Remote Passive Acoustic Barrier with Maritime Unmanned Systems: preliminary tests during REPMUS-21

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Abstract. Using a Maritime Unmanned System (MUS) always involves a trade-off between the ability to autonomously accomplish tasks of increasing difficulty and the possibility for a human operator to take decisions concerning the ongoing mission. This aspect requires a communication architecture to share frequently updated information between the MUS and a Command and Control Station (C2S), capable of monitoring and supporting the system during its tasks. Within this context, this paper describes a marine System of Systems (SoS), consisting of 3 collaborative MUSs, acting as an Anti-Submarine Warfare (ASW) passive barrier. The preliminary experimental trials of the presented SoS took place in Sesimbra (Portugal), in September 2021, during the annual military exercise Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems (REPMUS), in which the Naval Support and Experimentation Centre (CSSN) of the Italian Navy was involved. In REPMUS-21, the capacity of the proposed system to detect artificial targets transiting in the operational area was demonstrated along with the capabilities of its multi-domain communication infrastructure, which allowed to monitor and control an underwater vehicle from a C2S exploiting a surface vehicle as a gateway.

Keywords. Maritime Unmanned System (MUS), ASW, Bearing Only tracking, Acoustic Vector Sensor, Maritime Surveillance, Multi domain Communications

1. Introduction

Over the last few years the considerable development of Maritime Unmanned Systems (MUSs) in terms of reliability and autonomy has given the opportunity to expand their application in different scenarios. Concerning the military field, the usage of MUS is

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spreading both during experimentation campaigns and international demonstrations [1]. Indeed, unmanned vehicles can bring several advantages to military applications, such as: reducing the risk to human operators by keeping them away from potentially hazardous areas; extending the operational range of a ship operating at the same time; guaranteeing the persistence of surveillance in an area of interest [2].

Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems (REPMUS) is an annual military exercise, hosted by the Portuguese Navy and NATO, in which interoperability, procedure and tactics for MUSs are tested, reproducing an experimental scenario coherent with the real applications. Thanks to the contribution of different tech companies, universities and navies from several NATO countries, the exercise becomes a true technological booster for the specific area of research. REPMUS-21, which took place in Sesimbra (Portugal) in September 2021, involved more than 40 entities, including 17 navies, 15 research & development entities, 1 university and 8 organizations of NATO. Complete details about the REMPUS-21 exercise can be found in the dedicated webpage: https://lsts.fe.up.pt/index.php/fieldexperiment/repmus21.

Naval Support and Experimentation Centre (CSSN) of the Italian Navy, to which some of the authors belong, joined the exercise to test a marine System of Systems (SoS) for Anti-Submarine Warfare (ASW) scenarios. The proposed SoS, composed of 2 Autonomous Underwater Vehicles (AUVs) and an Autonomous Surface Vehicle (ASV), acts as a passive barrier aiming at detecting any potential target entering the supervised area. The global system has been designed considering the trade-off between the level of autonomy of each individual unmanned system, and the intervention capability by a human operator exploiting a communication infrastructure for the exchange of information in quasi-real-time. Indeed, a robust communication link between the controlled vehicle and a Command and Control Station (C2S) is required to monitor and support the AUV, especially when the latter is submerged.

During the experiments, artificial targets performed predefined trajectories within the operational area while transmitting an unknown acoustic signal, which the SoS had to detect and elaborate to obtain Direction of Arrival (DoA) data. The acquired information were then transmitted to the C2S to be used by the human operator to monitor the mission status and act in case of necessity. The targets trajectories, estimated by their navigation systems, will serve as ground truth and will be compared with the DoA measurements, obtained by the authors' multi-vehicle system, in future analyses.

The rest of the paper is organised as follows: Sec.2 presents the marine system exploited during the experimental campaign. In particular Subsec.2.1 describes the MUSs composing the SoS, their functionalities and their interoperability, while Subsec.2.2 focus on the multi-domain communication architecture. The REMPUS-21 activities are detailed in Sec.3, along with the collected data. Finally, in Sec.4 conclusions and some possible future works are summarized.

2. Marine System of Systems

Exploiting MUSs in ASW applications is an important milestone for the military field [3], [4]. The basic concept is to use a team of heterogeneous marine vehicles, some of which equipped with passive acoustic sensors to cover a specific area and detect intruders. Each vehicle can be considered as a node in a network, sharing some information with the other nodes and cooperating to achieve a common goal. In the development of the SoS proposed within this work has been considered that the information of a possible intruder has to be delivered as soon as possible to the C2S, resulting in a communication infrastructure able to exchange data among surface and underwater assets in quasi-real-time.

2.1. System Description

The designed marine SoS consists of 3 MUSs: 2 AUVs, equipped with acoustic vector sensors to detect targets [5], and an ASV, able to localise and exchange data with the AUVs. Indeed, the presence of a surface vehicle in the team is necessary to monitor the position of the AUVs during their underwater missions and to act as communication gateway between the submerged robots and the C2S.

The marine assets composing the system are modular and re-configurable vehicles, manufactured by Graal Tech company, that can be easily customise by the final user. The X300 AUVs, shown on the right-hand side in Fig. 1, are torpedo-shape vehicles equipped with GPS and Altitude and Heading Reference System (AHRS), utilised for navigation purposes. Moreover, S2C M 18/34 Evologics acoustic modems are integrated to communicate via acoustics. A peculiarity of these AUVs is that they can also operate as gliders: an internal bladder connected to a pump allows to modify their buoyancy, while a sliding battery pack permits to correct their pitch angle. This configuration enables them to move in a certain direction without activating the thrusters. Further details about the vehicles are reported in Tab. 1.

X300 Description	
Length [m]	2.222
External diameter [m]	0.155
Weight in air [kg]	39
Mass variation range in water [kg]	$-0.35/+0.35$
Moving mass displacement range [m]	0.08
Battery type	Li-Ion
Autonomy at full speed [hours]	12
Max depth [m]	300
Max speed [m/s]	4

Table 1. X300 Technical Specifications

In the ASW context of this work, different models of acoustic vector sensors were mounted on the two X300 AUVs: an AN/SSQ-53F Direction Frequency Analysis and Recording (DIFAR) and a Wilcoxon VS-301. DIFAR is a passive low frequency detector that can be considered as an omnidirectional hydrophone with two orthogonal dipole sensors placed on the horizontal plane. Thus, it is able to estimate the DoA of an acoustic source with respect to the Magnetic North, as depicted on the left-hand side in Fig. 1. Wilcoxon, on the other hand, is a 3D vector sensor which provides both bearing and elevation angles with respect to the detected acoustic source.

The Mobile Gateway Buoy 300 (MGB300) ASV, depicted in Fig. 2, has similar characteristics with respect to the X300 AUVs, thanks to the robots modularity which allows to utilise some parts of the underwater vehicles also for the surface one, and is equipped

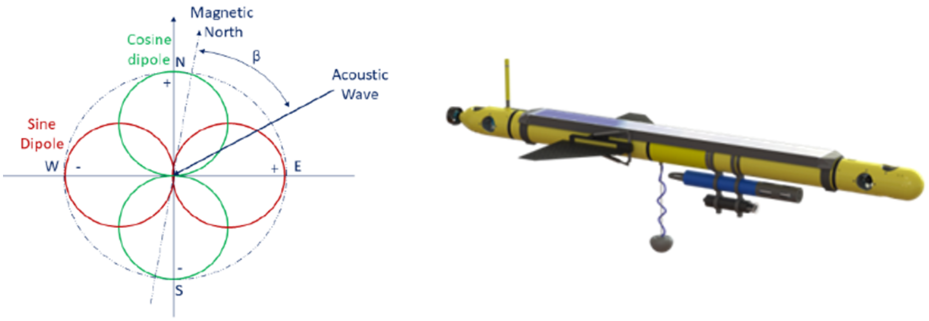

Figure 1. On the left, a polar graph of the theoretical acoustic beam pattern of the DIFAR vector sensor. On the right, an X300 AUV equipped with a DIFAR sensor.

with the same suite of built-in sensors (GPS, AHRS). Furthermore, the MGB300 has WiFi and radio antennas rigidly mounted on an aluminum structure and a modem with Ultra-Short Baseline (USBL) capabilities attached below the vehicle hull, which is exploited to actively localise and to communicate with the AUVs via acoustics. The relative positions measured by the USBL sensor are compensated through the on-board AHRS and GPS to retrieve the AUVs absolute position [6]. These data can then be sent to a C2S to monitor the position of the underwater vehicles during their mission. Indeed, the ASV can use either the Ultra High Frequency (UHF) radio modem to exchange data with the C2S in a range up to about 10 kilometers or the WiFi communication, characterised by a higher data rate and reliability compared to radio channel, whenever the ASV operates in the nearby of the C2S.

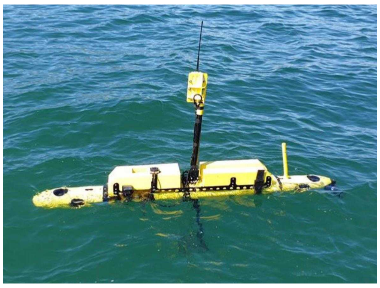

Figure 2. MGB300 ASV during at sea experimental activities

Having to work in an ASW scenario, the AUVs are required to perform a real-time analysis of the signals coming from the vector sensors directly on-board. In particular, each underwater robot periodically performs an ambient noise level computation to set a detection threshold, utilised during the signal processing to discern frequencies with a power density higher than ambient noise. The DoA of the frequency with the highest power density is then considered as the direction from which the target signal is coming, as detailed in [7]. The detection information, in terms of DoA, frequency of interest, and signal to noise ratio (SNR), are then sent via acoustics from the AUVs to the ASV, which redirects these data to the C2S via WiFi or radio channels, to be notified to the human operator.

2.2. *Communication Architecture*

Underwater environment poses severe limitations to the communication capabilities since it has to be performed via acoustics [8], resulting in low data rate, poor reliability and inherent latency of the acoustic channel. In addition, having to manage multiple assets that use the same channel to communicate, a schedule of transmission times for each robot is essential to avoid packet collisions. With this view, the marine SoS described in this work implements a communication architecture which guarantees a high level of autonomy to the MUSs, while maintaining the operator in the decision-making loop giving the possibility to intervene if necessary.

For what concerns the underwater domain, the proposed solution involves a specifically designed acoustic communication protocol to schedule the communication times of the MUSs. In the designed protocol, the ASV periodically interrogates and simultaneously localises the AUVs, utilising the USBL device and the acknowledgment functionality. An AUV can only respond to the ASV when interrogated and within a predetermined time slot, after which the ASV will move on to query another AUV. Thus, the detection information processed by the underwater robots must be sent to the surface vehicle within this time frame. The time slot duration, dedicated to each interrogation, was computed considering the Round Trip Time (RTT) of an acoustic signal and the time needed to the AUV to transmit back its packet, considering a maximum inter-vehicular distance of $200m$, assumed to be consistent with the application scenario. This choice allows to avoid any prior vehicles' clocks synchronization, since each MUS can work with its machine time, and prioritise the positioning rate of each AUV.

The data directly acquired by the surface vehicle, as the AUVs positions, or received via acoustic communication, as the detection information, are made available in real-time to the C2S using radio or WiFi communication, depending on the distance. Finally, the human operator is able to send specific task to the AUVs to change their scheduled mission plan or to stop the mission execution. A representation of the described communication infrastructure is shown in Fig. 3

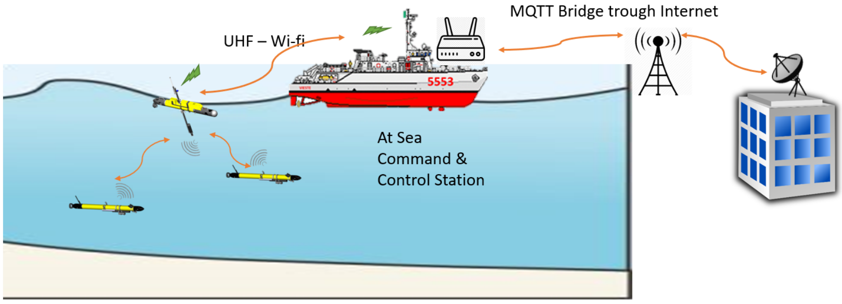

Figure 3. Communication architecture of the marine SoS

3. Experiments Descriptions

The marine SoS described in this work was tested in at sea experiments during REPMUS-21, which lasted two weeks from September 13th to September 24th, 2021. Within this period, the activities were scheduled to use the first week to setup and make the systems operative, while the data acquisition campaign was focused in the second week.

Thanks to the collaboration among several entities from different NATO countries, an ASW scenario was reproduced. In particular, an extensive passive acoustic barrier, composed of various independent assets from the different participating entities, was deployed at sea. The SoS presented in this paper was part of such barrier and acted to recognise artificial targets approaching the guarded area. The targets were mostly AUVs performing predefined missions in the operative area, while carrying an acoustic source which transmitted signals with an acoustic signature unknown to the MUSs in the barrier, at a fixed rate. Also a Rigid Hull Inflatable Boat (RHIB) was exploited as target, in this case the barrier tried to detect the acoustic noise produced by the boat.

The dataset collected during the tests, along with the possibility to have reliable ground truth information provided by the targets navigation systems, constitute an important asset which will be exploited for future analysis.

3.1. Experimental Setup

During the REMPUS-21 exercise the assets composing the barrier were daily deployed at sea and arranged in a linear formation considering the maximum detection range at predefined environmental conditions, in accordance with [9]. When the barrier was in place, the targets started their missions following predefined trajectories in the nearby of the formation. The emitted acoustic signature of the target had to be detected by the barrier and the C2S had to be notified of the presence, and possible location, of the intruders. Meanwhile, 3 ships were stationed at a distance of more than $3km$, monitoring the operations and ready to intervene if necessary. In particular, during the ASW experimentation, STO-CMRE (NATO) was on-board the NRV Alliance, WTD71 (Germany) was on-board the Planet, and TNO (The Netherlands) and CSSN (Italy) were aboard GEOSEA.

Due to a malfunctioning to the X300 AUV mounting the Wilcoxon vector sensor, occurred during the week of experiments, the tests concerning the SoS involved only the X300 AUV equipped with the DIFAR and the MGB300 ASV.

The activities during the day were designed to be carried out mostly autonomously by the system, with human intervention relegated only to the deployment and recovery of vehicles, and in case of necessity. Therefore, the AUV was programmed to reach predefined coordinates within the operative area and then dive at a depth of $20m$. Once the desired depth was reached, the underwater vehicle turned off its thrusters and was left to drift, in order to avoid any acoustic noise that might had affect the DIFAR sensor. However, strong sea current in the area caused the AUV to drift for more than $300m$. Therefore, the daily missions were divided in sub-missions of 30 minutes each to allow the AUV to emerge and reposition itself at the predefined coordinates, before starting a new sub-mission. While underwater, the AUV was able to detect incoming acoustic signals exploiting the on-board vector sensor, which were processed online to compute a DoA of the acoustic source. The detection information (DoA, frequency of interest, and SNR) were then sent by the AUV to the ASV, according to the acoustic protocol described in SubSec 2.2. Following, the ASV transmitted the data to the C2S via radio frequency and made available to the human operator. Lastly, utilising MQTT bridge and internet connection, the information were sent in real time to a control room on the shore.

3.2. Results

The overall experimental campaign allowed to collect 25 hours of data of an ASW scenario, composed of acoustic signatures from multiple targets and their processing results computed online. Tab. 2 reports a comprehensive list of missions performed during REPMUS-21.

Day	Overall Duration	Target	Number of Detections
20 Sept	7h	RHIB / SEMA TNO	23 / 1723
21 Sept	6h	GAVIA WTD71	1189
22 Sept	4h	RHIB	4
23 Sept	8h	OEX / SEMA TNO	892 / 421

Table 2. Dataset collected during REPMUS 21 exercise

As stated by Tab. 2, the small number of detections obtained using the RHIB as target mean that the system had significant difficulties in sensing the acoustic signature of the boat moving in the operative area. However, the proposed system successfully detected signals for those missions involving AUVs carrying acoustic sources. The online processing performed by the X300 AUV provided DoA data of the sensed acoustic signals, as shown in Fig. 4. To further evaluate the system performance, in terms of detection accuracy with respect to the ground truths, a deeper analysis will be performed on the dataset.

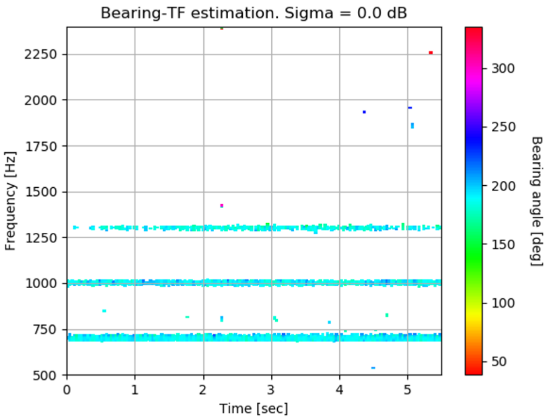

Figure 4. Spectrogram of the received signal within a single time window; 3 clear and persistent lines in light blue are likely associated to an artificial target. Colormap is associated to the estimated DoA

4. Conclusions & Future Works

This work present a marine SoS composed of 2 AUVs and an ASV, acting as an ASW passive acoustic barrier. Each AUV is equipped with a vector sensor to detect intruders in the operational area. An on-board processing allows the underwater vehicles to compute the DoA of the acoustic signals sensed within a time window. Such information, together with the frequencies of interest and the SNRs, are then sent to the C2S, exploiting the multi-domain communication bridge made available by the ASV. In REMPUS-21, the correct operation of the proposed system was demonstrated, allowing to collect a rich dataset of the ASW scenario, which will be exploited in future works to evaluate the system performance and to develop new solutions. Cooperation between heterogeneous assets is a key aspect of the system which will be further investigated, along with the communication standards, like the one described in [10], which are mandatory to exchange data among multi-vendor vehicles. Finally, tracking strategies to provide a continuous estimate of the target position will be explored.

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