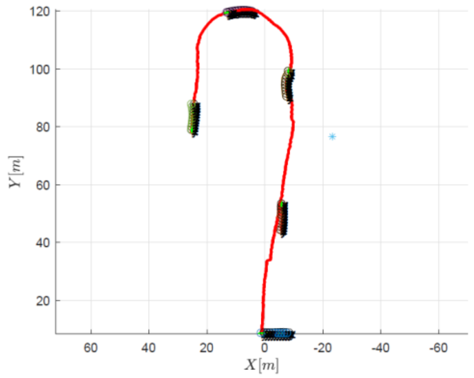

Fig. 11 Plot of the desired trajectory (red), and few snapshots showing the AUV and hydrophones real and estimated positions

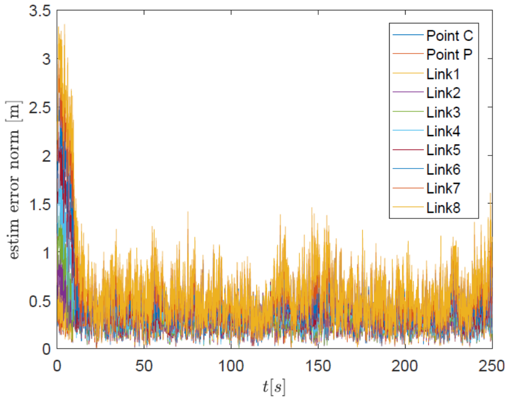

Fig. 12 Plot of the desired trajectory (red), and few snapshots showing the AUV and hydrophones real and estimated positions

IV. CONCLUSIONS

In this paper we presented the advancement stage of the the H2020 European Project WiMUST, with a specific focus on the contribution of the Italian Center on Integrated Systems for the Marine Environment (ISME). In particular we focused on the use of Autonomous Surface Crafts and Autonomous Underwater Vehicles for geoseismic surveying. It is expected that the use of the WiMUST system will be beneficial in a vast number of applications in the fields of civil engineering and oil & gas industry, where seabed mapping, sea floor characterization, and seismic exploration play a key role.

It is worth remarking that, beyond the geoseimic survey application discussed in the framework of the WiMUST project, ISME is also involved in other research activities concerning sampling missions by mean of AUVs and ASCs. As an example, ISME was involved in the FP7 European project named CO^{3}AUVs, it is involved in the H2020 projects DEXROV and ROBUST on the use of

Remotely Operated Vehicle for underwater intervention, it is involved in the H2020 EUMR project on the realization of a shared robotic research infrastructure, it is actually performing research on adaptive sampling [11] and it will be involved in a project with CMU Doha starting in 2018 on the use of team of marine surface vessels and aerial vehicles for monitoring in the marine environment.

V. ACKNOWLEDGEMENT

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