Thesaurus: AUV teams for archaeological search. Field results on acoustic communication and localization with the *Typhoon*

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Abstract—**The *Thesaurus* project, funded by the Tuscany Region, had among its goals the development of technologies and methodologies for archaeological search with Autonomous Underwater Vehicles working as a team in exploration missions. This has led to the design and realization of a new AUV class, the *Typhoon*, on the basis of the archaeological requirements, and of an appropriate acoustic simultaneous communication and localization scheme. The paper describes the project background, the technical characteristics of the *Typhoon* AUVs, and the field results in acoustic localization as obtained in the CommsNet13 cruise, led by the NATO CMRE (Centre for Maritime Research and Experimentation), to which the Thesaurus project teams of the University of Pisa and Florence took part. In particular, the fields result reports the performance of acoustic localization through on-board USBL communicating with fixed modems placed in initially unknown locations.**

I. Introduction

The Tuscan Archipelago is situated in the North Tyrrhenian Sea, part of the Mediterranean Sea, facing the coast of Tuscany and the towns of Pisa and Leghorn. This land is rich with historical remnants, dating back to the Etrurians (VII - VIII Century B.C.), a pre-Roman population whose territory extended from Tuscany to the land where Rome was founded. Travelling by sea along the coast was the preferred way of goods transportation since these ancient times, to avoid swamps and marshes along the land paths. Sailors could take advantage of the numerous islands in the archipelago (Elba Island being the major one) offering shelter and port call opportunities. Moreover, some of the goods were produced on the islands, as is the case with the iron ores in Elba Island. Commercial navigation in the area has been continuously active throughout the centuries, from Roman to medieval times, in which Pisa was a ”maritime republic”, competing with Genoa and Venice in controlling the commercial trade over the Mediterranean. In the modern era, while Pisa decayed, the nearby harbour of Leghorn raised its importance as a trade market, importance which is kept till to these days, and as a base for foreign navies involved in operations in the Mediterranean (as the British Navy in the 18th / 19th centuries, or the U.S. Navy during Worl War II; today Leghorn is also hosting the Italian Navy Academy). A network of satellite smaller harbours along the coast and in the islands of the Archipelago had throughout been developed and kept.

It is no surprise that, given the intensity of maritime traffic in the region, and its very wide time span, the area is also rich in marine relicts of precious historical and archaeological content, some of them unique founds. Underwater archaeological sites are mostly identified by chance, through the occasional indication of the amateur diver, or by fishermen. The Superintendence of Cultural Heritage of Tuscany, i.e., the Authority responsible for the identification and preservation of such sites, has conducted in the last twenty years a series of cruises for systematic search of marine archaeological sites in selected areas of the Archipelago; these searches, however, are quite expensive, requiring the availability of fully equipped ships, and can cover only limited portions of the seabed at a time. Nevertheless, as the result of these activities along the years, the archaeologists have come to the conclusion that in coastal areas with water depth less than 70 - 80 m the most relevant relicts have already been found and identified, or by now have been spoiled by amateur divers. The challenge for archaeologists is now to identify deeper water relicts that, while less frequent than shallow water ones, may lead to discoveries of completely preserved cargoes. Some examples of both modern and ancient relicts at depth exceeding the 100m have already been found in the Archipelago [1].

With the above background, the Tuscany Region has funded a project devoted to the development of Autonomous Underwater Vehicles (AUVs) purposely designed for deep water archaeological search and documentation, to be used in autonomous team search. The main idea is that autonomous vehicles can greatly reduce the costs associated to current search and exploration trials, while operation in team can speed-up the search, make available heterogeneous payloads installed on different vehicles, allow better navigation through a scheme of team localization, in which surface vehicles, with GPS access, communicate their position to the underwater ones. Since underwater communication is restricted to acoustic signals, the underwater vehicles can determine their relative position with respect to the surface ones from the acoustic messages themselves, and answer back their position. This communication/localization mechanism allow for mission monitoring, adaptation and reconfiguration.

Search, exploration and sampling with autonomous platforms is a concept that can be traced back at least to the seminal paper by Curtin *et al.* on Autonomous Ocean Sampling Network [2]; however, only in recent years AUV technology has become mature enough to allow for experimentation of cooperative missions. These include the Monterey Bay series of experiments [3], [4] and a set of European Union (EU) funded projects as CogAUV [5], [6], Grex [7], Morph [8]. Networked acoustic communication with AUVs and fixed nodes has also been the object of the investigations, among others, of the UAN EU project [9], [10].

The project, called *Thesaurus*, started in March 2011 and ended in August 2013, and capitalized on the experience gained in the previously cited projects. It has also to be mentioned that the project included two teams (Pisa and Florence) from ISME, the Interuniversity Res. Ctr. on Integrated Systems for the Marine Environment, a consortium of different Italian universities active in the field of marine technologies and oceanic engineering. ISME collaborates with the Tuscany Superintendence since 2001, and has participated in several research initiatives on the application of robotic techniques to underwater archaeological work [11], [12].

With respect to the previously cited experiences, the *Thesaurus* 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 maneuverability, 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 exisiting AUV depth ranges. From the cooperative localization point of view, the *Thesaurus* scheme relies on the presence of one of the vehicles equipped with an enhanced acoustic modem capable of Ultra Short Base Line (USBL) localization. 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 availble, 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 communication/localization scheme of the AUV team has already been described in detail in [13].

In this paper, in the next Section, the technical characteristics of the Typhoon vehicles are reported and described in detail. In Section III a brief summary of the localization scheme is given. In Section IV the field results obtained by the USBL vehicle in underwater navigation communicating with a net of bottom fixed modems are reported. These field results were obtained in the CommsNet13 sea trial, September 2013, organized and scientifically led by the NATO Sci. & Tech. Ctr. on Maritime Res. and Exp. (CMRE), in the Gulf of La Spezia, North Tyrrhenian Sea. The interest in the experiments relies on the fact that the position of the bottom moored modems is not known in advance, but it is estimated by the USBL AUV; using the estimated position as fixes, the AUV can then navigate underwater. Since the procedure may work even with a single modem at the bottom, it may represent a relatively cheap and fast procedure for reliable underwater navigation.

II. Typhoon class vehicles

The primary design requirements for the Typhoon vehicles are: maximum operating depth of 250 meters; autonomy ranging from 8 to 10 hours; maximum speed of 5-6 knots; and low cost.

A first fleet of three different underwater vehicles has been developed, as visible in Figure 1 ([14]–[16]). The three vehicles can be characterized as follows:

- Vision Explorer: a vehicle equipped with cameras, laser and structured lights for an accurate visual inspection and surveillance of archaeological sites. Visual inspection involves a short range distance (few meters) between the vehicle and the target site, and the capability of performing precise manoeuvring and hovering;
- Acoustic Explorer: preliminary exploration of extended area to recognize potentially interesting sites involves the use of acoustic instruments, such as side-scan-sonar. This kind of vehicle can perform long range, extended missions. Consequently, navigation sensors able to compensate the drift of the inertial sensors, such as a DVL (Doppler Velocity Log), have to be installed on board;
- Team Coordinator: a vehicle with extended localization and navigation capabilities is used to coordinate the team. This vehicle periodically returns to surface providing the GPS positioning and, more generally, detailed navigation information that can be shared with other vehicles of the team.

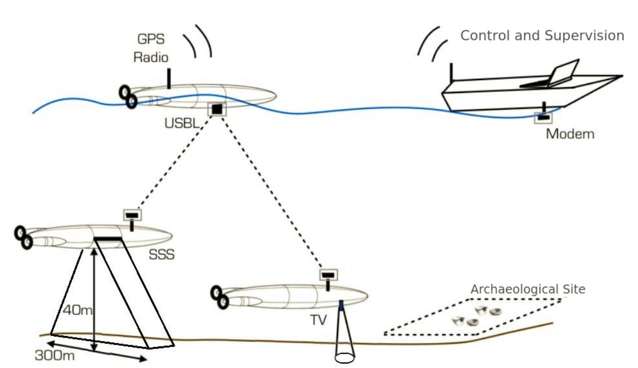


Fig. 1. Typhoon AUVs in team formation

In accordance with the project requirements, a hybrid design, able to satisfy different mission profiles, has been

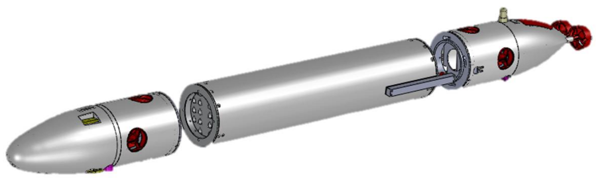


Fig. 2. Typhoon AUV: CAD design

Fig. 3. Typhoon AUV: final version

preferred, to reduce the engineering and production costs and to assure vehicle interchangeability. Each vehicle of the team can be customized for different mission profiles; so the team composition can be altered, e.g. two vehicles may be equipped for the visual inspection of a site.

A. Typhoon Hardware

Typhoon vehicle is a middle-sized class AUV, whose features are comparable with other existing vehicles. Considering the vehicle sizes (length of about 3600 mm, external diameter of about 350 mm, weight of 130-180 kg according to the carried payload) and the expected performances (maximum reachable depth of about 300 m, at least 10 hours of autonomy and a maximum speed of 5-6 knots) the vehicle can be considered an intermediate one compared to the smaller Remus 100 and the bigger Remus 600. In Figure 2 and Figure 3 the Typhoon CAD design and its final built version can be seen.

1) On board equipment and payload: Since every vehicle can be customized to manage different payloads and mission profiles, the system was designed by dividing the on board subsystems in two main categories [16]:

- Vital Systems: all the navigation, communication and safety related components and functions of the vehicle are controlled by an industrial PC-104, called Vital PC, whose functionality is continuously monitored by a watchdog system. Most of the code implemented on the Vital PC is quite invariant with respect to the mission profiles and payloads, assuring a high reliability of the system;
- Customizable Payloads: all the additional sensors and functions related to variable payloads are managed by one or more Data PC. In particular, the Data PC also manages the storage on mass memories (conventional hard discs or solid state memories) and the data coming from the connected sensors. This way, all the processes introduced by additional payloads are implemented on a platform which is also physically separated from the vital one; from an electrical point of view the two parts are protected independently through fuses and relays.

The on board integration utilizes MOOS (Mission Oriented Operating Suite) as software infrastructure [17]. MOOS is a publish/subscribe system for interprocess communication (IPC), which supports dynamic, asynchronous, and distributed communication. Its basic functioning, usual in all pub/sub systems, relies on a dispatcher, which is responsible 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 (called MOOSDB).

For reason of brevity here is only reported a list of the on board sensors and payloads:

- 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. The device measures the orientation of the vehicle in a 3D space in a accurate way thanks to an estimate inner owner algorithm;
- 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. Moreover, if it detects the seabed it is also able to measure the distance from it (like an altimeter);
- 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 can measure the distance from the first obstacle(s) placed in front of the vehicle;
- STS DTM depth sensor: digital pressure sensor used to measure the vehicle depth;
- 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.

2) Propulsion system: The vehicle movements are given by its propulsion system: in Figure 4 a simplified scheme of the proposed layout is shown.

Linear motions along x, y, z directions and pitch and yaw rotations are directly controlled by a system of actuators composed of two main propellers (longitudinal) and

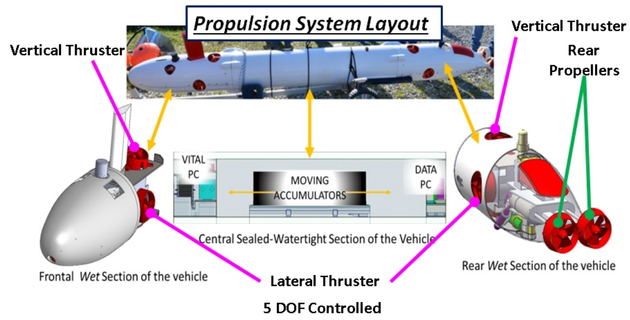


Fig. 4. Propulsion system design

four thrusters (two vertical and two lateral). Moreover the longitudinal position of the accumulators can be modified to control the vehicle pitch.

III. Acoustic Localization

One of the AUVs within the team has extended localization and team coordination capabilities as its main feature. To this aim, the vehicle is equipped with a GPS an USBL head, which is able to measure the distance and the orientation of another acoustic modem with respect to itself by interrogating it and waiting for the synchronized answer. The relative position of the interrogated modem is thus provided as a vector resolved in the USBL reference frame. The module of the vector is calculated on the basis of the round-trip time of the acoustic message and the speed of sound into the acoustic channel. The orientation, instead, is estimated from the phases of the signal received back by each transducer constituting the USBL head. When the GPS/USBL capable vehicle is at the surface, the absolute position of the interrogated modem is thus obtainable by adding the measured distance to the known absolute position of the USBL, provided by the GPS. We remark that the relative position is expressed in the USBL reference frame, so it has to be compensated both for the mounting of the USBL and the attitude of the vehicle in order to be consistent with the absolute vehicle position.

A Medium Access Control (MAC) policy is needed in order to interrogate the modems ensuring an exclusive access to the transimission channel and thus avoiding possible collisions. To this goal, the Typhoon communication system relies on a Time-Division Multiple Access (TDMA), bi-directional broadcast scheme. Such a choice permits to create a flexible structure capable of ensuring low-delay communication and the unique periodic control of the medium access.

Given this architecture, the USBL vehicle can start interrogating the other nodes of the network as soon as its temporal slot for the transmission is available. When a new measurement is provided, the vehicle can fix the interrogated node position with the procedure described above. While the procedure is general, i.e., it can be used in presence of both fixed and moving nodes, in presence of fixed nodes of unknown a-priori position it provides a method to allow underwater navigation of the USBL vehicle. When the modem nodes are fixed, by acquiring several measurements for each one with the USBL-vehicle at the surface, a spatial distribution of their measureded positions is obtained. The estimate of the position of each node can thus be obtained by eliminating any potential outliers and by averaging the respective measurements. The absolute position of the acoustic nodes can then be used for navigation purposes: the vehicle can indeed localize itself using the on-board USBL with the inverse procedure with respect to that used for the localization. Note that this procedure, which is experimentally illustrated in the next section, can be applied even with a single fixed node.

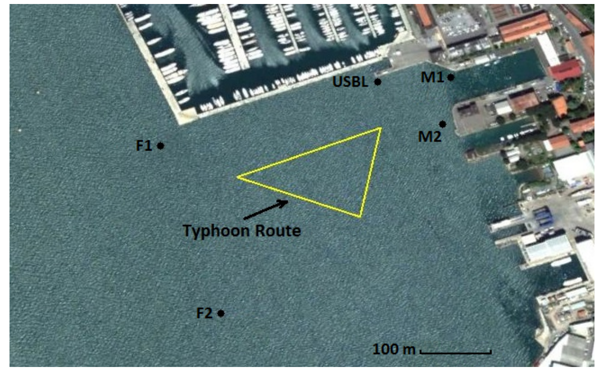


Fig. 5. Set-up of the Sept. 12 mission. The modems F1, F2, M1, M2 and USBL constitute the ad-hoc acoustic network of fixed nodes.

IV. Results

The localization procedure has been tested in several configurations and conditions during the CommsNet13 sea trial, led by CMRE in the Gulf of La Spezia, September 2013. Here we report the results as obtained with the data collected on the Sept. 12 tests, carried out both in the morning and in the afternoon. In the morning trial, the Typhoon has executed an autonomous surface mission within the La Spezia harbour, consisting in the repetition of a triangle-shaped path with vertices placed in the waypoints WP1, WP2 and WP3. In this area, shown in Figure 5, some battery-operated modems were deployed to build an ad-hoc installation of fixed nodes. The absolute position and the attitude of the vehicle are given by the on-board GPS and IMU respectively.

Figure 6 shows the results of the localization procedure. The results are obtained with respect to a North-East-Down (NED) reference frame which origin is assumed to be in proximity of the position of the Alliance. A planar projection model is employed to approximate the Earth surface in the navigation area, since the navigation task was enclosed inside a *small enough* area. The circles indicate the absolute positions of the acoustic sources evaluated from the rough measurements. We can see that the spatial distributions of the rough measurements are concentrated around the geographical positions where the modem were supposed to be deployed. The diamonds on the GPS path indicate the points in which a new USBL fix relative to corresponding acoustic node is available.

In Figure 7a is reported an enlargement of the network installation area. The mean values of each spatial distribution are represented by the crosses. Note that the mean value of the M1 position is obtained by neglecting the outlier, marked

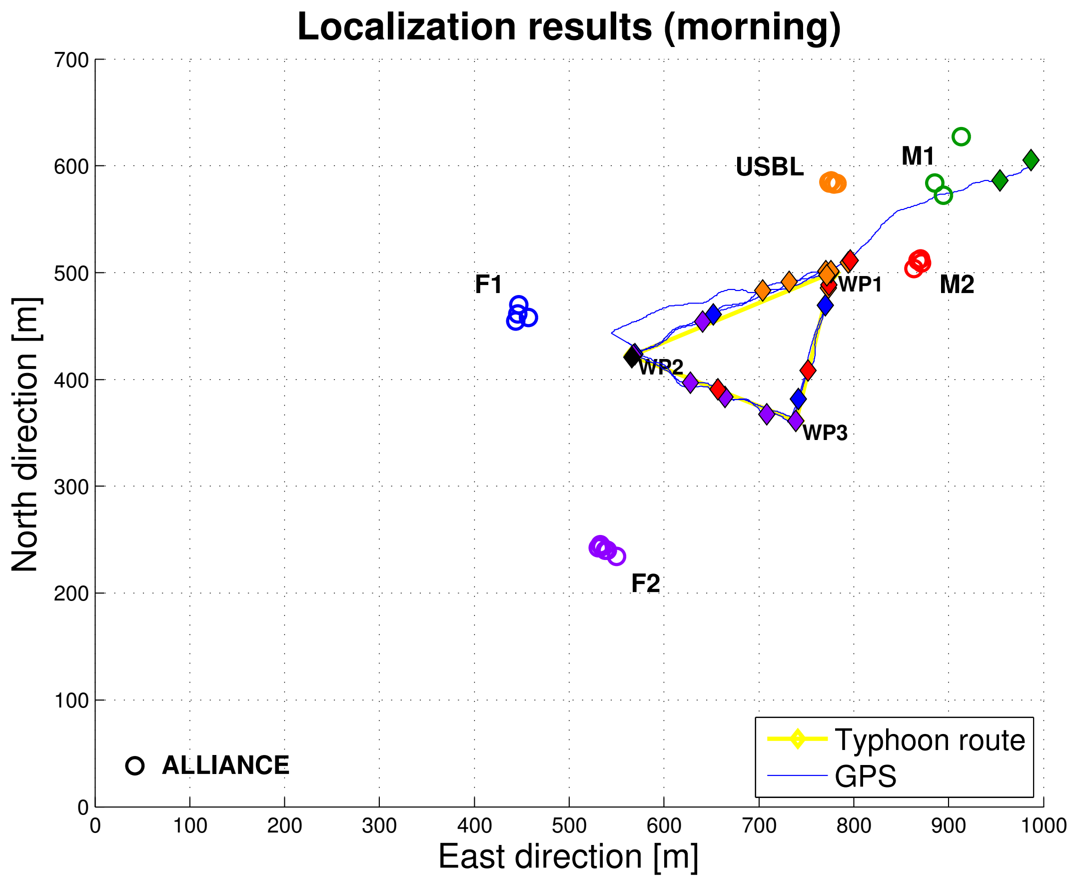
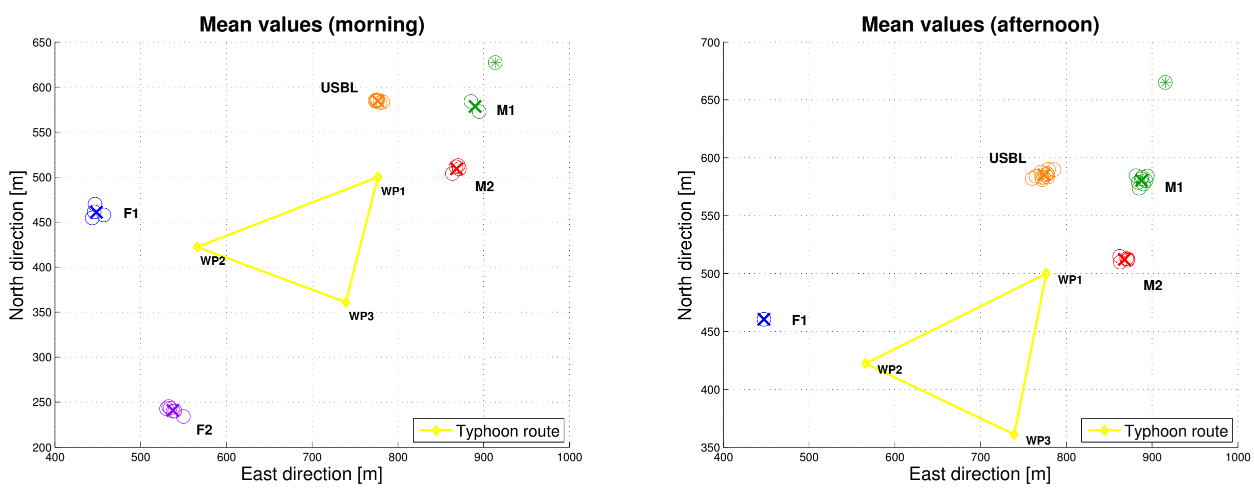


Fig. 6. Estimated positions of the acoustic sources, represented by the circles. The coloured diamonds on the GPS path show the points in which a USBL fix has became available from the corresponding modem.



(a) (b)

Fig. 7. Mean values of the estimated positions, represented by the crosses, and corresponding spatial distributions.

with the starred circle. As can be seen, the rough estimated positions are nearly concetrated around the correspondent mean value, highlighting a precision suitable for a successive underwater navigation purposes. This consideration is furthermore strengthened by calculating the stardard deviations of the USBL measurements, reported in Table I.

In the afternoon, Typhoon was supposed to autonomously travel along the same path of the morning at a depth of 5 meters, surfacing every two and a half minutes to reset the drift in the position estimation through a GPS fix. Figure 7b shows, similarly to Figure 7a, the mean values of the estimated positions of the acoustic nodes, obtained with the measurments acquired during the resurfacing periods. We note that, with respect to the morning trial, the number

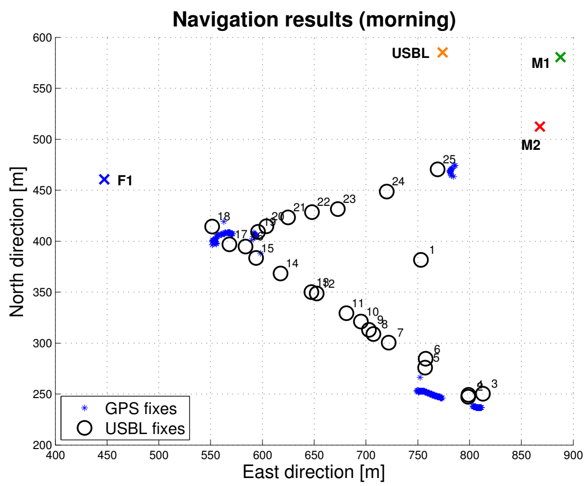


Fig. 8. Acoustic path estimated from the USBL measurements.

of fixes from M1, M2 and USBL is increased. On the other hand, only one measurement has been observed from F1 and no one from F2. Another outlier from M1, marked with a starred circle, is however present. In Table II are summarized the standard deviations of the USBL measurements, comparable to those obtained in the morning trial.

Finally, Figure 8 shows the self-positioning of the USBL with respect to the fixed nodes during the submerged path. The black circles represent the rough estimation of the vehicle position, obtained by combining the USBL measurements with the positions of the fixed acoustic nodes. The positions of the fixed nodes are considered to be equal to the mean values previously estimated. The blue stars indicate the GPS fixes in the resurfacing periods. We do not report here an error measurements between the GPS position and the acoustic one because we do not have GPS and acoustic data at the same time - moreover, we are not applying any navigation filter to the presented data. However, the spatial difference at the water surface between the GPS signal and the last received USBL fix is in all cases always less than 15m. This result, which represent the worst case performance, since it can be consistently improved by applying appropriate navigation filters, is by itself showing that the proposed localization method is indeed, even "as it is", suitable for navigation purposes.

TABLE I. STANDARD DEVIATION OF USBL MEASUREMENTS.

Source	no. of pings	σ (m)
M1	2	0.79
M2	4	4.11
USBL	7	1.99
F1	4	5.21
F2	6	4.55

TABLE II. STANDARD DEVIATION OF USBL MEASUREMENTS.

Source	no. of pings	σ (m)
M1	8	4.24
M2	5	3.67
USBL	12	6.39

V. CONCLUSION

The background and the motivations of the *Thesaurus* project, the Typhoon AUVs, designed within the project, and the results of a field trial devoted to the testing of acoustic localization and navigation procedures are described within the presented paper. The field test results give a practical confirmation that indeed a vehicle with on-board USBL capabilities can navigate exploiting a network of fixed nodes (potentially just one). Theoretically, this result is not surprising - however, it has to be considered that in the test case the localization process is embedded in a networked communication scheme, with the associated problems (delays, overloads, packet losses). Work is currently in progress with data from the same cruise in order to evaluate the performance of the navigation filter in the same experimental conditions, and how much the localization results can be improved by the filter.

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