Autonomous Underwater Vehicles for Cooperative Surveys of Deep-Water Sites

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Abstract

Experimental results obtained with the Autonomous Underwater Vehicles developed in the "Thesaurus" project are reported. The Thesaurus AUVs, "Typhoon", are low-cost torpedo-shaped 300 m depth-rated vehicles implementing a distributed communication and localization scheme based on acoustic modems, one of them with Ultra Short Base Line (USBL) capabilities. Communication and localization results obtained in the experimentation of the Thesaurus project and the CMRE (NATO Ctr. Maritime Res. Exp.) cruise CommsNet13 show that the modem-based acoustic localization has the capacity of correcting the navigation drift of low-cost inertial units even at the very low and time-varying communication rates encountered in experimental conditions.

1. Introduction

The Tuscan Archipelago (North Tyrrhenian Sea) has been one focal point of maritime activities and ship traffic since pre-roman times, up to these days. Naval battles and events have seen these waters as their theatre as well, including the medieval battles between the Maritime Republics of Genova and Pisa, to World War II events. It is then no surprise that the Tuscan Archipelago is also rich in underwater relicts and marine archaeological sites of the greatest historical importance, some of them unique founds. The Tuscan Superintendence on Cultural Heritage (SBAT – Soprintendenza dei Beni Archeologici della Toscana), the sole branch of the Ministry of Cultural Heritage responsible for the localization, exploration and preservation of such sites, has identified the currently known relicts mostly thanks to occasional indications of amateur divers, fishermen, etc. Only starting in the late '90s SBAT has been able to start a program of systematic exploration of the marine areas of interest, in cooperation with the Italian Navy and research centres, as ISME, the Italian Interuniversity Res. Ctr. on Integrated Systems for the Marine Environment, to which the Authors belong. These searches, however, are quite expensive, requiring the availability of fully equipped ships, and have concentrated only on the shallow areas reachable by amateur diving (down to 60 – 70 m). The challenge is now to identify deeper water relicts that, while less frequent than shallow water ones, may lead to discoveries of completely preserved cargoes.

With this background, the Tuscany Region has funded a research project (Thesaurus) aiming at the development of technologies and methodologies for the enrichment and preservation of the knowledge gained with underwater archaeological sites *Caiti et al. (2013a)*. The project, that run for 30 months from March 2011 to August 2013, was coordinated by Centro Piaggio, University of Pisa, and included partnership with the Dept. Industrial Engineering of the University of Florence, the Inst. of Information Science and Technology of the Italian National Research Council (ISTI-CNR), Pisa, the Laboratory for Cultural Heritage (LARTTE) of the Scuola Normale Superiore, Pisa. There were several specific objectives in the project, all concurring to its general goal, including the definition of a data base for use of SBAT, the creation of videos and materials for the dissemination of knowledge on underwater sites to the public at large, etc. One of the biggest project efforts, however, consisted in the functional definition, design and test of a team of Autonomous Underwater Vehicles (AUVs) that can explore in autonomy the deeper seabed in the Tuscan Archipelago area.

One of the key challenges of this objective consisted in designing AUVs keeping their costs limited, while guaranteeing the mission goal. This has been achieved as a combination of ingenious solutions in several of the AUV sub-systems (for instance, by designing efficient propellers and then realizing them with 3-D printer technology, *Allotta et al. (2014)*). The design trade-off between costs and system capabilities is particularly critical in the case of the navigation system. Inertial Navigation Systems (INS) of marine and navigation grade may have an horizontal drift as limited as less than 2000 m per day, but at costs that can reach and overcome 1 Million €(un-aided INS are considered here, i.e., inertial systems without support from additional sensors) *Vector Navigation Tech. (2014)*. On the other hand, a tactical grade INS, whose cost is in the range € 5,000 – € 30,000, has the same horizontal drift but within an hour. Industrial grade INS, at even lower costs, may lead you to typical horizontal drifts of 50 – 60 m per minute. Within Thesaurus, it has been decided to use the information exchanged by the AUVs in the team as an aid for inertial navigation. In this way, inertial instrumentation at the lower side of the tactical grade range can be afforded, greatly limiting the system navigation costs. The “information exchange” to which we have just made reference is related to the acoustic messaging that the AUV team has to establish among its members, in order to conduct the operation, and that acoustic messaging allows estimating at least range from the two-way travel time of the acoustic signals. Indeed, some commercially available acoustic modems have been modified to include an array of receivers so that also angle of arrival of the message can be determined, achieving a functionality equal to those of Ultra Short Base Line (USBL) localization systems *Kebkal et al. (2012)*. The Thesaurus project concept has been that of using these localization-enhanced acoustic modems so that one AUV at the surface could geo-reference the two below the surface, and then messaging to them the position, Fig.1.

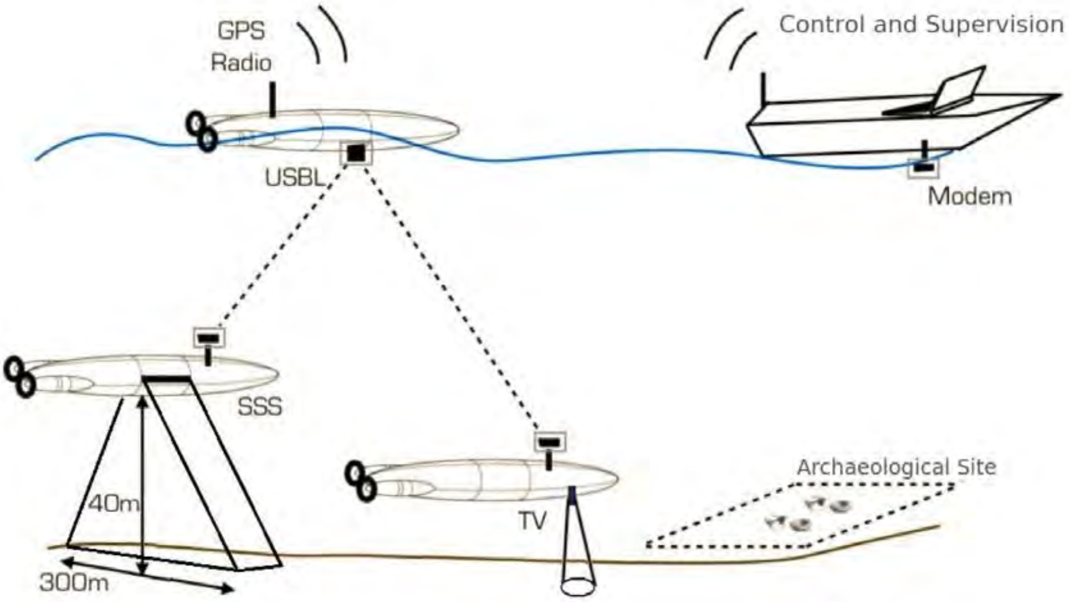

Fig.1: Concept of a team of 3 AUVs with acoustic messaging and localization capabilities: The surface vehicles, able of reading GPS signals, gets the relative position of the underwater ones through the USBL modem. Relative positions are translated into absolute (geo-referenced) positions and retransmitted as a standard message to the underwater AUVs.

Several questions rise from the operative point of view. In particular, will the mixed localization/communication scheme provide enough corrections, or corrections with fast enough rate, to maintain a sufficient accuracy in the navigation? As often happens in underwater acoustic related problem, simulations may let the designer get useful insights, but the system performance must be evaluated in the field, since the ocean is a dynamic, time-variant environment.

2. The Typhoon class AUV

Specification for the vehicle functionalities came from the collaboration of the Thesaurus members with the Tuscan Superintendence. In particular, the team focused the mechanical vehicle design toward the requirement of reaching depth of 250 m, in open sea with potentially strong current, and offering high agility and manoeuvrability, including hovering. The designed vehicle class, named ‘Typhoon’, is intermediate between shallow-water AUVs (as Remus100, Iver2) and deep-water AUVs (as Hugin), filling a gap in the existing AUV depth ranges, *Martin (2013)*.

2.1. Electromechanical characteristics and sensors

The Typhoon is a fiberglass torpedo-shaped 3.70 m length, 0.35 m diameter, 150 – 170 kg weight in air vehicle. It has six independent propellers: two at the stern, aligned along the surge axis; two lateral (sway) thrusters, and two vertical (heave) thrusters. All the propellers are counter-rotating and realized through a 3-D printer after an optimized design. The thrusters are standard 200 W brushless motor fed by the 48 V provided by the batteries and controlled through an industrial CAN bus. In addition to the heave-aligned thrusters, pitch is controlled also by internal displacement of the battery pack. Steering is obtained by combination of both the surge and the sway thrusters. Overall, all vehicle degrees of freedom can be controlled, but the roll. Figs.2 and 3 illustrate the vehicle design, the propulsion system and the first realized vehicle at the end of the test phase.

The sensors installed on board are here summarized:

- Inertial Measurement Unit (IMU) Xsens MTi: device made up of a 3D gyroscope, 3D accelerometer and 3D magnetometer furnishing dynamic data at a maximum working frequency of 100 Hz. This is the sensor used for inertial navigation;
- Doppler Velocity Log (DVL) Teledyne Explorer: sensor measuring the linear speed of the vehicle, with respect to the seabed or with respect to the water column beneath the vehicle. The DVL has been installed only on one of the three vehicles built during the project
- Acoustic modems (single modem or USBL-enhanced) by Evologics: for the underwater communication and localization;
- Echo Sounder Imagenex 852: single beam sensor, mounted in the bow of the vehicle and pointing forward. It is used as an obstacle avoidance sonar;
- STS DTM depth sensor: digital pressure sensor for depth measurement;
- PA500 echo-sounder, pointing downward, to measure the vehicle elevation from the seabed;
- Tritech Side Scan Sonar (675 KHz)for acoustic survey of the seabed.

Fig.2: CAD rendering of the Typhoon. The cylindrical central part is the dry part, with the electronics, batteries, etc. The two parts at bow and stern are the wet parts. Toward the stern is the side-scan sonar (port array).

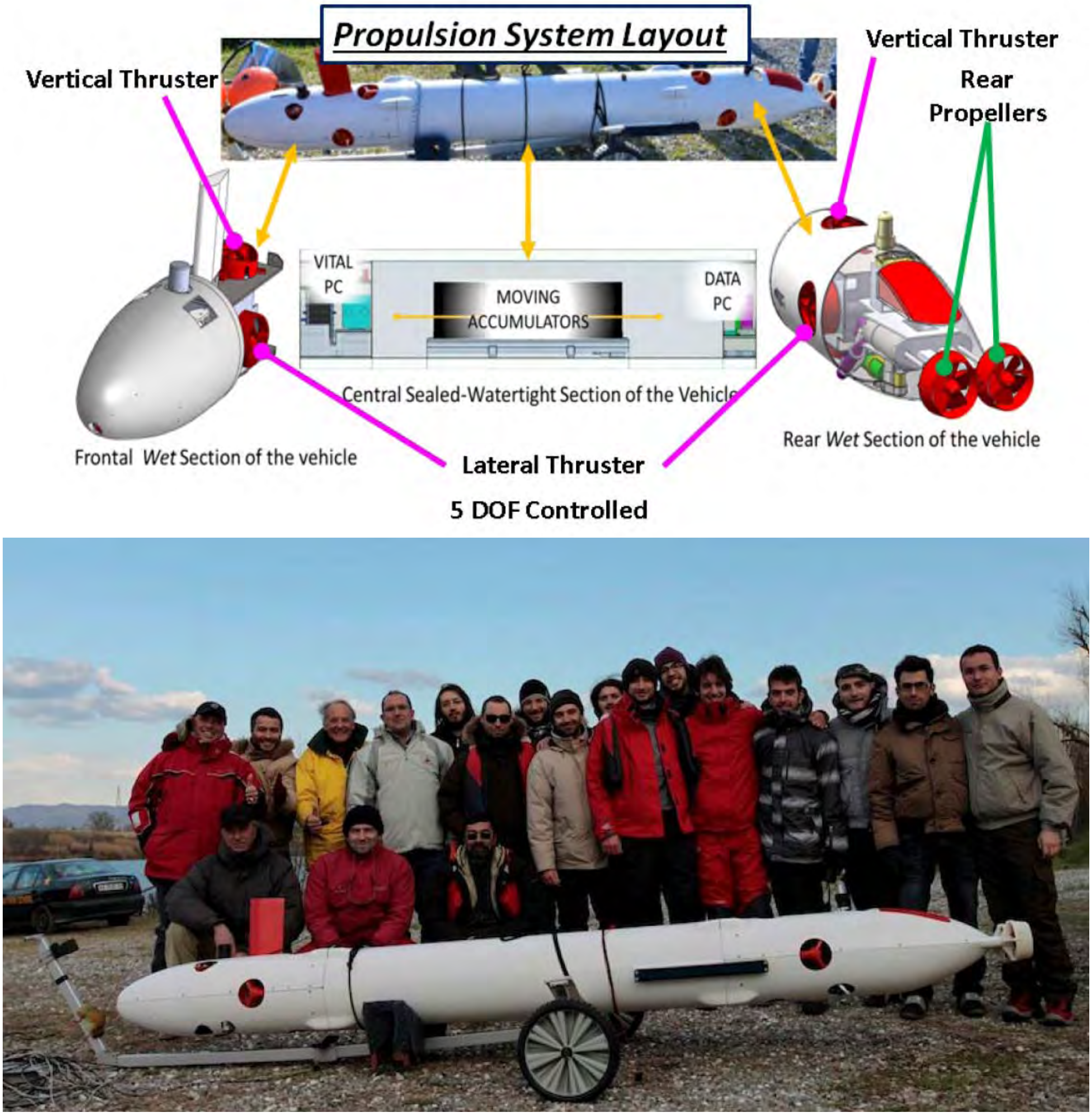

Fig.3: Top: Distribution of the actuators, in the design and in the real vehicle.
Bottom: Thesaurus team at the wet test of the first Typhoon, Roffia Lake. The acoustic modem and the radio/GPS antenna are visible on the bow section.

The on-board integration utilizes MOOS (Mission Oriented Operating Suite) as software infrastructure. MOOS, *Newman (2003)*, is an open-source publish/subscribe system for inter-process communication, which supports dynamic, asynchronous, and distributed communication. Its basic functioning relies on a dispatcher, for routing messages from publishers to subscribers. The messages are routed based on their topics, which is an information descriptor contained in the messages themselves. In MOOS the dispatcher is represented by a central database (the MOOSDB).

By exchanging messages within the MOOS framework, the Typhoon(s) can communicate with each other or with any external compatible node or even network. To this aim, the vehicles establish a communication network based on a time-sharing bi-directional/broadcast communication scheme. The goal was to create a flexible structure capable of ensuring low-delay communication and the reliable transmission of specific messages necessary for the safety of the exploration missions. The final network structure design includes few layers, avoiding most of the complexity typically present in terrestrial networks. Note that, with a limited number of layers, the network becomes less flexible and on the average less efficient: you cannot implement smart re-routing, re-scheduling algorithms, or network discovery algorithms, for instance. However, in underwater communication with few nodes, the efficiency is most of the time dependent on the physical layer, i.e., on how the channel transmit the signal. Since this is by far the predominant aspect, the absence of a more flexible structure does not compromise the network performance beyond what can be achieved due to the medium characteristics. Indeed, considering the case of a small and known in advance number of nodes in the network, adding layers can compromise robustness of the network without reward, ultimately decreasing the network performance.

We have opted for a Time Division Multiple Access (TDMA) broadcast messaging scheme, with no multi-hop (hence routing) capability. In the implemented network architecture, the bottom layer is represented by commercial acoustic modem/USBL *Kebkal et al. (2012)*, which manages the physical transmission of the signal into the water. The adopted communication mode provided by the modem, namely instant messaging, does not require connection establishment procedures, allows for broadcast messaging and permits a message maximum size of 64 bytes. The modem also implements collision avoidance techniques (Medium Access Control - MAC) and provides basic network functionalities, including an addressing system that can be exploited at the link layer. The medium access control is completed through a channel time division mechanism: time is divided into slots and each node is assigned a slot where it has to concentrate its entire communication burden. The network link layer is composed by a combination of the modem networking features and of MOOS services.

To increase the throughput of the network and the probability that an important message is transmitted without unnecessary delays, messages are organized in a priority queue: four classes of messages have been identified, each of which associated with a decreasing priority; among them, the localization messages, periodically exchanged between the vehicles to have USBL updates or range measurements, and relevant to the localization algorithm. To avoid indefinite growth of the queue, when an application generates data at a higher rate than the acoustic channel can support, at each step the messages are filtered on the basis of the time slot duration and those that cannot fit into the available time are discarded. Moreover, the organization of the queue is performed both during the non-communication periods and the communication time slot available to the vehicle; this way, the network supports almost real-time data delivery, meaning that the data are produced, organized and then transmitted during the communication period of the node. Finally, in the network link layer an additional service has been include, namely the performance/network layer, used to adapt the requests coming from the application level to the constraints of the layers below it and of the acoustic channel. The highest layer, namely the application layer, utilizes MOOS as software infrastructure. Messages to be sent through the network are published by any process to the appropriate subscriber topic, and those processes that may need to receive messages from the network register as subscribers of the relevant topics. In this way, the network becomes completely transparent from the application point of view, and indeed, from the application stands, it is not even known whether the message will be transmitted acoustically or through radio-link, as it happens when (some of) the nodes are at the sea surface and can establish radio contact

From the cooperative localization point of view, the Thesaurus scheme relies on the presence of one of the vehicles equipped with USBL-capable modem. The USBL vehicle can localize the others and update their absolute position at intervals, allowing a reset of the on-board navigation system. Indeed, the navigation system on board each vehicle relies on an Extended Kalman Filter (EKF) fusing together the on-board sensors (inertial and, if available, doppler velocimeters), the absolute positioning as communicated by the USBL vehicle, the range position from any other vehicle as measured from the acoustic messages. The EKF localization algorithm of the AUV team is described in detail by *Caiti et al. (2013b)*.

3. Typhoon tests within Thesaurus and communication performance in very shallow water

After a set of laboratory and pool tests, including pressure chamber tests to verify the hold of the dry part up to 300 dBar pressure, the first Typhoon underwent wet test in the Roffia Lake, conveniently located mid-way between the towns of Florence and Pisa, where the two working groups have their labs, in February 2013. The lake depth in the authorized area (2 – 3 m) prevents complex underwater navigation tests; nevertheless this testing was of paramount importance to tune many aspects of the implemented software. Moreover, using the other available modems in fixed position along the lake shore, it was possible to test communication architecture and to determine some network communication performance that will be reported later on in the paper. In May 2013 a second week of lake tests was performed with the same vehicle, and then in July the vehicle was put at sea for another week of engineering tests in Antignano, few miles south of Leghorn, at depths down to 25m. While the Typhoon no. 1 ("TifOne") was being tested at sea, the second and third one were tested in the lake in July and August. By the end of August, Typhoon 1 was used in its first archaeological mission, operated by the underwater squad of the Leghorn Fire Brigade, under the supervision of the Tuscany Superintendence: Typhoon 1 identified through the side-scan sonar the relict of a World War II US ship sank about 1.5 miles off Leghorn harbour. The relict was known to the Superintendence that had already photographic documentation, and selected as a test case of the vehicle capacities, Fig.4.

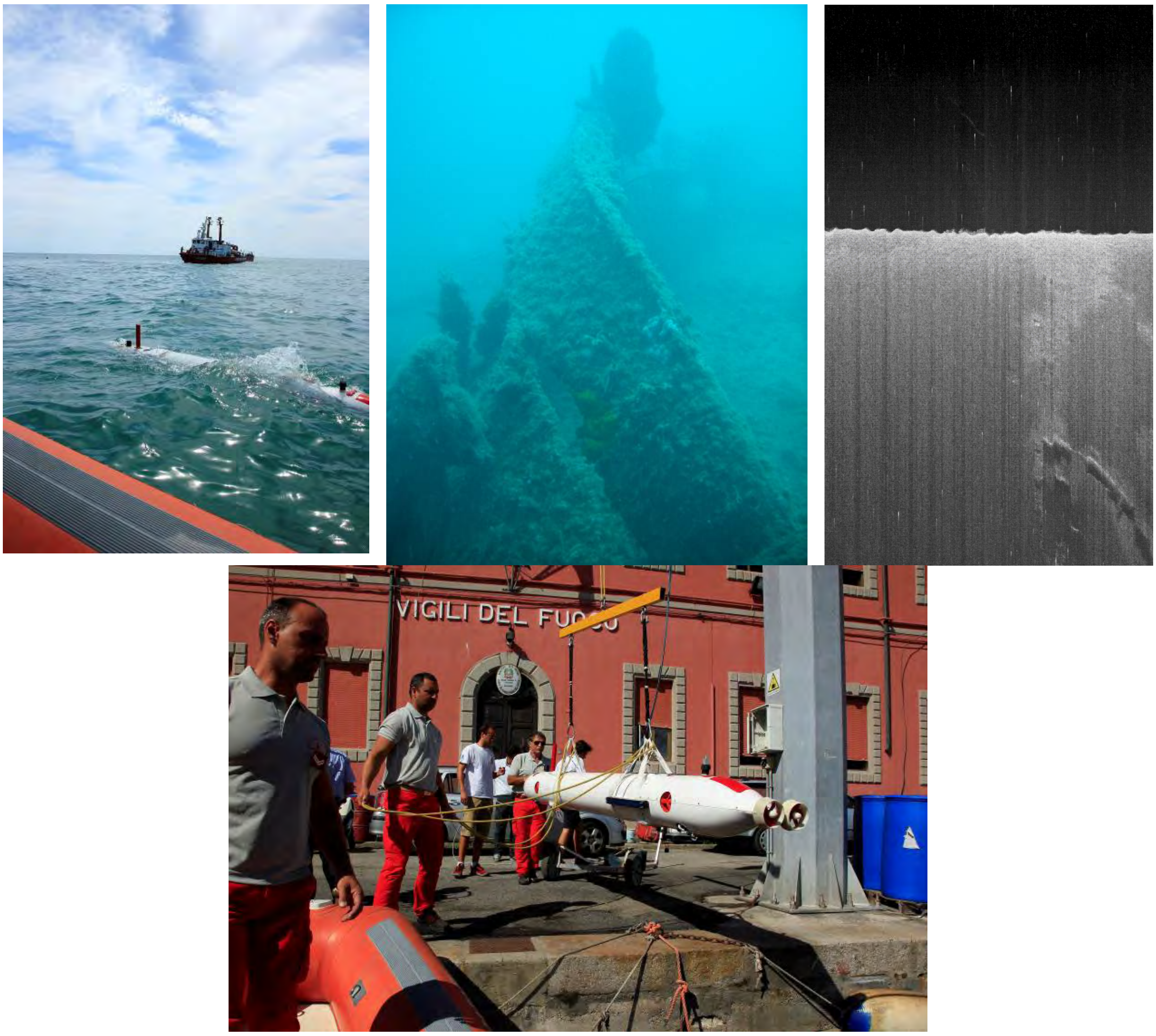

Fig.4: Top left: 'TifOne' in navigation during the archaeological test; Top middle: previous documentation of the World War II relict; Top right: side-scan sonar view of relict. Bottom: 'TifOne' deployed by Fire Brigade squad in Leghorn. (Images courtesy of Fire Brigade, Leghorn)

Right after the Leghorn field test, all three Typhoons, plus one additional shore-cable modem, were tested in the lake in particular as for the networking and communication capabilities, Fig.5). In order to evaluate the performance, the chosen metric is the packet loss percentage from one node to each other. Each packet is one message, so packet loss is equivalent to message loss. The relevant results are reported in Table I for one node as a source toward the others. Changing the source gives similar results. Nodes ranging goes from 50 m to few meters. While these results are obtained with all the sensors close to the water surface and in about 2 m of waters, i.e., in quite a challenging situation for acoustic communication, they indicate a quite important message loss probability. This loss percentage has an impact to the localization scheme, i.e., acoustic localization updates will reach the vehicles at an even slower rate than that imposed by the TDMA scheme.

Fig.5: Three Typhoons plus one shore-cabled modem in the final lake test of networking communication: 4 nodes, 20 s time slot each (Roffia Lake, August 2013)

Table I: Communication performance measured as packet loss percentage in Roffia Lake. Node 1 is the source. Test # refers to different environmental conditions (morning / afternoon)

Test #	Node #	Packet loss (%)
1	2	46
1	3	60
1	4	79
2	2	62
2	3	60
2	4	61

4. Typhoon at CommsNet 13: Acoustic localization and underwater navigation

Right after the end of the Thesaurus testing, the ISME groups of the Universities of Pisa and Florence jointly participated, bringing two Typhoons, to the activities of the CommsNet13 cruise that took place in the Gulf of La Spezia, Northern Tyrrhenian Sea, from September 9 to 22. The CommsNet13 cruise was organized and scientifically led by the NATO Science & Technology Centre for Maritime Research and Experimentation (CMRE), and had the broad objective of testing and comparing methodologies for underwater communication, localization and networking. Several research institutions were invited to participate in the testing; the cruise was performed from on-board the R/V Alliance, and exploited the CMRE network of shore-cabled acoustic modem placed on the seabed in the experimental area, *Alves et al. (2012)*. Being these modems compatible with those of the Typhoons, the communication and localization scheme devised for Thesaurus could be effortlessly transferred to the CommsNet13 situation. In particular, Typhoon no. 2, the one with USBL modem, was used during the experimentation. The tasks of the USBL Typhoon were as follows:

- localize and geo-reference the sea-bed modem, interrogating them from the surface (i.e., exploiting its own geo-referenced position from GPS signal availability);

- use the geo-referenced position of the modem to get acoustic fixes during underwater navigation.

The latter task implies the use and evaluation of the on-board EKF fusing the Inertial Measurement Unit with the acoustic fixes. Note that the combined performance of the communication system between the USBL vehicle and the modems, as well of the data fusion navigation system, is crucial to evaluate the possibility of using an acoustically aided low-cost inertial navigation system.

In the following, we will report the results of both phases for one indicative day of the cruise, using a navigation track on the surface in which the GPS signal is only used to initialize the filter, but then not used in the navigation data algorithm. In this way we can use the measured GPS as ground truth against which compare the INS+acoustic navigation performance. Fig.6 shows some image of the experimental campaign.

Fig.7 shows the experimental configuration for the day considered. The Typhoon was going to repeat a triangle route, indicated in yellow, while the seabed modems are nominally located in the position of the black dots. The effective localization of the sea-bed modem was obtained by the USBL Typhoon. The Typhoon was at the surface, going through the repeated triangle path and navigating with the GPS, while interrogating the various modems with the TDMA communication procedure. The interrogation allowed estimating the relative position of the modems with respect to the vehicle, and then the GPS vehicle position is used to geo-reference the modem. The geo-referenced modem position is taken as the average of the various measured positions, with outliers excluded. Standard deviation of the position estimate varies between 0.8 and 5.2 m. Note that there are 6 nodes in the network. The average packet loss during the day of the USBL Typhoon toward any other node has been of 38 % - water depth in the area was varying between 16 and 6 m.

Fig.6: Images from the CommsNet 13 cruise. From top left, clockwise: the CMRE R/V Alliance from the coast of Portovenere, Gulf of La Spezia; Typhoon no.2 in navigation; Typhoon no.2 and Alliance; the two Typhoons brought on board the Alliance for the cruise operations.

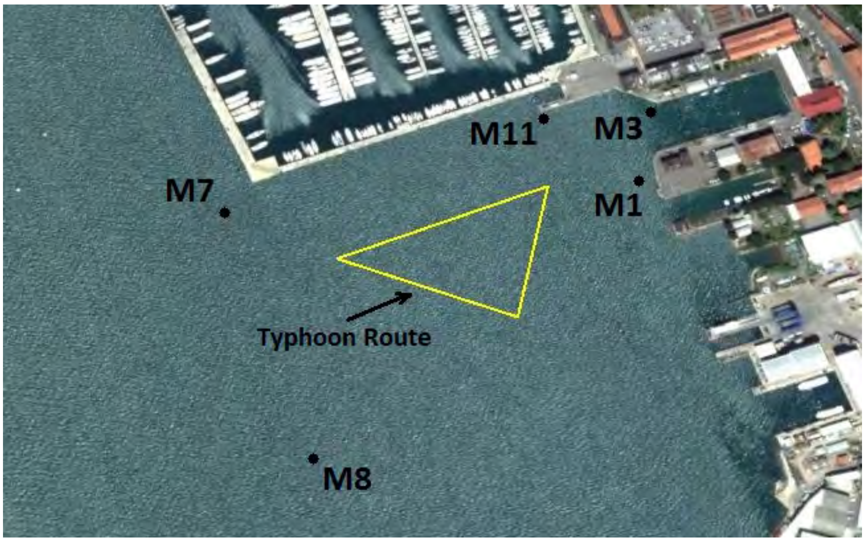

Fig.7: Experimental configuration for the CommsNet13 exercise reported. The black dots indicate the seabed modem nominal positions; the yellow trinagle the nominal Typhoon route. Each triangle side has a length of approximatedly 150 m.

After the initial phase for the modem geo-localization, the USBL Typhoon started the runs over the nominal triangle route, staying at the surface and navigating with the GPS. As the experiment ran, the vehicle was interrogating the modems and receiving localization information, that could be used for its own geo-referencing thanks to the on-board presence of the USBL modem (i.e., no additional messaging was necessary in this case. Due to relatively large number of modems and to the packet loss, the USBL acoustic fixes were not too frequent. Fig.8 shows the effective vehicle route, according to the GPS, and the difference between the GPS position and the acoustic position as received from the USBL.

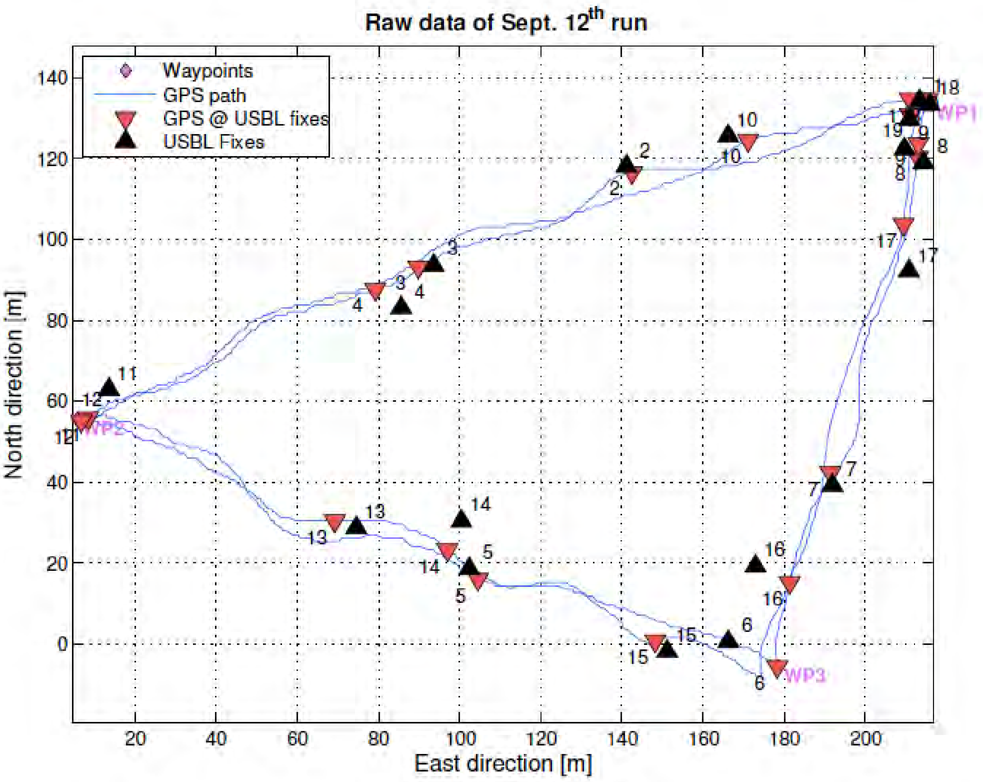

Fig.8: Typhoon effective route according to GPS (thin line); GPS positions at the time of USBL acoustic fixes (red triangle, pointing down); USBL acoustic fixes (black triangle, pointing up)

Table II reports the difference between the GPS and USBL position. Note that the data in Table II are interesting because they represent the inherent error of the acoustic correction that is then injected in the acoustic-aided inertial navigation filter.

Table II: Difference between GPS and USBL position

Fix #	Error (m)	Fix #	Error (m)
1	2.27	10	8.48
2	3.38	11	2.15
3	8.18	12	5.94
4	3.04	13	8.44
5	13.23	14	4.26
6	2.91	15	9.83
7	1.89	16	11.55
8	3.11	17	1.32
9	5.09	18	1.16

Fig.9 shows the estimated navigation with the acoustically aided INS system compared with the GPS, assumed as ground truth. Fig.10 shows the error as a function of time, showing the instant in which the acoustic fix is injected in the filter. The INS drift can become quite consistent with the delays experienced in the experiment, but it has been always reset by the acoustic fix; the acoustic fix itself is not able, because of its inherent error, to reset the navigation error completely to zero. However, this level of accuracy is still compatible with the archaeological search which is the original motivation of the project. Note also that, using the network of seabed modem as acoustic pingers, i.e., not treating them as nodes in network capable of messaging, greatly reduces the time interval between one acoustic fix and the next. Depending on the application and situation, the system performance can be improved, but, we fear, not beyond the precision of the USBL system itself.

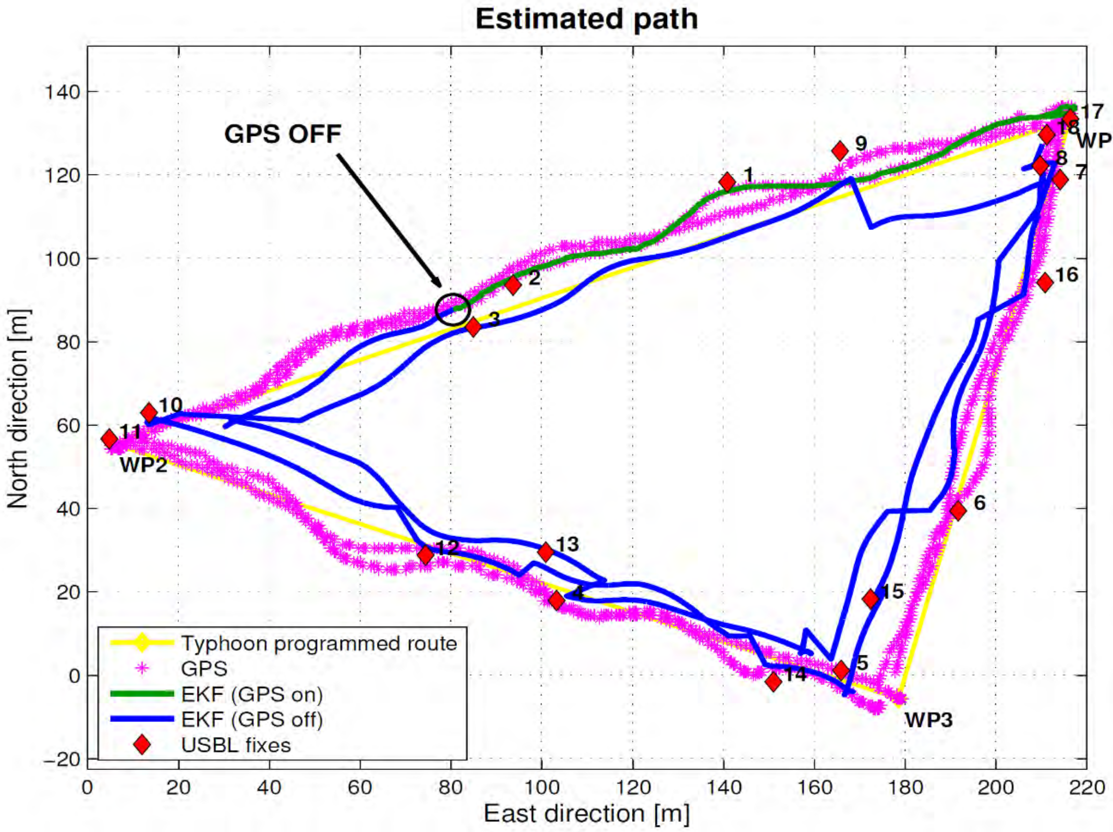

Fig.9: GPS route (purple, asterisks), acoustically aided INS route (thin line), initialized with GPS. Red diamonds indicate the GPS fixes.

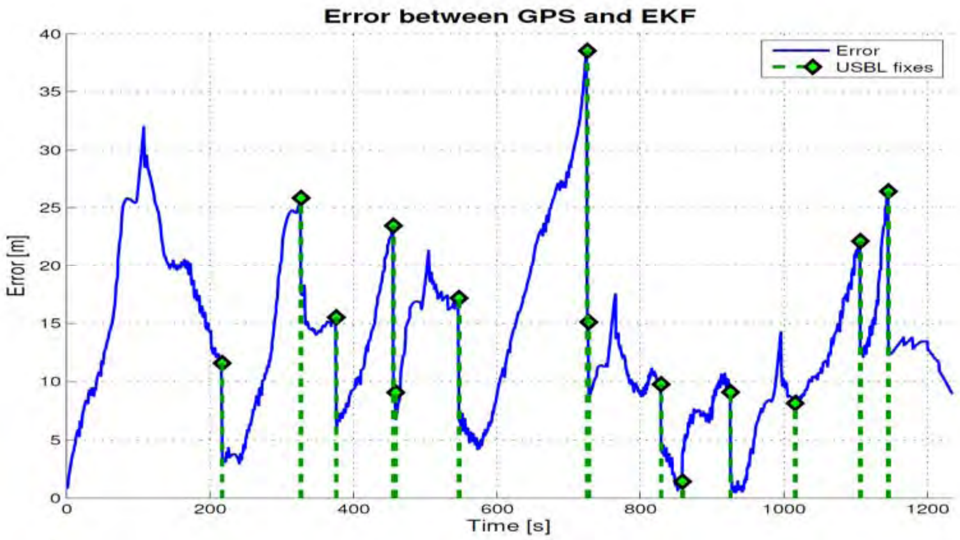

Fig.10: Error vs. time between the GPS and the acoustically aided INS system. Green diamonds correspond to the time of USBL fix arrival

5. Conclusions

The paper has reported some general features regarding the development of the Typhoon AUVs, developed for archaeological search in cooperative missions, and then has concentrated on the communication and localization capabilities of the developed system. In particular, the localization and navigation data shows that acoustic localization can indeed reset the navigation drift typical of low cost IMU, as those employed on board the Typhoons. However, an increase in the acoustic fixes rate could further improve the navigation performance. Such increase has to come out from a trade-off between message passing for mission management and acoustic pinging for localization only applications.

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