Implementation of an Underwater Acoustic Network using Multiple Heterogeneous Vehicles

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***Abstract*—In this paper we investigate the creation of a heterogeneous underwater network with static and mobile assets cooperating together in coordinated missions using acoustic links. Each underwater device combines communication, networking, and sensing capabilities, and cooperates with the other devices to accomplish a given task. The flexibility and capability of the proposed system allows to overcome the limitations of commercial solutions currently available in the market, mostly addressing point to point communications. SUNSET framework has been used to provide acoustic communication and networking capabilities to AUVs, ASVs and moored systems developed by the Oceans Systems Group, at the University of Porto, in Portugal. New solutions have been developed and tested allowing to combine together acoustic data transmission and ranging estimation, to control the underwater nodes acoustically and to instruct the vehicles on keeping a given formation using acoustic links. To validate the proposed approach several experiments with increasing complexity have been conducted at the laboratory and in the field. The experimental results confirm the validity, efficiency and reliability of the proposed solution opening to several possibilities for future developments.**

***Index Terms*—Underwater acoustic networks, sea trial testing, ranging estimation, vehicle formation, SUNSET, MARES AUV, Zarco and Gama ASVs.**

I. Introduction

The utilization of robotic systems for operation in the underwater environment has became increasingly common in the last years. In most of these systems, real-time communication with a mission supervisor is needed, for a combination of reasons such as safety and control of the performed actions, or the need to periodically transmit data from onboard sensors. In the underwater environment, radio frequencies typically used over the air are not usable in practice, and optical signals are greatly attenuated. Although there are significant efforts to find viable alternatives, acoustics are still the main technology in use for underwater communication. Nonetheless, acoustic solutions suffer from long transmission delays, low data rates and several factors affecting the quality of the channel (multipath, attenuation, etc).

The current commercial solutions available in the market for acoustic communications are dedicated to provide a point to point exchange of information. This may be sufficient to address the need of a great number of marine operations, but starts to fall short when it comes to scenarios requiring the use of complementary assets in coordinated missions. In such scenarios, the communication infrastructure is a critical aspect to ensure proper operation of the whole network. This communication infrastructure has to be designed to take advantage of the multiple communication devices available at the *nodes*, either fixed or mobile, and to be flexible enough to accommodate any updates on communication capabilities of each asset, or the inclusion of new assets in the network.

In this paper, we discuss the design aspects and the implementation of an acoustic network enabling underwater communications among multiple moving platforms and, at the same time, navigation of underwater vehicles: we describe the main requirements for the overall system, we detail the solutions adopted for the implementation in the various vehicles, and, finally, we present experimental data from the first in-water trials.

II. Main Requirements for the Network

The main motivation for this work arises from the need to integrate a fleet of heterogeneous vehicles in a

Figure 1: The MARES AUV with an externally mounted Conductivity, Temperature and Depth (CTD) sensor.

Figure 2: Zarco and Gama during a trial at the Douro river.

communication network, including Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs) and moored systems. Providing to these devices the capabilities to communicate and cooperate in a distributed way strongly increases the capability and flexibility of the entire network, enlarging the number of operations and actions that can be performed. In this section, we describe the different devices we have considered and used in our heterogeneous network and the benefits obtained by the presence of an underwater communications network.

The MARES AUV

The MARES AUV [1] is a small sized vehicle developed by the Oceans Systems Group, at the University of Porto, in Portugal (Figure 1). It has a torpedo shaped body, with about 1.5 meters of length and 20cm of diameter, weighting slightly over 30kg in its basic configuration. Due to the body modularity, the vehicle can easily include any additional system, by designing the proper mechanical section and inserting it in the right position. Unlike similar sized vehicles, MARES does not have any moving fins to adjust heading and depth. Instead, motion is provided by thrusters, which allows the vehicle to hover in the water column and/or approach any structure for detailed inspection.

The main MARES navigation system is based on a Long Base Line (LBL) acoustic positioning system – the vehicle software continuously fuses ranges to a set of acoustic beacons, together with compass heading, inertial data, depth and velocity, to compute the estimated position in real-time. At the end of the mission, a smoothing algorithm improves the accuracy of the position estimates throughout the mission. Depending on the environmental conditions, the current acoustic beacons can be located at a maximum distance of 1–2 Kms of the AUV.

With the new acoustic network, MARES should be able to share information with the other nodes, within practical ranges. At the same time, the new system should also provide information to enable and improve vehicle navigation, for example, by providing ranges to other nodes with known positions (not only static acoustic beacons but also mobile platforms which can estimate their own position in real-time).

Zarco and Gama ASVs

Zarco and Gama are two small Autonomous Surface Vehicles (ASVs) (Figure 2), developed by the Ocean Systems Group to conduct experiments in navigation, control, and vehicle cooperation [2], [3]. The vehicles have been used to carry several types of sensors for bathymetry and water quality monitoring, and they have also been used to transport the acoustic beacons for AUV navigation, acting as virtual moorings. Both ASVs have multiple communication capabilities, taking advantage of the solutions available using radio (from Wi-Fi to long range RS-232 communication). The availability of differential GPS (DGPS) receivers ensures an absolute position with errors less than one meter. With the implementation of this new acoustic network, the ASVs should be able to act as moving gateways to exchange information with AUVs and also to provide acoustic beacons for AUV navigation.

Navigation and Instrumentation Buoys

Navigation and Instrumentation Buoys (NIBs) are moored floating platforms with onboard electronics and energy management system (Figure 3). The basic configuration includes rechargeable Li-Ion batteries, an ARM-based single board computer with Wi-Fi, a compact GPS receiver and a low-power radio modem. Optionally, we can also include commercial-off-the-shelf modems for long range satellite communications, such as Iridium. NIBs can carry a great variety of sensors and transmit data in real-time, working as portable surface observatories. During AUV missions, they get relevant information about the environment (such as current profiles or reference sensor data, for example), to allow for post-mission data processing and interpretation.

NIBs are also used as acoustic navigation beacons for AUVs. They have electronic boards to receive and decode acoustic signals sent by the vehicle and respond by transmitting other coded pings into the water. Since

Figure 3: A Navigation and Instrumentation Buoy.

they are deployed in positions known by the AUV, forming an LBL acoustic network, the vehicle can determine its own position by trilateration. Alternatively, the buoys may send synchronized signals, so that the AUV may estimate ranges based only on one way travel time [4]. During an AUV mission, the buoys also relay navigation information back to the mission control station, allowing for vehicle trajectory tracking, following a passive tracking algorithm described in [5]. Without any communication capabilities, the GPS location of the NIBs is logged throughout a mission, to allow for post-mission corrections of sensor data location, since there may be significant changes of buoy position due to wind and/or currents. With the availability of the acoustic network, these variations can be forwarded to the AUVs in real-time, together with any relevant information regarding the environmental characteristics (currents, salinity, etc), thus significantly improving the AUVs position estimation.

III. Control Architectures of the Heterogeneous Vehicles

In this section, we describe the on board architecture for the control of each autonomous vehicle and also for the control of groups of vehicles. These architectures can handle commands provided to the system in real-time, changing the mission scripts accordingly.

A. *Control architectures*

Autonomous vehicles: One of the most important aspects in the control of an individual autonomous vehicle is the specification of trajectories. Versatile trajectories and, more generally, behaviors, require the control architecture to include elemental *maneuvers*. A control software has been designed so that each robotic platform (ASV and AUV) is able to perform five types of maneuvers, which are briefly described as follows:

- **Line-following** – The vehicle tracks a line, while keeping a possibly time-varying velocity;

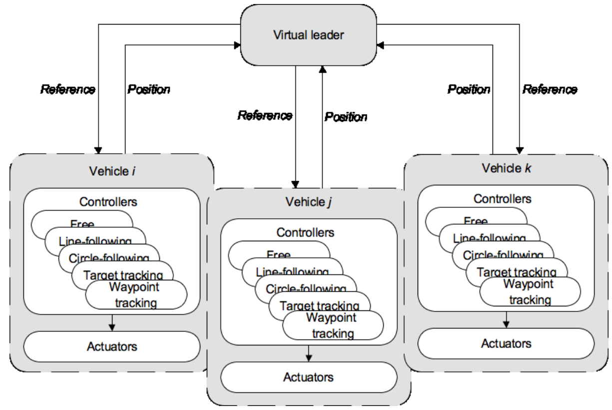


Figure 4: Control architecture of the autonomous vehicles

- **Circle-following** – Given a point and a radius, the vehicle tracks the respective circumference;
- **Target tracking (station-keeping)** – The vehicle tracks a (possibly time-varying) point and remains stationary;
- **Waypoint** – This maneuver is concluded once the vehicle reaches a preset position;
- ***Free* maneuver** – Each degree of freedom can be commanded directly by setting either velocity or pose references.

Using this set of maneuvers, any type of complex trajectory can be followed by setting a coherent sequence of instructions. This can be set either by using a static mission script or by instructing the vehicles on-the-fly via a communication link. From the robotics point of view, the maneuvers can be seen as a set of feasible tasks. This small, yet versatile, set of tasks enables a clear interaction with and among the vehicles, thus fitting well in a distributed scenario using a higher-level cooperation algorithm.

This architecture has already been successfully implemented in several robotic heterogeneous marine platforms such as Zarco and Gama ASVs [2], the MARES AUV [1] and, more recently, the TriMARES Hybrid AUV/ROV [6], [7].

Coordination algorithm: The coordination of the vehicles is achieved through a centralized algorithm, based on [8]. It includes two types of elements: A *virtual leader*, which coordinates the vehicles operations, and a *follower* node, which is instructed by the leader on the actions to perform. The virtual leader generates the position references for each of the followers which are physical robots that individually track their respective references. Figure 4 depicts the main structure of the approach by exemplifying it in the case of three vehicles. The virtual leader can be coincident with any of the physical robots and even can run on it. The evolution of the formation takes into account the tracking errors of each robot. For the sake of illustration, if any of the robots deviates from its respective reference, the virtual leader generates new reference points allowing the followers to maintain the given formation.

Although centralized, this approach is particularly well-suited for arbitrary trajectories of possibly time-varying formations. Moreover, the stability of the formation is not strongly affected by possible delays on the communications. Of course, the latency on the interaction among the robots degrades the overall performance of the coordinated system but the algorithm still guarantees stability.

B. Interaction with the control layer

According to the previous points, the interaction with the control layer is made by simply setting the desired maneuvers along with the respective parameters. In the case of *target tracking*, for example, only the desired final position must be defined, while for the *line-tracking*, two points must be provided to the control algorithm. During certain maneuvers, the references can be commanded on-line during the execution, therefore allowing for more dynamic motions. This capability is of special interest to achieve coordination of vehicles and has been explored in this work.

IV. Implementation of Communication Capabilities

To provide networking and communication capabilities to the underwater nodes and to create an underwater network, the Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET) [9] has been used. SUNSET has been interfaced with all three different devices described above, allowing the creation of an underwater heterogeneous network. Using SUNSET the different devices can self-organize themselves and cooperate in a distributed way, exchanging data and information and instructing each other on the actions to perform. In what follows we describe the SUNSET architecture and how networking and communication capabilities have been combined together and interfaced with static and mobile underwater nodes. We also introduce the protocol solutions we have considered during the tests and how we have combined ranging estimation together with acoustic data transmissions.

A. The SUNSET architecture

SUNSET is a new solution to seamlessly simulate, emulate and test in real-life novel communication protocols. It is based on the open source and well known network simulator ns-2 [10] (and its extension ns2-Miracle [11]) and it has been made freely available to the research community [12]. SUNSET provides a tool to implement a complete protocol stack for underwater acoustic sensor networks. The development of the entire protocol stack is almost independent from the communications devices (some constraints may be imposed by the specific hardware used for the transmissions in terms of maximal packet size for data or control packets) giving the possibility to implement new protocol solutions in an easy and fast way. Several routing, MAC and cross-layer solutions have already been implemented, including: CARP [13], TDMA, CSMA [14], Slotted CSMA, T-Lhoi [15], DACAP [16], Flooding-base solutions, Depth Based Routing [17], Focused Beam Routing [18], an improved version of the routing solution presented in [19], etc.

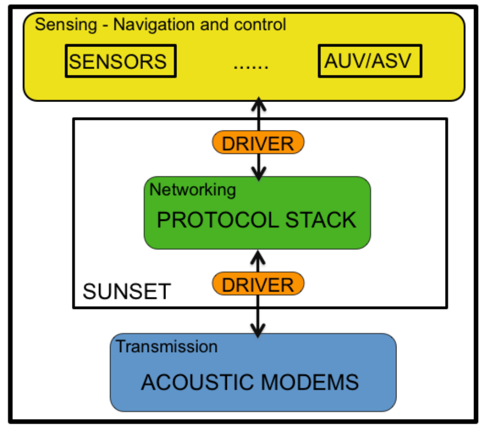
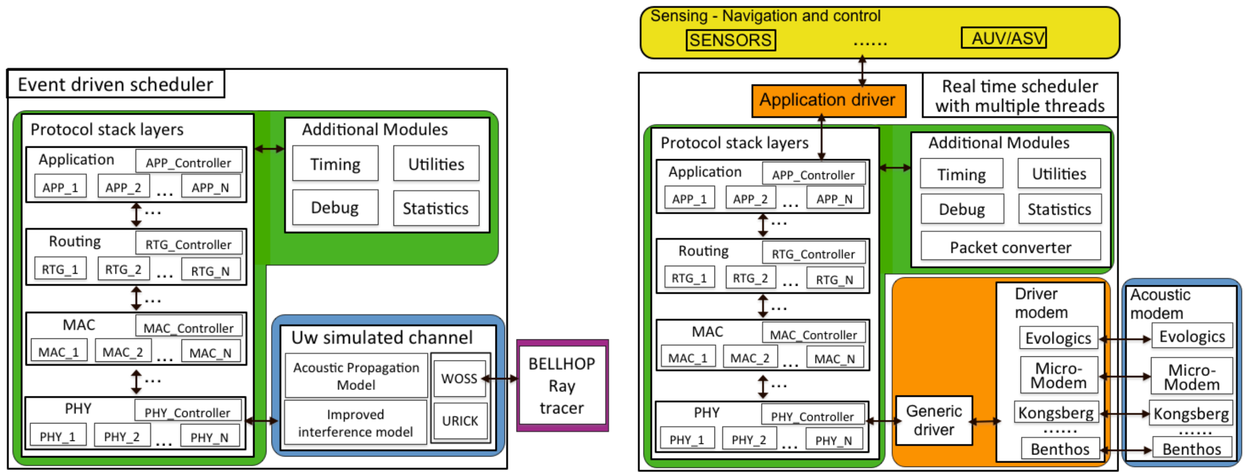


Figure 5: SUNSET for real life applications.

SUNSET allows to first test protocol solution running simulations (by means of the network simulator ns-2), which speeds up the development and debugging process. The same networking protocols implementation can be then used in emulation and at sea testing without any code re-writing, adopting real acoustic modems for data transmission and additional external devices for sensing and navigation operations (Figure 5).

When running simulations (Figure 6a), SUNSET can use different underwater acoustic channel models, such as empirical formulas [20] and Bellhop ray tracing [21] via the WOSS [22] interface. When running in emulation mode (Figure 6b), instead, real acoustic modems and additional devices are used. New modules and several drivers have been developed to allow a proper interaction with the external real hardware and to make transparent to the user the switch between a simulated underwater channel and the use of real acoustic modems. Different off-the-shelf acoustic modems are already supported by SUNSET for underwater data transmission: WHOI Micro-Modem [23], Evologics modems [24], Kongsberg modems [25] and Teledyne Benthos modem [26]. SUNSET has also been successfully integrated and interfaced with different types of devices, including sensors for underwater measurements [27] and the AUV, ASV and



(a) SUNSET modules in simulation mode.

(b) SUNSET modules in emulation mode.

Figure 6: SUNSET architecture: Simulation and emulation mode.

NIB devices described above. Given its open architecture, SUNSET can be easily interfaced with whatever acoustic modem, mobile or static nodes, sensor, navigation system, underwater device, etc., once APIs are provided to control the operation of the specific device.

The time needed to design and implement the specific driver is very short and proportional to the complexity of the operations required by the specific hardware. Radio, optical and other type of communication devices can be interfaced to SUNSET as well, thus providing the possibility to explore and take advantage of multiple communication interfaces available at a given node to improve the network performance and capability.

To make easier the deployment at sea, SUNSET code has successfully been ported on small portable devices (Gumstix, PC104 or other ARM-based systems), thus allowing us to embed it inside modem or AUV and ASV housings.

B. SUNSET interaction with mobile vehicles

To allow SUNSET to use and interact with different devices, such as AUV or ASV navigation control systems, a driver is needed at the application layer to properly handle the device functionalities, data exchanges and interactions with these devices (see Figure 6b). The application driver provides the methods to set and get parameters of the specific device and it provides the functionalities to execute different actions, e.g., navigating to a given location, changing depth or velocity, etc. Specific drivers for the different devices have to be implemented in order to translate the intended actions in a set of instructions known by the specific device. Once a driver for the specific device has been implemented, the new hardware can be plugged to the SUNSET architecture and it is ready to be used.

Preloaded missions are usually used when operating with underwater vehicle without any real-time interaction with the vehicle once it is underwater. Using the acoustic communications and networking capabilities provided by SUNSET, requests and commands can be delivered to a remote node (via single-hop or multi-hop transmissions), thus allowing the remote control of the device using acoustic links in a real-time and on-line way. Mobile underwater vehicles can therefore be controlled while they are operating underwater, thus significantly improving the vehicle flexibility when performing a given mission.

For what concerns ASVs, they operate at the surface level. Communication and interaction with this kind of device are therefore typically performed by means of radio communication as it provides higher bit rate and lower propagation delay. However, a surface vehicle would greatly benefit from acoustic communication capabilities for several reasons: 1) The ASV could be used (similarly to instrumentation buoy) as a gateway node to interact with the AUV while it is underwater; 2) the ASV could be used as a mobile transponder for the AUV navigation; 3) the ASV could use the acoustic communication as a back-up line, in case the radio communication is not working properly, due to interferences, too long transmissions distance, or bad weather.

C. SUNSET ranging capabilities

Data transmission and ranging estimation are two operations which usually interfere with each other: When the vehicle is ranging it cannot transmit acoustic data and when it transmits data it cannot estimate ranging to the other nodes. Moreover, they usually require separate hardware. Being able to exchange data and information while ranging using the same hardware would effectively improve the vehicle and network capabilities. For this reason, a new SUNSET module which combines together communication and ranging operations has been designed and investigated. This new module uses Evologics modem synchronous instant messages [28] to estimate ranging information while exchanging data packets with the other nodes in the network. Distances are estimated based on the round trip delay between ranging request and response messages. Moreover, in each range request and response message additional information, such as the estimated position of the node, can be transmitted, allowing the use of mobile nodes as transponders for navigation support.

V. Experimental results

In order to demonstrate the viability of the proposed approach, we have conducted several trials with increasing complexity at the Ocean Systems Group laboratory and at the Douro river, close to Porto, Portugal. SUNSET running on embedded device (Gumstix [29]) has been integrated inside the vehicles and the instrumentation buoys. The specific drivers have been used for the interaction with the different vehicle navigation and control systems. The integration of the SUNSET embedded device was quite smooth. Gumstix are very small, low power devices, only requiring 5V input, readily available in all platforms. As far as communications are concerned, they interfaced with the onboard computers using Ethernet. Evologics acoustic modems S2C R 18/34 have been attached to SUNSET (Gumstix) on the different devices and the specific driver has been used for acoustic data transmissions and receptions. SUNSET was responsible to provide communication and networking capabilities to allow the interaction and data exchange among the different nodes in the network. It was used to locally interact with the underwater node and to deliver commands and requests sent over the acoustic channel to the vehicle control layer.

The integration of the modems requires some special care, particularly in the case of the MARES AUV. In terms of power consumption, the 80W peak transmission power is quite significant, when compared to the typical hotel load of 10-20W, and a dedicated power converter had to be installed for the experiments. With respect to mechanical integration, the unit we had available had a standard housing and had to be attached to the outside of the MARES hull, somehow compromising the radiation pattern for the transducer, affecting vehicle hydrodynamics and requiring a proper ballast compensation. Naturally, with a OEM version, this integration would be smoother, as we could use the AUV housing to install the electronics and leave only the transducer in the outside. The integration onboard the ASVs was much simpler, with the physical units hanging down from vertical poles, with adjustable height.

A. *Tests with the MARES AUV*

First tests have been conducted in February 2012, where the MARES AUV driver and its integration with SUNSET have been tested in the test tank at the Ocean Systems Group laboratory. SUNSET running on the Gumstix inside the AUV has been used to control the vehicle operations using both radio and acoustic links. One Evologics modem has been connected to a control station running SUNSET on a PC and another one to the Gumstix inside the vehicle. Acoustic commands have been sent from the control station to instruct the vehicle on the requested operations to perform. SUNSET was responsible for delivering the acoustic packet from the central station to the vehicle and vice versa. Moreover, when the vehicle was at the surface, we also switched to radio communication to connect to SUNSET and locally instruct the vehicle on the operations to perform.

Different types of maneuvers have been tested including the variations of pitch and yaw angles (and rates) and of vehicle depths. Promising results have been obtained showing that the AUV was able to receive, process and correctly execute commands in real-time. The command execution latencies were about $400ms$ and $1500ms$ when radio or acoustic communications were used, respectively. The longer delays are due to the lower bit rate and additional overhead and delays of the acoustic modem and to the longer propagation delay introduced by the acoustic channel. Moreover, part of the additional delay was due to the necessity to encode and decode the acoustic remote commands, which is needed to improve the acoustic channel utilization. The obtained results confirm the validity of the proposed solution when controlling the vehicle using both radio and acoustic communications.

B. *Tests with ASVs and NIBs*

In July and August 2012, different tests considering surface vehicles and instrumentation buoys have been first conducted at the Ocean Systems Group laboratory and then at the Douro river, close to Porto. Two surface vehicles, Zarco and Gama, and two NIBs have been considered. All the considered devices have been equipped with Gumstix running SUNSET and Evologics modems for acoustic communication. The operations of the ASVs have been controlled by a central station (running SUNSET on a PC) using acoustic messages. As for the MARES vehicle, radio communication has been also tested to connect to SUNSET and locally instruct the vehicles on the operations to perform. The two NIBs were used as monitoring stations, listening to the channel, collecting the information transmitted by the ASVs and replying to requests coming from other nodes. While the tests at the Ocean Systems Group laboratory were mostly addressing the correct integration and operability of ASVs and NIBs with SUNSET, the tests at the river were in the direction of real in field operations using the different devices. Tests on the combination of ranging estimation and data transmission, to provide an improved support for AUV navigation, and on the cooperation of the devices using acoustic messages have been performed.

Ranging tests

The combination of ranging estimation and acoustic communication has been performed at various distances with the two vehicles moving in opposite directions and two NIBs statically deployed. Each of the two vehicles was periodically broadcasting a range requests message and the other nodes were replying with a range response message.

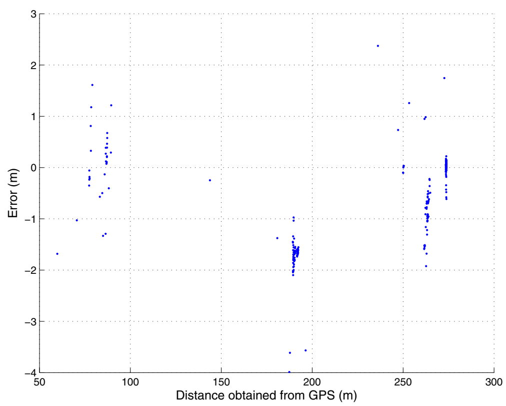


Figure 7: Difference between the distance estimated acoustically and computed using GPS data.

Figure 7 shows the ranging error results computed by subtracting the range obtained from acoustic modems to the range obtained using the vehicles GPS. The error of the acoustic modem ranging estimation varies from few centimeters to two meters: The higher errors are due to the fact that vehicles are moving when performing the ranging estimation and to the intrinsic error in the GPS measurements. As it is well known, GPS devices are affected by errors (in the order of 1 meter for the equipments used on Zarco and Gama). Therefore, we stress that the GPS-based measurements validate the ranges measured using the modems but they do not act as ground-truth in this scenario.

In each range request and response message the information about the vehicle position (obtained by the GPS) was also transmitted. During this test the two vehicles have been mimicking the scenario where they were acting as mobile transponders for the position estimation of an AUV. In fact, while the AUV is estimating the distances to the surface vehicles it can also collect the updated ASV positions while they are moving in order to properly estimate its own position. Moreover, the AUV can inform the ASV about its estimated position providing also additional information, such as direction, velocity, depth, etc., so that the surface vehicles can follow the underwater node and can provide a mobile support for the underwater positioning estimation.

Even though the vehicles were transmitting *almost continuously*, we could notice that for some locations/ranges there were no replies, as can be confirmed from the gaps in Figure 7. There are many factors that affect the propagation of underwater sound waves, but unfortunately, we were not able to conduct enough testing to allow for proper conclusions. Therefore, this is something that needs to be better investigated, in order to find a suitable combination of modem settings to alleviate the problem (gain, transmission power, etc.). However, the first results on the combination of ranging estimation and data transmission have been really promising, showing a good efficiency for the implemented mechanism and a high accuracy for the estimated ranging information.

ASV control tests

During these experiments the use of acoustic communication to instruct Zarco and Gama has been extensively tested. Several acoustic commands have been sent from the control station to both the vehicles and from one vehicle to the other. The two ASVs were cooperating using acoustic messages, instructing each other on the tasks to perform. Moreover, the coordination algorithm described above has been developed for SUNSET and adapted to use acoustic communication. All the communications to control the vehicle and to keep the formation were performed in real-time using acoustic links.

1) Moving following a square (Mission 1): During this mission the two ASVs have been interacting using SUNSET communication and networking capabilities. A control module has been implemented on SUNSET to handle the transmission and reception of commands and requests to the vehicle navigation and control system. When a remote command is transmitted to the destination node, the control module waits for a feedback to be sure on the correct reception and execution of the requested command. If no feedback is received within a given timeout, the remote command is retransmitted. A CSMA protocol without acknowledgment packets has been used at the MAC layer on SUNSET. Gama was instructing Zarco (in a real-time and on-line way) on following a predefined path. A square path with sides of $\sim$ 30m has been selected. The square corner latitudes and longitudes are reported in Table I.

First Gama has been instructed by the control station to reach the middle point “M” in the square (Figure 8) and once there Gama was holding the position and it started instructing Zarco on the reference position. Target-tracking maneuver commands with different desired points were used for this purpose. Zarco was first instructed to move to point A; once there it sent a

Point	Latitude	Longitude
A	$41°3'35.66''N$	$8°27'18.99''W$
B	$41°3'36.66''N$	$8°27'18.99''W$
C	$41°3'36.66''N$	$8°27'17.69''W$
D	$41°3'35.66''N$	$8°27'17.69''W$
M	$41°3'36.16''N$	$8°27'18.34''W$

Table I: Location of square corners.

Figure 8: Square corners at Douro river.

"maneuver accomplished" message to Gama. At this point Gama asked Zarco to navigate to point B. Once in B, Zarco informed Gama and it was then sent to C and so on. The interaction between the ASVs continued and Gama made Zarco moving along all the square corners.

Figure 9 shows the mission results where the positions of the two vehicles have been obtained by the GPS information. We can see that Gama is keeping its position in the middle of the square while Zarco is instructed to move along the square corners (blue dotted line).

All the acoustic messages between Zarco and Gama were correctly transmitted and received at the destination. No packet loss or retransmission occurred.

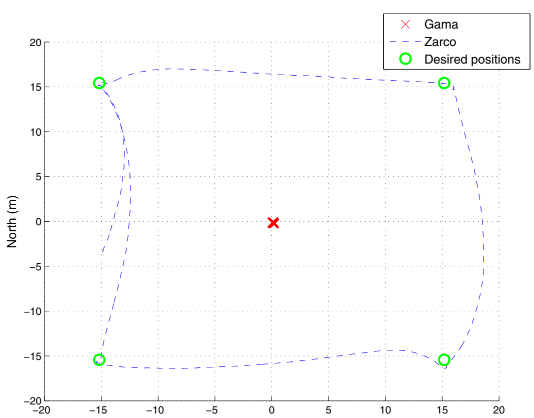


Figure 9: Mission 1 at Douro river.

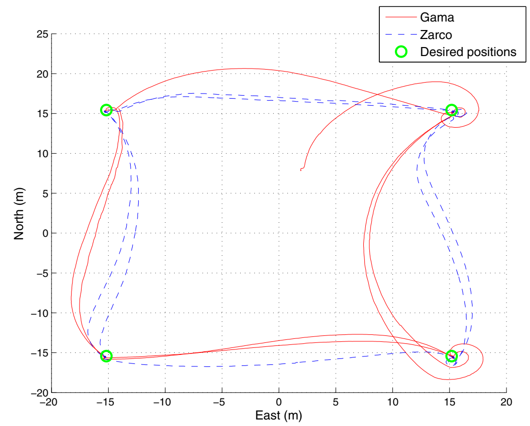


Figure 10: Mission 2 at Douro river.

2) Moving following a square (Mission 2): During this mission the two vehicles were instructing each other on the actions to perform, moving alternatively along the square corners. Same SUNSET control and MAC solutions of Mission 1 have been assumed also in Mission 2. For the sake of illustration, consider that Zarco is instructed to move to the point A. Once arrived at the destination, it instructs Gama to move to the opposite corner point C. Once Gama gets to C, it instructs Zarco to move to the opposite corner (point B). When Zarco reaches B it instructs Gama to move to D and so on.

The sequences of points followed by Zarco and Gama were $A \to B \to C \to D$, and by Gama $C \to D \to A \to B$, respectively. Figure 10 shows the trajectories, red steady line for Gama and blue dotted line for Zarco. In order to cooperate, each vehicle instructs the other to move to another point using the *target tracking* controller (see section III-A). In this case, the effects of disturbances (wind and current) made the vehicles adopt the curvilinear trajectories shown in Figures 9 and 10. Note that the vehicles are only trying to reach the points, and not following straight lines.

During this test about 10% of data packets were lost at the MAC layer and the control solutions had to retransmit the requested commands. A possible reason for packet loss was the passing of boats by the testing area, with the generated noise impairing acoustic communication. However networking capabilities of SUNSET allowed to correctly deliver all request commands to the destination node and the mission ended successfully.

3) ASVs coordination tests: During this experiment the ASV coordination algorithm has been investigated using acoustic messages. The two ASVs were acting as follower nodes and a virtual leader was running on the control station. Although a configuration with only two communicating nodes (the ASVs only) would have been

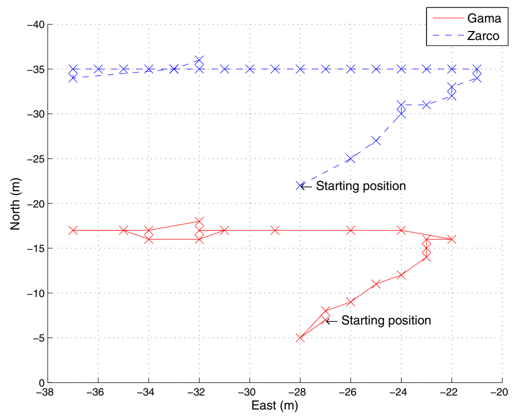


Figure 11: Zarco and Gama trajectories while coordinating. The crosses indicate the communicated positions.

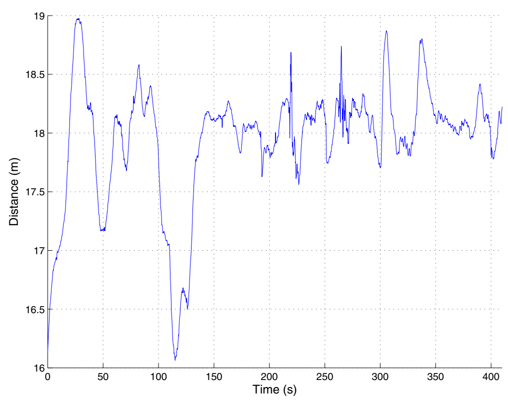


Figure 12: Distance between Zarco and Gama ASVs while keeping the formation.

possible, the inclusion of a third modem on shore made it possible to monitor the on-going mission.

The same control solution used in the previous missions, this time with no immediate feedback, has been assumed. A TDMA protocol has been used at the MAC layer, repeating a period of three slots, one for the leader and two slots for the followers (one per follower). According to the coordination algorithm, the leader starts instructing the followers according to the specific formation to keep. Once the followers receive the navigation instruction sent by the leader, they reply in their own slot informing the leader on their current position. If a follower node does not receive the leader message, it does not reply and its own slot is empty. According to the received positions of the two followers, the leader was estimating the new instruction for each of the followers.

Experiment results are shown in the Figure 11, red steady line for Gama and blue dotted line for Zarco. The plot shows the trajectories of Zarco and Gama perceived by the virtual leader, i.e., the trajectories generated by using the data communicated acoustically by the ASVs. We emphasize that the adopted resolution for both references and position feedback was one meter. The crosses on each trajectory indicate when the virtual leader was able to correctly receive the location transmitted by the respective vehicle. We have estimated that the leader has been able to correctly deliver 86% of the transmitted packets to Zarco and 84% to Gama. Moreover, Zarco has been able to correctly deliver 8% more responses to the leader than Gama. For this reason the trajectory followed by Zarco is more in line with the leader instruction than the one followed by Gama. Although the presence of packet loss together with natural disturbances such as wind and currents have repercussions on the performance of the coordination of the ASVs, the stability of the overall system was not affected, as both vehicles accomplished their mission successfully.

While moving, both vehicles were logging their own position at a rate of 10Hz. In Figure 12, we show the distance between the ASVs resulting from the post-processed logged data. The average distance between the two vehicles is about 18 meters with a maximum deviation below two meters when using acoustic links for vehicle cooperation. Additional tests have been performed where radio communications have been used to keep the vehicle formation, in this case the maximal deviations is below 10cm. As expected , the results show a less accurate motion when using acoustic transmissions due to longer latency, loss of packets and decreased resolution in both references and positions. Nevertheless, even under such constraints, the variance of the distance between the two ASVs remains relatively small and the coordination algorithm provides satisfactory performances, demonstrating that it can accommodate the latency and the loss of data. Moreover, the considered coordination algorithm has been designed assuming the use of radio transmissions and it has been here only adapted to use acoustic communication. Several improvements can be therefore investigated to make it more suitable when used in the underwater domain.

VI. Conclusion and Further Work

In this paper we describe the implementation of an underwater acoustic network to support the operation of heterogeneous systems, including AUVs, ASVs, and moored devices. The SUNSET framework has been used to provide acoustic communication and networking capabilities to a set of robotic platforms developed by the Oceans Systems Group, at the University of Porto, in Portugal. Several experiments have been conducted at the laboratory and in the field, showing both the networking capabilities and also the accuracy of range measurements between the nodes. The successful accomplishment of these trials demonstrates that both the vehicles architectures and SUNSET proved to be adequate to address the initial challenges. Furthermore, we think that the modularity and versatility of the system may be further exploited, so that the communication network may be expanded to include a much larger number of systems, both fixed and mobile.

Following this proof of concept, the next effort will be concentrated on the integration of the full system, including vehicle/formation control and localization using solely ranges obtained via the acoustic network. In order to achieve this, it is essential to perform a thorough evaluation of system performance, by extensive testing in field operations, particularly in difficult scenarios.

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REFERENCES

[1] N. A. Cruz and A. C. Matos, "The MARES AUV, a modular autonomous robot for environment sampling," in *OCEANS 2008*, 2008, pp. 1–6.

[2] N. Cruz, A. Matos, S. Cunha, and S. Silva, "Zarco - an autonomous craft for underwater surveys," in *Proceedings of the 7th Geomatic Week, Barcelona, Spain, February 2007.*, 2007.

[3] A. Matos and N. Cruz, "Coordinated operation of autonomous underwater and surface vehicles," in *OCEANS 2007*, 29 2007-oct. 4 2007, pp. 1 –6.

[4] R. Almeida, N. Cruz, and A. Matos, "Synchronized intelligent buoy network for underwater positioning," in *Oceans 2010*, Sept. 2010.

[5] N. Cruz, L. Madureira, A. Matos, and F. L. Pereira, "A versatile acoustic beacon for navigation and remote tracking of multiple underwater vehicles," in *Oceans 2001*, Honolulu, HI, USA, Nov. 2001, pp. 1829–1834.

[6] N. A. Cruz, A. C. Matos, R. M. Almeida, B. M. Ferreira, and N. Abreu, "Trimares - a hybrid auv/rov for dam inspection," in *OCEANS 2011*, sept. 2011, pp. 1 –7.

[7] B. M. Ferreira, A. C. Matos, and N. A. Cruz, "Modeling and control of TriMARES AUV," in *Robotica 2012: 12th International Conference on Autonomous Robot Systems and Competitions*, E. Bicho, F. Ribeiro, and L. Louro, Eds. Guimarães: Universidade do Minho, 2012, pp. 57–62.

[8] M. Egerstedt and X. Hu, "Formation constrained multi-agent control," *Robotics and Automation, IEEE Transactions on*, vol. 17, no. 6, pp. 947 –951, dec 2001.

[9] C. Petrioli and R. Petroccia, "SUNSET: Simulation, emulation and real-life testing of underwater wireless sensor networks," in *Proceedings of IEEE UComms 2012*, Sestri Levante, Italy, September, 12–14 2012.

[10] The VINT Project, *The ns Manual*. http://www.isi.edu/nsnam/ns/, 2002.

[11] N. Baldo, F. Maguolo, M. Miozzo, M. Rossi, and M. Zorzi, "ns2-MIRACLE: A modular framework for multi-technology and cross-layer support in network simulator 2," in *Proceedings of the 2nd International Conference on Performance Evaluation Methodologies and Tools, ValueTools 2007*, Nantes, France, October 23–25 2007, pp. 1–8.

[12] SENSES Lab, "SUNSET: Sapienza university networking framework for underwater simulation, emulation and real-life testing." [Online]. Available: http://reti.dsi.uniroma1.it/UWSN_Group/index.php?page=sunset

[13] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "Channel-aware routing for underwater wireless networks," in *Proceedings of IEEE OCEANS 2012*, Yeosu, Korea, May, 21–24 2012.

[14] S. Basagni, C. Petrioli, R. Petroccia, and M. Stojanovic, "Optimized packet size selection in underwater WSN communications," *IEEE Journal of Oceanic Engineering*, vol. 37, no. 3, pp. 321–337, July 2012.

[15] A. Syed, W. Ye, and J. Heidemann, "Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 9, pp. 1731–1743, December 2008.

[16] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks." *IEEE Communications Letters*, vol. 11, no. 12, pp. 1025–1027, December 2007.

[17] H. Yan, Z. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. of IFIP Networking*, Singapore, May 2008.

[18] J. M. Jornet, M. Stojanovic, and M. Zorzi, "Focused beam routing protocol for underwater acoustic networks," in *Proceedings of the third ACM International Workshop on UnderWater Networks (WUWNet '08)*, San Francisco, California, USA, September 15 2008, pp. 75–82.

[19] J. Alves and G. Zappa, "Low overhead routing for underwater acoustic networks," in *Proceedings of IEEE OCEANS 2011*, Santander, Spain, June, 6–9 2011.

[20] R. Urick, *Principles of Underwater Sound*. McGraw-Hill, 1983.

[21] M. Porter *et al.*, "Bellhop code." [Online]. Available: http://oalib.hlsresearch.com/Rays/index.html

[22] F. Guerra, P. Casari, and M. Zorzi, "World ocean simulation system (WOSS): a simulation tool for underwater networks with realistic propagation modeling," in *Proceedings of the Fourth ACM International Workshop on UnderWater Networks*, ser. WUWNet '09, Berkeley, California, USA, 3 November 2009, pp. 1–8.

[23] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI Micro-Modem: An acoustic communications and navigation system for multiple platforms," http://www.whoi.edu/micromodem/, 2005.

[24] Evologics, "Evologics S2C acoustic modems." [Online]. Available: http://www.evologics.de/

[25] Kongsberg maritime, "Instruction manual cnode maxi transponder." [Online]. Available: http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/4ADD212486A1B94EC125780000355234/

[26] Teledyne Benthos, "Teledyne benthos undersea systems and equipment." [Online]. Available: http://www.benthos.com/acoustic-telesonar-modem-product-comparison.asp

[27] A. Annunziatellis, S. Graziani, S. Lombardi, C. Petrioli, and Petroccia, "CO2Net: A marine monitoring system for CO_2 leakage detection," in *Proceedings of IEEE OCEANS 2012*, Yeosu, Korea, May, 21–24 2012.

[28] O. Kebkal, K. Kebkal, and R. Bannasch, "Long-baseline hydro-acoustic positioning using d-mac communication protocol," in *Proceedings of IEEE OCEANS 2012*, Yeosu, Korea, May, 21–24 2012.

[29] "Gumstix inc." [Online]. Available: http://www.gumstix.com