Cooperative navigation of AUVs via acoustic communication networking: field experience with the Typhoon vehicles

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Cooperative Navigation of AUVs Via Acoustic Communication Networking

Field experience with the Typhoon vehicles

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Abstract A cooperative navigation procedure for a team of Autonomous Underwater Vehicles (AUVs) is described and validated on experimental data. The procedure relies on acoustic communication networking among the AUVs and/or fixed acoustic nodes, and it is suitable as a low-cost solution for team navigation. Embedding the acoustic localization measurements in the communication scheme causes delays and sometimes loss of acoustic data, depending on acoustic propagation conditions. Despite this drawback, the results obtained show that on-board localization estimates have an error of the order of few meters, **improving the overall navigation performance and leading the system towards long-term autonomy in terms of operating mission time, without the need of periodic resurfacings dedicated to reset the estimation error.** The data were collected during the *CommsNet '13* experiment, led by the NATO Science and Technology Organization Center for Maritime Research and Experimentation (CMRE), and the *Breaking The Surface '14* workshop, organized by the University of Zagreb.

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1 Introduction

Autonomous Underwater Vehicles (AUVs) are becoming an increasingly widespread tool for a large variety of marine tasks, such as oceanographic surveys, coastal patrol, seabed and bathymetric data collection. Some of these applications may last days, or even months (in case of oceanographic gliders), requiring long endurance capabilities for the vehicles, in particular low consumption or high energy storage, but also long term navigation capabilities. Although these two aspects may seem at first sight uncorrelated, they are tightly coupled. Indeed, *navigation* consists in determining the vehicle "position, course, and distance traveled. In some cases velocity and acceleration are determined as well" (Fossen 2002). An accurate navigation increases the efficiency of the mission, and hence is instrumental in extending the endurance by increasing the operating time of the vehicle.

The way to achieve long endurance is however strongly dependent on the type of the mission to perform. For this reason, both the power supply and the navigation systems have to be carefully designed in order to obtain an acceptable trade-off between performance and costs. In deep water applications, where periodic resurfacings are impractical, long term autonomy can be achieved by increasing the battery power and adopting a pure inertial navigation via dead-reckoning. This will result in large, high performance vehicles, equipped with a very accurate but expensive Inertial Navigation System (INS), as in Whitcomb et al (2010) and Caiti et al (2014). On the other hand, teams of cooperating, low-cost AUVs with a relatively ease of deployment are preferably employed for shallow water tasks that are often executed periodically, i.e. environmental exploration and monitoring. In this case, an improved mission efficiency may be more convenient with respect to increasing resources (batteries, INS) on-board each vehicle. Efficient energy management and power saving can be obtained for instance with a smart design of the propulsion system (Bellingham et al 2010), or by providing the vehicle with a recharging system (Hagerman 2002). Long term navigation with low-cost sensors is generally obtained by compensating the position drift introduced by dead-reckoning with measurements from other navigation aids, in particular acoustic systems such as Ultra-Short Base Line (USBL), Long Base Line (LBL) and acoustic modems (Milne 1983). In such a framework, acoustic measurements are used by the navigation system to *localize* the vehicle, i.e. determining its position within the operating area at any given time, and consequently to estimate the whole navigation state.

When the location of the beacons constituting the LBL is not a priori known, the navigation system can exploit the acoustic measurements also to perform *mapping*, i.e. localize the beacons in the mission area, using Simultaneous Localization and Mapping (SLAM) techniques (Stutters et al 2008). In Petillot et al (2010) simulations of a range-only SLAM method for an AUV navigating within an LBL are provided, while Becker et al (2012) propose a SLAM-like approach with a single transponder used as landmark, an approach similar to the one used in this paper with a network of transducers. In Bayat et al (2015) an observability analysis of the range-only localization problem in the presence of unknown marine currents is addressed, even in the case in which the position of the beacons are unknown. Based on the obtained results, a range-based localization system is then designed and validated through experimental trials.

Furthermore, acoustic communication allows the vehicles of the team to share pose estimates as well as relative positions, improving their own localization precision. AUV teams can be classified in two main branches, depending on the hierarchy of the vehicles within the team: heterogeneous and homogeneous (Paull et al 2014). In the former case, one or more vehicles have enhanced localization capabilities and support the other members with periodic updates of the navigation status, playing the role of *team leaders* (Bahr et al 2009; Allotta et al 2014). Within a team of homogeneous AUVs, instead, all the vehicles are on the same level and cooperative navigation is performed by exploiting both range and relative position measurements (Fallon et al 2010). Acoustic cooperative navigation has received considerable attention in recent years, and it has been the subject of several theoretical and experimental investigations. In particular, without being exhaustive (the interested reader can refer to the survey work of Paull et al (2014), and references therein), Webster et al (2013) reports methods and results on localization using range only measurements among the vehicle team, while Walls and Eustice (2014) analyze the effect of severe communication limitations among the team members. Finally, applications of mixed USBL/LBL AUV navigation scheme have also been reported in Furfaro and Alves (2014).

In this work we present a cooperative navigation and localization methodology for a team of heterogeneous, low-cost AUVs navigating within a network of fixed acoustic transponders with the goal of exploring a predefined area. In the presented framework, a vehicle equipped with an USBL acts as the *team leader*, while the other vehicles of the team are treated as mobile nodes of the acoustic network. The navigation filter of the team leader exploits the acoustic measurements to simultaneously localize itself within the network and estimate the navigation status, initially supposed unknown, of both the fixed and the mobile nodes. A motion model is employed to estimate the navigation status of the network nodes, constituted by their position and velocity. In this way, the team leader can generate a map of the fixed nodes network and track the path followed by the mobile nodes. Given the peculiarity of the proposed problem and the strong similarity with the SLAM algorithms largely studied and developed in the Visual Navigation community, we named this framework an *"Acoustic-based SLAM" (A-SLAM)* algorithm. Every time a new acoustic measurement is received from a network node, the leader uses this measurement to refine the estimation of the network topology, via the A-SLAM algorithm, and sends the updated topology of the network through the acoustic channel to make it available to the other members of the team. Clearly, if the measurement was generated by a mobile node (i.e. one of the other vehicles of the team), the updated topology includes the navigation status of this node. In this case, such node uses the information communicated by the leader to update its own navigation status and, consequently, sends the refined estimate back to the leader. Finally, the leader performs a further correction of the navigation status with the last information received.

In the proposed approach, acoustics is oriented to bound the typical drift of the INS estimation error. Acoustic positioning, as well as data exchange among the members of the team,

are effective in improving the overall navigation performance and allow the team to extend the operating mission time by avoiding periodic resurfacings dedicated to the reset of the position error. Results show that the estimation error remains bounded for the entire mission duration, contributing to provide the system with long-term navigation capabilities. It is underlined that the proposed method differs from others because it combines all the following:

- the fixed nodes position is not a priori known, and the fixed nodes are used as features in an acoustic SLAM procedure;
- acoustic localization messages are embedded in the general communication scheme, causing delays in reciprocal ranging between pairs of vehicles;
- the vehicles are equipped with low-cost measurement devices, and affordable to most research groups.

Note that some of the above are limitations, and not enhancing features. The purpose of the paper is to experimentally quantify the navigation error bounds attainable by such a scheme; and, as a consequence, if the procedure has the disruptive potential of providing acceptable localization performance at much lower costs. In this paper, the navigation error is estimated by post-processing real experimental data, collected during several sea trials performed with our self-developed AUV, the Typhoon.

The paper is organized as follows: in Section 2 the main characteristics of the Typhoon AUV are presented. Section 3 describes in details the proposed A-SLAM algorithm for cooperative navigation. Finally, in Section 4 the main results obtained on the data collected are reported for various mission scenarios.

2 The Typhoon AUVs

A new class of AUVs, called Typhoon, has been developed in the framework of the Italian THESAURUS project (2011-2013). Three Typhoons were built, able to cooperate in swarms to perform navigation, exploration and surveillance of underwater archaeological sites. Typhoon is a middle-sized AUV able to reach a maximum depth of 300 meters. This depth specification was chosen taking into account the archaeologists' interest: it is prohibitive for usual diver operations and it is also higher compared to the depth specification of many commercial low-cost AUVs. The vehicles can carry suitable payload for the specific underwater mission to perform.

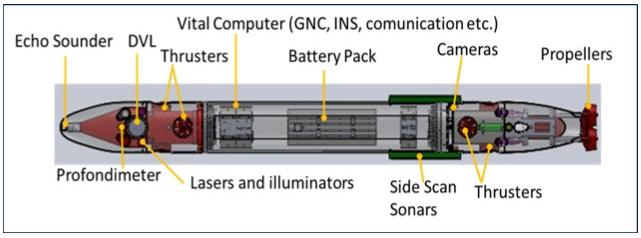


Fig. 1: TifOne AUV customized for both acoustic and visual inspection of a site.

At the moment, two Typhoons AUVs are fully operative and already performed several missions at sea: the vehicles are called TifOne and TifTu (italian pronunciation of TifTwo). TifOne can be customized for different mission profiles: for instance, for an individual mission in which both acoustic and visual inspection of an archaeological site are required using a single vehicle, TifOne can house optical cameras and acoustic payload, e.g. Side-Scan-Sonar (SSS), as shown in Fig. 1.

The naval and the electromechanical design was focused on a common vehicle class, since each vehicle differs only in terms of sensor layout and payload. TifTu currently has no payload on-board: TifTu usually navigates on surface and mounts in its lower part an USBL acoustic head useful to relatively localize TifOne when the latter navigates underwater. The USBL is a device for underwater acoustic localization constituted by an array of transceivers. By successfully completing a round-trip communication with a transponder, the USBL can determine the relative position of the transponder with respect to itself. In particular, the range (i.e. the module of the relative position vector) is calculated on the basis of both the two-way travel time of the acoustic ping and the speed of sound into the channel, while the orientation is determined from the phases of the signal received back by each transducer constituting the USBL head. The adopted configuration in the THESAURUS project is that the USBL is located on a surface support vehicle (i.e. TifTu or a support ship); the transponder is instead an acoustic modem rigidly mounted on-board of one of the AUVs navigating underwater (i.e. TifOne).

The roles of the two vehicles are the following:

- TifTu - team coordinator: this vehicle always navigates or periodically returns to surface providing the Global Positioning System (GPS) information that can be shared with other vehicles of the team. Moreover, thanks to the GPS signal available and to the USBL mounted on the vehicle, TifTu can geo-localize TifOne navigating underwater;
- TifOne - vision and acoustic explorer: TifOne is equipped with cameras, laser, structured lights and

Fig. 2: The Typhoon AUVs: final versions of TifOne and TifTu on the NATO Research Vessel Alliance.

acoustic SSS. Preliminary exploration of extended area to recognize potentially interesting targets involves the use of the acoustic payload; then an accurate visual inspection of the archaeological sites can be performed. This kind of vehicle can perform long range, extended missions. Navigation sensors able to compensate the drift of the inertial sensors, such as a Doppler Velocity Log (DVL), can be installed on-board.

2.1 Typhoon Hardware

The Typhoon has a length of 3700 mm, an external diameter of 350 mm and a weight in air of 130-180 kg according to the carried payload (in particular TifOne weighs 180 kg whereas TifTu about 150 kg). The buoyancy is trimmed so that the vehicles in water are always slightly positive buoyant. The Typhoon has at least 10 hours of autonomy and a maximum longitudinal speed of 6 knots (the cruise speed is instead about 2 knots) (Allotta et al 2015b). In Fig. 2 the final versions of TifOne and TifTu can be seen.

2.1.1 On-board equipment and payload

Both TifOne and TifTu are moved by propellers. The propulsion system is composed of six actuators: two lateral thrusters, two vertical thrusters and two main rear propellers. The vehicle is assumed (or, at least, configured to be) metacentric stable along the roll axis, thus the propulsion system actively controls five degrees of freedom of the vehicle, the only one left passive being the roll one. A standard actuation unit with a brushless motor and drive directly fed by the batteries and controlled through an industrial CAN bus is adopted. The calibration of the pitch static attitude can be also performed by moving the accumulators whose axial position is controlled by a screw system.

The on-board equipment can be divided in two main categories, e.g. as shown in Fig. 3 considering TifOne configuration:

- Vital Systems: the navigation, communication and safety related components are controlled by an industrial PC-104, called Vital PC, whose functionality is continuously monitored by a watchdog system;
- Customizable Payload: the additional sensors and payload are managed by one or more Data PC. In particular, the Data PC also manages the storage on mass memories. This way, all the processes introduced by additional payloads are implemented on a platform physically separated from the vital one.

The power needed by the on-board propulsion systems and payloads was estimated as approximately 350 W: considering a mission duration of about 8-10 hours, the needed energy was calculated in about 3-3.5 kWh. Li-Po (Lithium-Polymer) batteries, having higher energy capacities compared to other kinds of commercial accumulators, have been chosen.

For sake of brevity, here is reported a brief list of the on-board sensors and payloads:

- Inertial Measurement Unit (IMU) Xsens MTi: device consisting of a 3D gyroscope, 3D accelerometer and 3D magnetometer furnishing (at 100 Hz) the orientation of the vehicle in a 3D space;
- Doppler Velocity Log (DVL) Teledyne Explorer (on TifOne): sensor measuring the velocity of the vehicle, with respect to the seabed;
- Echo Sounder Imagenex 852: single beam sensor, pointing forward and measuring the distance from the first obstacle placed in front of the vehicle;
- STS DTM depth sensor: digital pressure sensor used to measure the vehicle depth;
- PA500 altimeter: echosounder measuring the distance of the vehicle from the seabed;
- Optical cameras ace by Basler (on TifOne): optical stereo cameras for a detailed visual inspection of the targets;
- SeaKing 675 kHz Side Scan Sonar by Tritech (on TifOne): for the acoustic survey of the seabed;
- S2CR 18/34 Underwater Acoustic Modem by EvoLogics (on TifOne): acoustic device for the underwater communication;
- S2CR 18/34 USBL Underwater Acoustic USBL System by EvoLogics (on TifTu): device for the underwater acoustic localization. The USBL is fundamen-

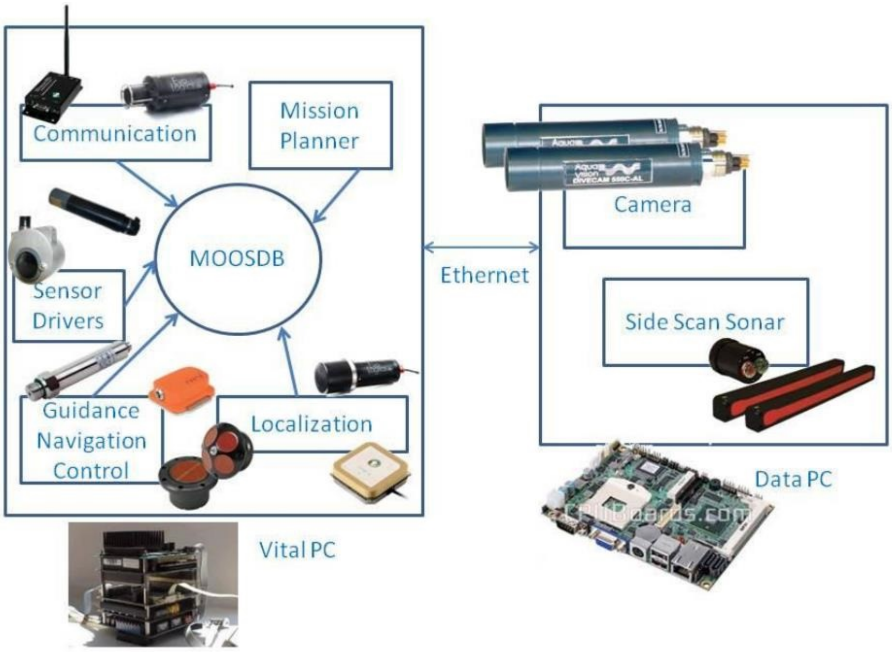


Fig. 3: TifOne on-board equipment.

tal for the geo-localization of the vehicle navigating underwater and thus also for the geo-referencing of the acquired data.

2.2 Missions at sea already performed

Starting from year 2012, the Typhoon vehicles have been largely tested in experimental campaigns at lake and sea and both in a single-vehicle and cooperative (multi-vehicles) configuration. The first official trials at sea with the Typhoons were performed in Livorno, Italy, at the end of the Italian THESAURUS project, August 2013. Such tests have been carried out in cooperation with the Livorno Fire Brigade and the Tuscan Superintendence on Cultural Heritage. Following these tests the Typhoon AUVs (TifOne and TifTu), operated by the teams of the Universities of Florence and Pisa, participated in the NATO *CommsNet '13* experiment, organized and led by NATO Science and Technology Organization Center for Maritime Research and Experimentation (CMRE). This sea trial was held in La Spezia (Italy). Then two weeks of sea trials were performed in Israel: the mission, funded by the Office of Naval Research Global - ONRG and supervised by the Marine Archaeology Unit, Israel Antiquities Authority - IAA, took place from June 17th to July 1st 2014 in Akko and Caesarea, Israel. Last but not least, TifOne and TifTu will be also part of the heterogeneous fleet of AUVs developed during the ARROWS European project (`www.arrowsproject.eu`). In the framework of these activities, an ARROWS Demo with the Typhoon AUVs has been performed during the *Breaking The Surface '14* workshop, Croatia, on October 2014.

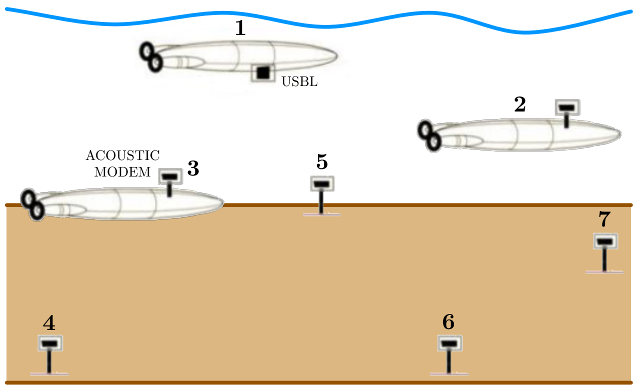


Fig. 4: A-SLAM scenario. The team of vehicles is constituted by n_m vehicles: one master equipped with an USBL (1) and some slaves (2 and 3), navigating within a network of n_f moored modems (4, 5, 6 and 7).

3 Cooperative Navigation

This section presents the details of the A-SLAM cooperative algorithm for a team of n_m heterogeneous underwater vehicles navigating within a network of n_f fixed acoustic transponders placed in unknown locations. Among the team, one of the vehicles is devoted

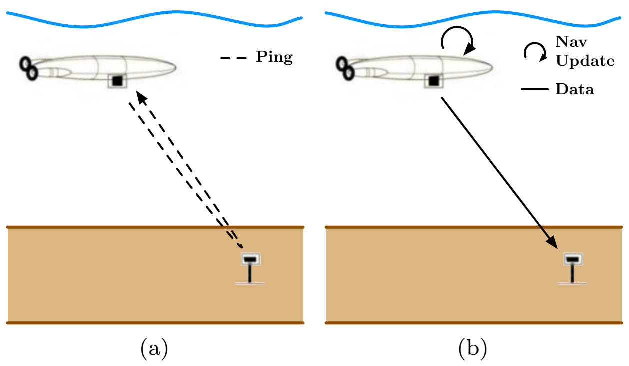


Fig. 5: The A-SLAM step of the navigation algorithm. (a) Localization: the team master pings a moored modem to get the USBL measurement. (b) A-SLAM update & data transmission: the team master exploits the USBL measurement to localize itself and the moored modem, updating the navigation state; after the correction, the team master sends the refined position to the moored modem.

to localize and coordinate the tasks of the team, being equipped with an USBL, which can also be used to communicate with the other agents, fixed or mobile. In the following, we will refer to this vehicle as the *team master*, to the remaining vehicles of the team as the *slaves* and to the fixed acoustic sensors as the *moored modems* (Fig. 4). All the vehicles are supposed to be equipped with a common set of basic navigation sensors, namely a low-cost, low-accuracy IMU, a GPS receiver and a depth sensor. In addition, each slave vehicle is considered to have some navigation aids to assist its own inertial unit and an acoustic modem to communicate with the other nodes of the network. Without loss of generality, we assume to use a DVL sensor as navigation aid for the slave vehicles. Within the network, each node, fixed or mobile, is identified by a univocal acoustic address. To prevent possible collisions during the communication between the vehicles, the Medium Access Control (MAC) is realized through a Time Division Multiple Access (TDMA) protocol: following a round-robin policy, each vehicle has a guaranteed time slot in which it is the only one allowed to transmit.

The cooperative navigation algorithm is executed as follows: each vehicle continuously estimates its own navigation status by integrating the measurements from both the inertial unit on-board and the navigation aids. Meanwhile, the team master periodically interrogates each other node of the network, fixed or mobile, sending it an acoustic ping through the USBL (Fig. 5a and Fig. 6a). The USBL measures the relative position of the interrogated node with respect to itself in its own reference frame $\{u\}$. The team master can thus exploit the acoustic measurement to update its navigation state, localizing itself and the interrogated node at the same time. In particular, the moored modems are treated as landmarks and their acoustic measurements are used by the navigation algorithm of the team master to build a map of the modems network, while localizing the vehicle itself within the map (Fig. 5b), as described in Allotta et al (2015a). This "Acoustic-based SLAM" procedure relies on a dynamic database of the observed nodes, initially empty: every time the team master receives an acoustic measurement from an unobserved node, the database is augmented with the navigation state of the considered node. Any eventual future measurement received from that node will be used to execute the A-SLAM update step. After the correction, the team master sends the refined absolute position of the considered node through the acoustic channel (Fig. 5b and Fig. 6b). If the considered node was one of the slave vehicles, it uses the received correction to update its own navigation status and sends the refined estimation back to the master (Fig. 6c). Finally, the team master fixes further the navigation status of the considered slave vehicle (Fig. 6d) and repeats the described procedure with the next node. By interrogating in turn all the nodes, the team master can generate a map of the moored modems while estimating the path followed by each vehicle of the team (including itself) in the operating area. Note that, as a special case, if the team master is the only mobile agent, the proposed methodology is capable to estimate at the same time the navigation status of the vehicle and the topology of the fixed network, as previously presented in Allotta et al (2015a).

It is worth to note that the MAC protocol and the navigation system, although connected, are two independent subsystems. This means that the assumptions made for the navigation module from now on do not condition the communication scheme. Clearly, the choice of the networking protocol imposes some constraints in the mission scenario and has an impact on the performance of the navigation system. Time division communication, for instance, introduces a scalability issue: as the dimension of the team grows, the position updates for each vehicle become less frequent and the overall navigation can be degraded. Notwithstanding this limitation, TDMA is a reasonable networking solution in the case of small AUV teams that are surveying an area remaining within their communication range. However, assessing how different networking protocols can influence the performance of the navigation system is beyond the purposes of this paper. An inter-

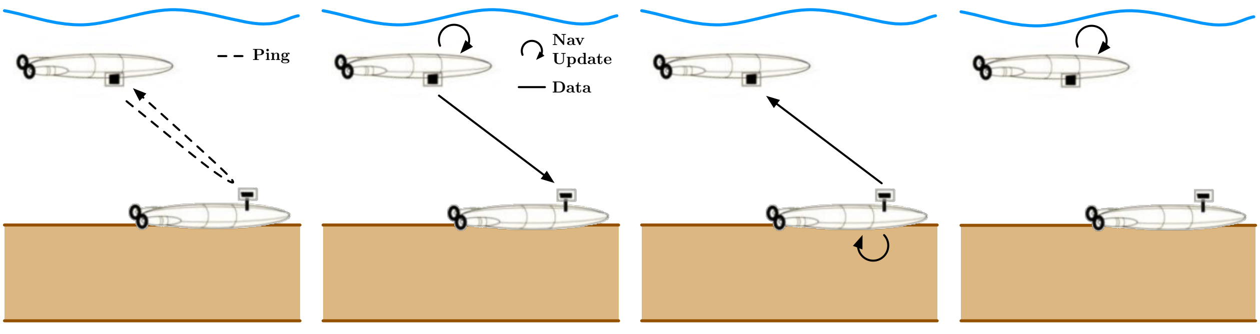


Fig. 6: The cooperative step of the navigation algorithm. (a) Localization: the team master pings a slave vehicle to get the USBL measurement. (b) Master update & data transmission: the team master exploits the USBL measurement to localize itself and the slave, updating the navigation state; after the correction, the team master sends the refined position to the slave. (c) Slave update & data transmission: the slave vehicle employs the information received by the master to correct its navigation status and sends back the refined estimation. (d) Final update: the team master use the received estimation to perform a further correction of the navigation status of the slave.

ested reader can find more details in Lloret (2013) and references therein.

For the purposes of this work, we assume that the local navigation frame $\{n\}$, defined in North-East-Down (NED) coordinates, can be considered not to change its orientation with respect to the global Earth-Centered Earth-Fixed (ECEF) frame, during the whole navigation task. This means that the Earth is approximated as a flat surface in the neighborhood of the starting point. By putting the NED reference frame on the Earth surface at the location corresponding to the starting point, all the inertial quantities can be considered in local coordinates. This is a realistic assumption in the framework of the proposed work, since the motion of the vehicle was assumed to be enclosed inside a *small enough* area. Moreover, the attitude of the vehicle is assumed known. More specifically, the attitude $\boldsymbol{\Theta}$, expressed in Euler angles, is *pseudo-measured* by the inertial unit on-board the vehicle, via integration of the gyroscopes measurements together with the sensed gravity and the Earth magnetic field measurements in an Attitude Heading Reference System (AHRS) fashion (Gebre-Egziabher et al 1998).

3.1 State model

Upon the above hypothesis, the *local* continuous-time navigation equations relative to any slave vehicles can be written by:

$$\dot{\boldsymbol{p}}_n = \boldsymbol{v}_n, \tag{1a}$$

$$\dot{\boldsymbol{v}}_n = {}^n\mathbf{R}_b(\boldsymbol{\Theta})\boldsymbol{a}_b, \tag{1b}$$

$$\dot{\boldsymbol{a}}_b = \boldsymbol{\nu}_{\boldsymbol{a}}, \tag{1c}$$

$$\dot{\boldsymbol{\epsilon}}_b = \boldsymbol{\nu}_{\boldsymbol{\epsilon}}, \tag{1d}$$

where $\boldsymbol{p}_n$ and $\boldsymbol{v}_{\boldsymbol{n}}$ are respectively the position and the velocity of the vehicle in the frame $\{n\}$, whereas $\boldsymbol{a}_b$ and $\boldsymbol{\epsilon}_b$ denote respectively the vehicle acceleration and the accelerometers bias term in the body-fixed reference frame $\{b\}$. The velocity dynamics (1b) is obtained simply by transforming the vehicle acceleration in the navigation frame through the body-to-navigation matrix ${}^n\mathbf{R}_b$ evaluated on the basis of the vehicle attitude $\boldsymbol{\Theta}$. Since no a priori information is given about the nature of both the acceleration and the bias time evolution, their dynamics are modeled as random walks, where $\boldsymbol{\nu}_{\boldsymbol{a}} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{Q}_{\boldsymbol{a}})$ and $\boldsymbol{\nu}_{\boldsymbol{\epsilon}} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{Q}_{\boldsymbol{\epsilon}})$ are zero-mean white noises with constant covariances.

In the case of the team master vehicle, the navigation state is augmented with the motion variables of the fixed and mobile nodes in the acoustic network. Depending on the number of acoustically visible vehicles at the beginning of the mission and since the dimension of the network of fixed nodes is assumed unknown, it is not possible to define a state with a predefined dimension. We thus decided to deal with the most general case in which we assume to do not know either the number of available vehicles in the team and of fixed nodes in the network. We remark that this assumption is valid for the navigation system only: depending on the networking protocol employed, the knowledge of the nodes number may be necessary to the MAC module (as in the case of TDMA). The navigation state of the nodes a_i is thus built dynamically, by augmenting the state vector by 6 more components (i.e. the position $\boldsymbol{p}_{a_i,n}$ and the velocity $\boldsymbol{v}_{a_i,n}$ in the local navigation reference frame) every time a new acoustic measurement is received from a node (either fixed or mobile) which was unobserved yet. In this condition, the navigation equations (1a - 1d) are thus extended with the following:

$$\begin{aligned} \dot{\boldsymbol{p}}_{a_i,n} &= \boldsymbol{v}_{a_i,n} \\ \dot{\boldsymbol{v}}_{a_i,n} &= \boldsymbol{\nu}_{a_i} \end{aligned} \quad i \in \mathcal{V}(t) \subseteq \{1, \ldots, n_m + n_f - 1\}, \quad \text{(1e)}$$

where $\boldsymbol{\nu}_{a_i} \sim \mathcal{N}\left(\boldsymbol{0}, \boldsymbol{Q}_{a_i}\right)$ is a zero-mean white noise with constant covariance matrix that accounts for the unknown dynamics. The set $\mathcal{V}(t)$ denotes the set of the visible node at the time instant t. It explicitly depends on time because each node becomes visible only after the first reception of a measurement. Initially, $\mathcal{V}(t)$ is empty and its dimension increases with the reception of new acoustic observations, reaching eventually the maximum value, i.e. the dimension of the network $n_m + n_f - 1$, when each node has provided at least one measurement. Moreover, since the team master vehicle does not have any other navigation aid but the USBL, we need to keep the position error drift bounded in the time period between two consecutive acoustic measurements, which can be of several seconds, if not minutes, depending on the number of acoustic nodes in the network. Considering that the vehicle moves only along its own surge axis, we approximate the relation between the desired thrust and the velocity along that axis with the linear function $\tau_{\text{surge}} = K_{\text{thr}} v_{\text{surge}}$, in which the gain K_{thr} is supposed to be constant and initially unknown. Although this is a very simplified approximation, it is enough to make the position estimate not diverge in the short term. To estimate the value of the gain, we extend further the system model (1a - 1e) with the following additional equation:

$$\dot{K}_{\text{thr}} = \nu_K, \quad \text{(1f)}$$

where the white noise $\nu_K \sim \mathcal{N}(0, Q_k)$ takes into account the modeling uncertainty. In the following, we will refer to the whole state vector of a given vehicle with the symbol "$\boldsymbol{x}$", making no difference between the team master and the slaves when it is not relevant.

3.2 Output model

As previously said, the vehicles of the team have a common set of navigation devices, namely an IMU, a GPS receiver and a depth sensor. The measurements from the GPS device are used as corrections at the mission beginning to initialize the navigation algorithm, i.e. to make the estimate of the accelerometers bias converge. Then, GPS is used in the experimentation described here as *ground truth* only, meaning that the navigation system did not take advantage of the global localization system during the normal operation phase. Note that in practical situations the GPS signal is integrated in the navigation system, when available (Caiti et al 2013); note also that the configuration described here and used in the experimentation corresponds to underwater navigation, where GPS is not available. The measurement equations associated to these sensors can be thus written as:

$$\tilde{\boldsymbol{y}}_{\text{acc}} = \boldsymbol{f}_b + {}^b\mathbf{R}_n(\boldsymbol{\Theta})\boldsymbol{g}_n + \boldsymbol{\epsilon}_b + \boldsymbol{\eta}_{\text{acc}}, \quad \text{(2a)}$$

$$\tilde{\boldsymbol{y}}_{\text{gps}} = \boldsymbol{p}_{\text{gps},n} + \boldsymbol{\eta}_{\text{gps}}, \quad \text{(2b)}$$

$$\tilde{y}_{\text{depth}} = p_{\text{depth},n} + \eta_{\text{depth}}, \quad \text{(2c)}$$

where $\boldsymbol{f}_b$ are the *specific forces* (Rogers (2000)), that is the dynamic accelerations due to the resulting forces and moments acting on the floating body, expressed in the frame $\{b\}$, and $\boldsymbol{p}_{\text{gps},n}$ and $p_{\text{depth},n}$ contain respectively the North-East and the Down coordinates of the vehicle position in the frame $\{n\}$. In (2a) the term $\boldsymbol{g}_n$ accounts for the gravity acceleration sensed by the accelerometers, resolved in the body-fixed frame through the transformation matrix ${}^b\mathbf{R}_n(\boldsymbol{\Theta}) = {}^n\mathbf{R}_b(\boldsymbol{\Theta})^T$, while $\boldsymbol{\epsilon}_b$ represents the slowly varying bias term affecting the acceleration measurements. Each measurement is affected by noise, denoted with the "η" symbol, that we assume white, with zero mean and constant covariance matrix $\boldsymbol{R}_{\text{acc}}$, $\boldsymbol{R}_{\text{gps}}$ and R_{depth} respectively. Note that, although formally incorrect, the noises affecting the considered devices can be reasonably assumed as white in practice, having a constant spectrum in the frequency bandwidth of interest. Unless otherwise specified, we will always denote with the symbol $\boldsymbol{\eta}_{\text{dev}}$ a white, Gaussian noise with zero mean and constant covariance matrix $\boldsymbol{R}_{\text{dev}}$.

The navigation system of each vehicle can rely on further corrections depending on the vehicle specialized navigation equipment. In particular, the slaves can measure their own velocity in the body-fixed reference frame using the DVL, modeled as:

$$\tilde{\boldsymbol{y}}_{\text{dvl}} = \boldsymbol{v}_{\text{dvl},b} + \boldsymbol{\eta}_{\text{dvl}}. \quad \text{(2d)}$$

The team master, being equipped with the USBL modem, receives as correction fix the relative position of the i-th acoustic agent with respect to the vehicle itself expressed in the frame $\{u\}$, namely $\boldsymbol{p}_{\text{a}_\text{i}\text{-u},u}$. The model associated with this measurement is thus the following:

$$\tilde{\boldsymbol{y}}_{\text{usbl}_\text{i}} = \boldsymbol{p}_{\text{a}_\text{i}\text{-u},u} + \boldsymbol{\eta}_{\text{usbl}}, \quad \text{(2e)}$$

where $\boldsymbol{\eta}_{\text{usbl}} \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{R}_{\text{usbl}}\left(t\right)\right)$ is a zero-mean, white, Gaussian noise with a time-dependent covariance matrix $\boldsymbol{R}_{\text{usbl}}\left(t\right)$. The covariance matrix is evaluated on each reception of an USBL correction on the basis of the measurement accuracy provided by the USBL device itself. In particular, indicating with $\sigma\left(t\right)$ the precision of the measurement at the time instant t, the covariance matrix can be computed as:

$$\boldsymbol{R}_{\text{usbl}}\left(t\right) = \left(\frac{\sigma\left(t\right)}{3}\right)^2 \boldsymbol{I}_3.$$

Finally, the team master uses as last navigation aid the allocated thrust along the surge axis of the vehicle, namely $\tau_{\text{surge},b}$, considering null the motion along the remaining two components. The relative equation is the following one:

$$\tilde{\boldsymbol{y}}_{\tau} = \left[\tau_{\text{surge},b} \quad 0 \quad 0\right]^T + \boldsymbol{\eta}_{\tau}. \tag{2f}$$

The estimates of the navigation status exchanged between the vehicles can be modeled as correction fixes as well. To avoid possible ambiguities, we will indicate in the following with the superscript "[·]" the vehicle which has estimated the considered quantity. The team master, after updating the navigation status of the i-th slave vehicle with an USBL measurement, sends the refined position $\hat{\boldsymbol{p}}_{a_i,n}^{[\text{master}]}$ to the relative vehicle. In this way, the slave vehicle can feed its own navigation algorithm with the correction received from the team master. The measurement model results simply as follows:

$$\tilde{\boldsymbol{y}}_{\text{master}} = \hat{\boldsymbol{p}}_{a_i,n}^{[\text{master}]} + \boldsymbol{\eta}_{\text{master}}. \tag{2g}$$

Once the slave vehicle has updated its own position estimate with the previous information, it sends back to the master its refined navigation status, i.e. its own position $\hat{\boldsymbol{p}}_n^{[\text{a}_\text{i}]}$ and velocity $\hat{\boldsymbol{v}}_n^{[\text{a}_\text{i}]}$. The associated equation is thus the following:

$$\tilde{\boldsymbol{y}}_{\text{a}_\text{i}} = \begin{bmatrix} \hat{\boldsymbol{p}}_n^{[\text{a}_\text{i}]} \\ \hat{\boldsymbol{v}}_n^{[\text{a}_\text{i}]} \end{bmatrix} + \boldsymbol{\eta}_{\text{a}_\text{i}}. \tag{2h}$$

In order to fuse such measurements with the inertial navigation system, it is convenient to make explicit the dependence of all the above measurements with the inertial mechanization states. For this reason, we can write:

$$\boldsymbol{y}_{\text{acc}} = \boldsymbol{a}_b + {}^b\mathbf{R}_n(\boldsymbol{\Theta})\boldsymbol{g}_n + \boldsymbol{\epsilon}_b + \boldsymbol{\eta}_{\text{acc}}, \tag{3a}$$
$$\boldsymbol{y}_{\text{gps}} = \left[\boldsymbol{I}_2 \quad \mathbf{0}_{2\times N-2}\right]\boldsymbol{x} + \boldsymbol{\eta}_{\text{gps}}, \tag{3b}$$
$$y_{\text{depth}} = \left[0 \quad 0 \quad 1 \quad \mathbf{0}_{1\times N-3}\right]\boldsymbol{x} + \eta_{\text{depth}}, \tag{3c}$$
$$\boldsymbol{y}_{\text{dvl}} = {}^b\mathbf{R}_n(\boldsymbol{\Theta})\boldsymbol{v}_n + \boldsymbol{\eta}_{\text{dvl}}, \tag{3d}$$
$$\boldsymbol{y}_{\text{usbl}_\text{i}} = {}^u\mathbf{R}_b{}^b\mathbf{R}_n(\boldsymbol{\Theta})\left(\boldsymbol{p}_{a_i,n} - \boldsymbol{p}_n\right) + \boldsymbol{\eta}_{\text{usbl}}, \tag{3e}$$
$$\boldsymbol{y}_{\tau} = K_{\text{thr}}{}^b\mathbf{R}_n(\boldsymbol{\Theta})\boldsymbol{v}_n + \boldsymbol{\eta}_{\tau}, \tag{3f}$$
$$\boldsymbol{y}_{\text{master}} = \boldsymbol{p}_n + \boldsymbol{\eta}_{\text{master}}, \tag{3g}$$
$$\boldsymbol{y}_{\text{a}_\text{i}} = \begin{bmatrix} \boldsymbol{p}_{a_i,n} \\ \boldsymbol{v}_{a_i,n} \end{bmatrix} + \boldsymbol{\eta}_{\text{a}_\text{i}}, \tag{3h}$$

where N denotes the dimension of the state vector $\boldsymbol{x}$. Equation (3a) was obtained by observing that the specific forces term are actually coincident with the vehicle dynamic acceleration state in Equation (1c). Equation (3d) simply expresses the velocity of the vehicle in the frame $\{b\}$ to comply with the measurement given by the DVL. In (3e) the relative position of the i-th acoustic node with respect to the vehicle expressed in the frame $\{n\}$ is obtained by subtracting the respective absolute positions. Then, the result is first transformed in the body-fixed frame and thus in the USBL frame through the transformation matrix ${}^u\mathbf{R}_b$. Finally, equation (3f) expresses the linear approximation of the vehicle velocity in the frame $\{b\}$ to obtain the allocated thrust.

As a remark, we point out that the system model for the team master is just a slightly modified version of that presented in Allotta et al (2015a), in which we have added the velocity of the agent a_i in (1e) and used the accelerometers measurements as output instead as input. The reason behind this is that we look at the problem from a stochastic filtering point of view, thus treating the IMU as measurements depending on system states, i.e. the linear acceleration in body-fixed frame.

3.3 Filtering

According to the motion and sensitivity parameters dynamics in equation (1), given the model of the defined measurements (2) and the corresponding outputs (3), an Extended Kalman Filter both for the team master and the slave vehicles was designed and tested. Even though the models of the two types of vehicles (i.e. master and slaves) have some differences, the filtering process has a common structure, which is composed by two steps: in the *prediction* step, a rough estimation of the state is obtained by evolving the dynamical model (1) of the system. The second step is the *correction* step, which is executed when a new measurement is available from one or more of the auxiliary sensors, in order to reduce the error of the predicted state estimate. Note that, even though the auxiliary sensors have different frequencies, in general smaller than that of the IMU, per each prediction step at least the correction step due to the accelerometers measurements is always executed. The only difference between the navigation algorithms regards the estimation of the team configuration using the acoustic measurements provided by the USBL. As soon as a new acoustic measurement is made available, the filtering algorithm of the team master vehicle checks if the source is already present in the database; in this case it uses the observation as a fix to refine the predicted state. Otherwise, the source corresponding to this measurement is added to the database, the filter state is augmented with the position and the velocity of the new detected node and the current vehicle navigation is used together with the USBL measurement to initialize the new states. Should this agent be visible again in the future, its measurements are used as a fix to the filter.

For the purpose of numerical implementation, the motion and measurements model equations were time-discretized using the Euler integration method. The model of the system can be thus rewritten in the following compact form:

$$\boldsymbol{x}_{k+1} = f\left(\boldsymbol{x}_k\right) + \boldsymbol{G}\boldsymbol{\nu}_k, \tag{4}$$

$$\boldsymbol{y}_k = h\left(\boldsymbol{x}_k\right) + \boldsymbol{\eta}_k. \tag{5}$$

Here, the subscript k indicates that the quantity is referred to the k-th time instant. The prediction step is executed at each time instant $k > 0$ when a new inertial measurement is made available, by calculating the predicted state $\hat{\boldsymbol{x}}_{k+1}^-$ and the predicted covariance matrix of the estimation error $\boldsymbol{P}_{k+1}^-$, starting from the initial conditions $\hat{\boldsymbol{x}}_0$, $\boldsymbol{P}_0$:

$$\begin{aligned} \hat{\boldsymbol{x}}_{k+1}^- &= f\left(\hat{\boldsymbol{x}}_k^+\right), \\ \boldsymbol{P}_{k+1}^- &= \boldsymbol{F}_k \boldsymbol{P}_k^+ \boldsymbol{F}_k^T + \boldsymbol{G}\boldsymbol{Q}\boldsymbol{G}^T. \end{aligned} \tag{6}$$

The variables with the "+" superscript in the prediction equation are the refined estimations of the state and of the covariance matrix at the previous time step, obtained by running a Kalman update step with the past measurements from the available auxiliary sensors. In (6), the matrix $\boldsymbol{F}_k$ is obtained from (4) as follows:

$$\boldsymbol{F}_k = \left.\frac{\partial f\left(\boldsymbol{x}\right)}{\partial \boldsymbol{x}}\right|_{\hat{\boldsymbol{x}}_k^+},$$

and $\boldsymbol{Q} = \mathrm{diag}\left(\boldsymbol{Q}_{\boldsymbol{a}}, \boldsymbol{Q}_{\boldsymbol{\epsilon}}\right)$ is the noise covariance matrix. When a new measurement from the auxiliary sensors is available, the Kalman update step is executed, in order to correct the prediction obtained in the current step. It is worth to mention that each measurement has its own notification rate, thus it usually happens that at a given time step, not all the measurements can be available. Under these assumptions, the correction step is made by employing the available measurements at the current time, namely $\tilde{\boldsymbol{y}}_k$, and by selecting the entries in the matrices of the output model which correspond with the currently available measurements. The correction step is then executed by calculating the state estimate $\hat{\boldsymbol{x}}_{k+1}^+$ and the covariance matrix of the estimate error $\boldsymbol{P}_{k+1}^+$ as:

$$\begin{aligned} \hat{\boldsymbol{x}}_{k+1}^+ &= \hat{\boldsymbol{x}}_{k+1}^- + \boldsymbol{K}_k\left(\tilde{\boldsymbol{y}}_k - h\left(\hat{\boldsymbol{x}}_{k+1}^-\right)\right), \\ \boldsymbol{P}_{k+1}^+ &= \left(\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k\right)\boldsymbol{P}_{k+1}^-, \end{aligned} \tag{7}$$

where $\boldsymbol{H}_k$ is obtained from (5) as follows:

$$\boldsymbol{H}_k = \left.\frac{\partial h\left(\boldsymbol{x}\right)}{\partial \boldsymbol{x}}\right|_{\hat{\boldsymbol{x}}_{k+1}^-},$$

and

$$\boldsymbol{K}_k = \boldsymbol{P}_{k+1}^+\boldsymbol{H}_k^T\left(\boldsymbol{H}_k\boldsymbol{P}_{k+1}^+\boldsymbol{H}_k^T + \boldsymbol{R}_k\right)^{-1}$$

is the Kalman gain matrix, being $\boldsymbol{R}_k$ a block diagonal matrix composed by the covariance matrices of the noises of the measurements available at the time instant k. As previously said, the team master uses an eventual acoustic measurement as a correction only if the source is already present in the set $\mathcal{V}(k)$, otherwise the measurement will be temporarily saved and used to extend the filter state after the correction. At that point, the algorithm checks whether any acoustic measurement from an unobserved node was previously saved; in this case, the state of the filter is augmented with the position and the velocity of the node (and the set $\mathcal{V}(k)$ increases contextually) and initialized respectively with the values:

$$\begin{bmatrix} \hat{\boldsymbol{p}}_{k+1}^+ + {}^n\mathbf{R}_b(\boldsymbol{\Theta})^b\mathbf{R}_u\tilde{\boldsymbol{y}}_{\mathrm{usbl}_i,k} \\ \mathbf{0}_{3\times 1} \end{bmatrix},$$

where $\hat{\boldsymbol{p}}_{k+1}^+$ is the estimation of the vehicle position. Moreover, the covariance matrix $\boldsymbol{P}_{k+1}$ is also extended as follows:

$$\boldsymbol{P}_{k+1} = \mathrm{diag}\left(\boldsymbol{P}_{k+1}, \boldsymbol{P}_{\hat{\boldsymbol{p}},k+1} + \boldsymbol{R}_{\mathrm{usbl}}\left(k\right), \boldsymbol{I}_3\right),$$

where $\boldsymbol{P}_{\hat{\boldsymbol{p}},k+1}$ is the submatrix of $\boldsymbol{P}_{k+1}$ corresponding to the estimation of the vehicle position.

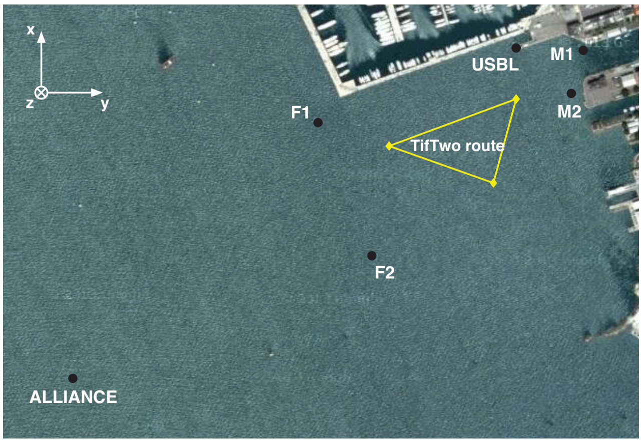


Fig. 7: Experimental set-up of the Sept. 12th trial during *CommsNet '13*.

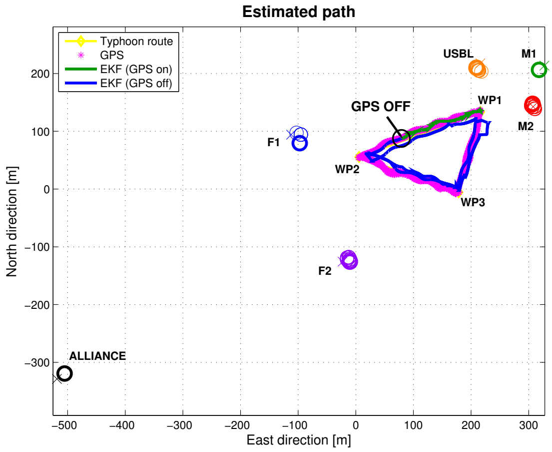


Fig. 8: Estimation of both the North-East path followed by TifTu and the network topology.

4 Results

The designed navigation algorithm was validated off-line on different scenarios. Considering the initial stage of a research activity, it is in fact quite common to preliminary test the navigation algorithms off-line before planning new experiments at sea. In this case the off-line validation exploited real data acquired during some experimental campaigns previously performed with the Typhoon vehicles (Allotta et al 2016). During all the sea trials, the navigation algorithm used on-board the vehicles relied on a dead-reckoning procedure only. The software on-board each vehicle allowed to simply store mission data logs, including all the raw sensors outputs. This allowed to run the proposed navigation filter in post-processing. The synchronization between the vehicles has been guaranteed by means of the GMT time received through the GPS (when available) signal.

We start considering a scenario in which the team master vehicle is the only mobile agent of the network, which is constituted by some fixed acoustic modems. Partial results about this scenario were already reported in Allotta et al (2015a). The data used in the post-processing elaborations were collected in the Sept. 12th, 2013 trial, during the *CommsNet '13* experiment. The considered scenario is shown in Fig. 7. The team master vehicle, i.e. the TifTu AUV, performed an autonomous, on-surface mission within an inside harbor area, consisting in the repetition of a triangle-shaped path of approximately 150 m side. In that area, some battery-operated acoustic modems were deployed close to the bottom, sometimes in the proximity of harbor structures (piers, etc.), to set-up the network infrastructure. The modem positions have been chosen for practical convenience, and no optimization with respect to localization accuracy has been attempted. Finally, an additional acoustic modem was deployed from the RV Alliance. In the following, we refer to the fixed-nodes constituting the network as M1, M2, F1, F2, USBL and ALLIANCE. The goal of this trial consisted in evaluating the performance of the TDMA-based communication scheme designed within the THESAURUS project in a network of larger dimension. For this reason, the existing networking policy was adapted just to deal with the number of the deployed modems (setting the duration of an entire round-robin cycle to 90 s), and hence not optimized for navigation purposes.

Fig. 8 shows the result of the acoustic-based SLAM algorithm. We can distinguish two parts: in the first one (solid green line), the GPS measurements were used as absolute position updates to initialize the estimation filter, i.e. to fix the initial conditions and to make the accelerometers bias and the gain K_{thr} converge. In order to verify the performance of the SLAM algorithm, the measurements from the USBL during this *initialization phase* were discarded: it is indeed straightforward to understand that combining the relative position with an absolute, non-divergent position information as the GPS one, the SLAM algorithm would be able to localize another node with just one USBL measurement. On the other hand, starting from a *rough estimate* of the vehicle absolute position, the filter needs more than one relative position measurement to make the SLAM algorithm converge. Starting from the point indicated by the black circle on the map, we simulated a GPS signal loss as in a normal underwater operation, and the forward thrust and the USBL measurements only were used as correction feeds to the estimation filter. In the navigation phase (solid blue line) the GPS was thus used as *ground truth* reference only. The colored cir-

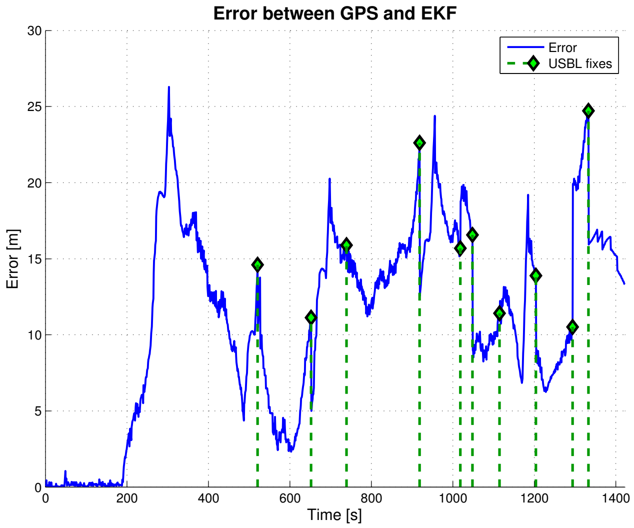


Fig. 9: Norm of the vehicle position error. The green diamonds represent occurrences of USBL fix reception.

Table 1: Statistics of the navigation algorithm run on *CommsNet '13* data.

Node name	Node ID	# USBL pings	Final error (m)
M2	1	3	5.0
M1	3	1	12.0
F1	7	4	9.8
F2	8	6	8.5
ALLIANCE	10	1	16.3
USBL	11	5	14.3

cles represent the estimation of the position of the fixed acoustic nodes in the environment: the heavy circles indicate the initial positions, evaluated on the first USBL fix reception for each node. Finally, the crosses represent the reference positions of the respective acoustic modems.

Fig. 9 represents the norm of the error between the estimated position and the GPS reference of the vehicle. We can see how in the first 200 s of the mission the error is zero since the GPS measurements were used as corrections to initialize the algorithm. Finally, in Table 1 we report the norm of the error between the estimated and the reference positions of the nodes of the network at the end of the mission. It can be noticed that, even with few, irregularly spaced in time corrections received from the USBL (indicated by the green diamonds), the navigation algorithm is able to keep both the vehicle position and the acoustic network topology estimation error bounded to a reasonable value for the considered task (i.e. 3-4 times the GPS precision). In some cases, the USBL correction leads to an increase of the estimation error. This may be due to the fact that the modems which have generated the measurements (namely, F1 and F2) were installed on-board two different vehicles hovering in mid-water. The motion disturbance caused by marine currents may thus have affected the localization measurement accuracy, leading to a degradation in the performance of the navigation algorithm. No data is available, though, to quantify this disturbance; however, even in these cases the estimation error remains bounded within its maximum value. Note that, a small number of USBL fixes is realistic in a situation that presents a non-negligible overhead introduced by the networked structure and strong multi-path effects affecting the USBL modem when the vehicle navigates at the sea surface. Moreover, the irregularity in the inter-arrival time of the USBL fixes is due to the fact that in the considered trial the acoustic communication suffered heavily from data loss.

Table 2: Position of the TifTu anchoring buoy.

Buoy Name	Latitude (°)	Longitude (°)	Depth (m)
B2	43.932533°	15.444468°	0

In the second scenario presented here, the team master hovers in a predefined position, while a slave vehicle navigates in the same area. The cooperative navigation algorithm with this configuration corresponds to the data collected during the *Breaking The Surface '14* workshop held in Biograd na Moru (Croatia) between Oct. 5th and Oct. 12th, 2014, in the framework of the testing campaign of the ARROWS project. The experiment involved the two existing vehicles of Typhoon class, TifOne and TifTu. In this trials, the team master vehicle, i.e. the TifTu AUV, was tied to a fixed surface buoy close to the shore, so that real-time communication through fiber optics could be possible for mission monitoring. The coordinates of the buoy position are reported in Table 2. The slave vehicle, i.e. the TifOne AUV, was autonomously performing a mission composed of five different waypoints defined in the bay of the Soline Camping Park in Biograd na Moru. The coordinates of the waypoints are reported in Table 3. The waypoints define a quadrangle shaped trajectory, with the first two legs on the surface and the last two ones underwater at a reference depth of 1.5 m.

In Fig. 10 the positions of the waypoints that define the mission of TifOne with respect to the position of the buoy where TifTu was tied are shown.

Fig. 11 shows the results of the cooperative navigation algorithm executed with the data collected in the Oct. 9th, 2014 trial. On the left, the Latitude-Longitude estimated paths are illustrated. For each run, the ma-

Table 3: Waypoints for TifOne mission.

Waypoint Name	Latitude (°)	Longitude (°)	Depth (m)
WP1	43, 932571°	15, 445007°	0.0
WP2	43, 932358°	15, 445458°	0.0
WP3	43, 932071°	15, 445167°	0.0
WP4	43, 932272°	15, 444689°	1.5
WP5	43, 932642°	15, 445087°	1.5

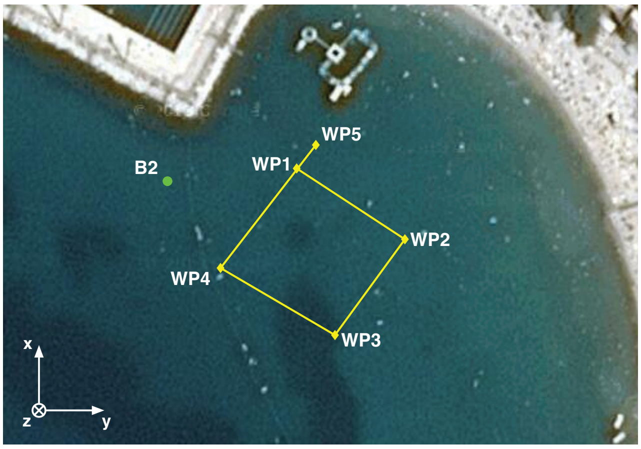
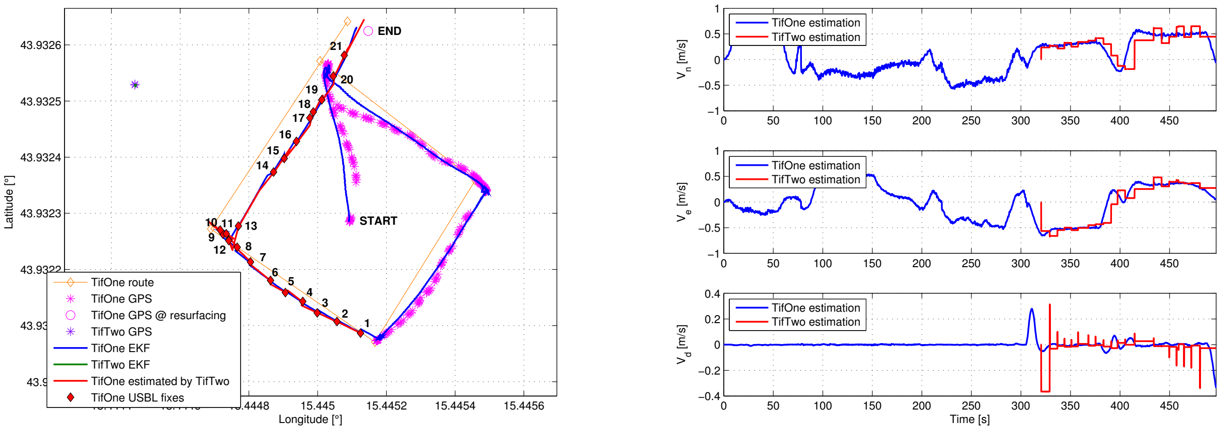


Fig. 10: Experimental set-up of the *Breaking The Surface '14* sea trials.

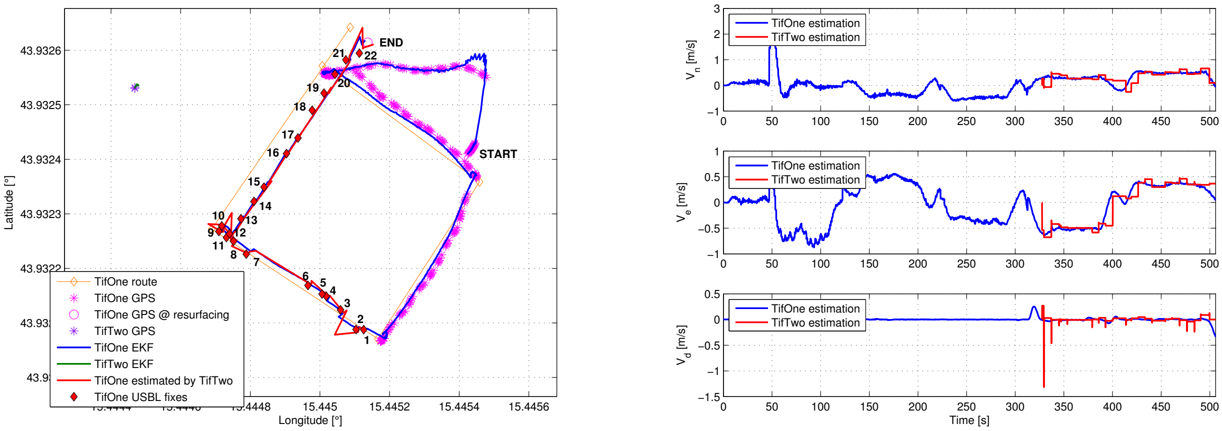
genta stars and the violet stars represent respectively the TifOne and the TifTu GPS position. As in the previous case, the GPS is used as a correction fix at the beginning only, in order to initialize the estimation filter of both the vehicles. The red diamonds indicate the position of the slave vehicle obtained by combining the raw USBL measurements with the GPS position of the team master, numbered in chronological order. The solid blue lines and the solid green lines are respectively the slave and the team master positions estimated by their own navigation algorithm. As can be noticed, after the team master has corrected the navigation status of the slave with a new USBL measurement and sent the updated position through the network, the slave vehicle uses the received information to fix its own position. Furthermore, it is possible to see how the estimated TifTu position is in effect overlapped with its relative GPS reference; we remark that the navigation algorithm of the team master uses the position given by the GPS receiver to fix the initial condition only. Finally, the solid red lines represent the TifOne position estimated by the TifTu navigation algorithm, obtained by integrating the USBL measurements with the TifOne navigation status corrections received through the acoustic channel. In the right column the TifOne estimated velocities in the local navigation frame coordinate (NED) are represented. The blue solid lines are the velocities estimated by the navigation algorithm of the slave vehicle, thus obtained by integrating measurements from DVL, accelerometers and depth sensor. The red solid lines are the TifOne velocities estimated by TifTu on the basis of both the USBL measurements and the navigation status updates received from the slave vehicle. In Table 4 some statistics about the previous three runs are presented. In particular, the last column shows the error between the TifOne GPS reference at the resurfacing (indicated in Fig. 11 with the magenta circles) and the corresponding position estimated by the vehicle own navigation algorithm. It is worth to note how the cooperative algorithm is able to keep the position error close to the GPS accuracy in all the three runs. We note that in the third run the error is higher, but the number of USBL fixes is smaller than in the other runs; moreover, it is possible to see from Fig. 11c that in the last part of the mission no USBL corrections were received, so the TifOne estimation filter cannot take advantage of the cooperative part. Finally, for the first two mission runs, in which the USBL fixes cover the entire underwater path, we evaluate the performance of the estimation filter in the borderline case in which the slave vehicle has not the DVL on-board, i.e. the velocity corrections are not used. Table 5 reports the norm of the error between the estimated position and the GPS reference of TifOne at the resurfacing, showing how the cooperative algorithm is able to keep the localization error bounded within the GPS accuracy even in the case in which the slave vehicle has a poorer set of navigation aids.

5 Conclusion

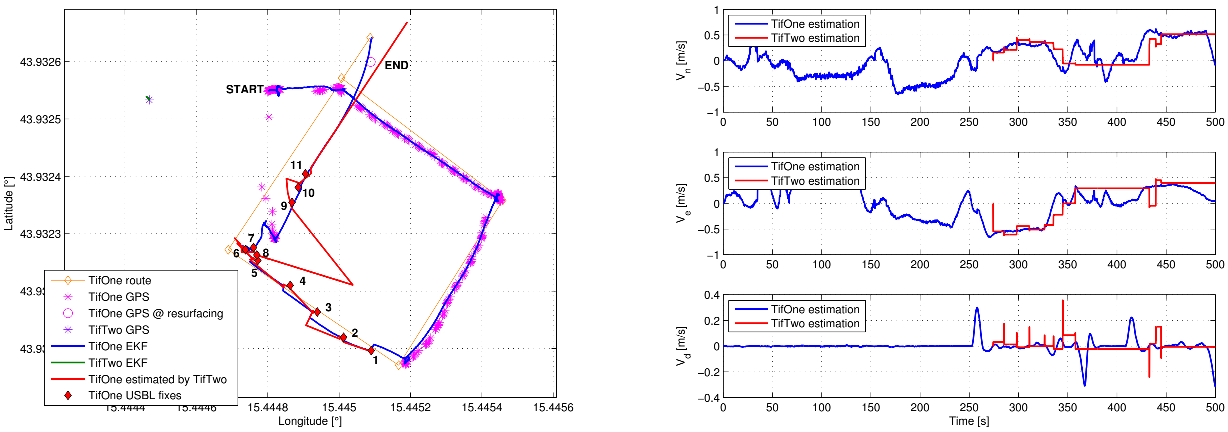
The paper has described a cooperative navigation procedure, and it has evaluated in post-processing the navigation error from experimental data. The reported results show that, despite the limitation in the instrumentation used, in the method itself, and in the experimental configuration, the absolute localization error can be close to the GPS accuracy (as in the *Breaking The Surface '14* experiment). In particular, acoustic fixes are quite effective in re-initializing the navigation filters, in much the same way as GPS signals do on land or in air; however, acoustic fixes have the drawback of arriving with important delays and irregularly in time, depending on the acoustic channel conditions, on the AUVs configuration and on the total number of available nodes. In particular, as in the *CommsNet '13* experiment, the presence of a total of seven nodes, plus adverse acoustic communication conditions, has led to an average error approximately one order of magnitude greater than *Breaking The Surface '14* case. **It is worth noting that the experiments reported,**



(a) First run.



(b) Second run.



(c) Third run.

Fig. 11: Results of the cooperative navigation algorithm in the three mission runs.

Table 4: Statistics of the navigation algorithm run on *Breaking The Surface '14* data.

Mission run	Estimated travelled distance (m)	# USBL pings	USBL error Mean (m)	USBL error Std. dev. (m)	Error at the resurfacing (m)
1	337	21	0.32	0.05	2.7
2	403	22	0.35	0.05	0.6
3	333	11	0.32	0.02	4.6

Table 5: Error at the resurfacing for the borderline case.

Mission run	Error at the resurfacing (m)
1	3.2
2	3.1

although limited in time, demonstrate the effectiveness of the proposed approach in characterizing the team of vehicles with long-term navigation features. The results reported may serve as a guideline to system configuration and dimensioning, depending on mission navigation accuracy requirements.

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References

Allotta B, Costanzi R, Meli E, Pugi L, Ridolfi A, Vettori G (2014) Cooperative localization of a team of AUVs by a tetrahedral configuration. Robotics and Autonomous Systems 62(8):1228–1237, DOI 10.1016/j.robot.2014.03.004

Allotta B, Bartolini F, Caiti A, Costanzi R, Corato FD, Fenucci D, Gelli J, Guerrini P, Monni N, Munaf A, Natalini M, Pugi L, Ridolfi A, Potter J (2015a) Typhoon at CommsNet13: Experimental experience on AUV navigation and localization. Annual Reviews in Control 40:157 – 171, DOI 10.1016/j.arcontrol.2015.09.010

Allotta B, Pugi L, Bartolini F, Ridolfi A, Costanzi R, Monni N, Gelli J (2015b) Preliminary design and fast prototyping of an autonomous underwater vehicle propulsion system. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 229(3):248–272, DOI 10.1177/1475090213514040

Allotta B, Caiti A, Costanzi R, Fanelli F, Fenucci D, Meli E, Ridolfi A (2016) A new AUV navigation system exploiting unscented Kalman filter. Ocean Engineering 113:121 – 132, DOI 10.1016/j.oceaneng.2015.12.058

Bahr A, Leonard JJ, Fallon MF (2009) Cooperative localization for Autonomous Underwater Vehicles. The International Journal of Robotics Research 28(6):714–728, DOI 10.1177/0278364908100561

Bayat M, Crasta N, Aguiar A, Pascoal A (2015) Range-based underwater vehicle localization in the presence of unknown ocean currents: Theory and experiments. Control Systems Technology, IEEE Transactions on PP(99):1–1, DOI 10.1109/TCST.2015.2420636

Becker C, Ribas D, Ridao P (2012) Simultaneous sonar beacon localization & AUV navigation. In: IFAC Conference on Manoeuvring and Control of Marine Craft, Arenzano, Italy, DOI 10.3182/20120919-3-IT-2046.00034

Bellingham J, Zhang Y, Kerwin J, Erikson J, Hobson B, Kieft B, Godin M, McEwen R, Hoover T, Paul J, Hamilton A, Franklin J, Banka A (2010) Efficient propulsion for the Tethys long-range autonomous underwater vehicle. In: Autonomous Underwater Vehicles (AUV), 2010 IEEE/OES, pp 1–7, DOI 10.1109/AUV.2010.5779645

Caiti A, Calabro V, Fabbri T, Fenucci D, Munafo A (2013) Underwater communication and distributed localization of AUV teams. In: OCEANS - Bergen, 2013 MTS/IEEE, pp 1–8, DOI 10.1109/OCEANS-Bergen.2013.6608166

Caiti A, Di Corato F, Fenucci D, Grechi S, Novi M, Pacini F, Paoli G (2014) The project V-fides: A new generation AUV for deep underwater exploration, operation and monitoring. In: Oceans - St. John's, 2014, pp 1–7, DOI 10.1109/OCEANS.2014.7003091

Fallon M, Papadopoulos G, Leonard J (2010) A measurement distribution framework for cooperative navigation using multiple auvs. In: Robotics and Automation (ICRA), 2010 IEEE International Conference on, pp 4256–4263, DOI 10.1109/ROBOT.2010.5509869

Fossen TI (2002) Marine Control Systems: Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles, 1st edn. Marine Cybernetics, Trondheim, Norway

Furfaro T, Alves J (2014) An application of distributed long baseline node ranging in an underwater network. In: Underwater Communications and Networking (UComms), 2014, pp 1–5, DOI 10.1109/UComms.2014.7017126

Gebre-Egziabher D, Hayward R, Powell J (1998) A low-cost GPS/inertial attitude heading reference system (AHRS) for general aviation applications. In: Position Location and Navigation Symposium, IEEE 1998, pp 518–525, DOI 10.1109/PLANS.1998.670207

Hagerman G (2002) Wave energy systems for recharging auv energy supplies. In: Autonomous Underwater Vehicles, 2002. Proceedings of the 2002 Workshop on, pp 75–84, DOI 10.1109/AUV.2002.1177207

Lloret J (2013) Underwater sensor nodes and networks. Sensors 13(9):11,782, DOI 10.3390/s130911782

Milne PH (1983) Underwater acoustic positioning systems, 1st edn. E. & F. N. Spon Ltd, London, UK

Paull L, Saeedi S, Seto M, Li H (2014) AUV Navigation and Localization: A Review. Oceanic Engineering, IEEE Journal of 39(1):131–149, DOI 10.1109/JOE.2013.2278891

Petillot Y, Maurelli F, Valeyrie N, Mallios A, Ridao P, Aulinas J, Salvi J (2010) Acoustic-based techniques for autonomous underwater vehicle localization. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 224(4):293–307, DOI 10.1243/14750902JEME197

Rogers RM (2000) Applied Mathematics in Integrated Navigation Systems, 3rd edn. American Institute of Aeronautics & Astronautics, Reston, Va, USA

Stutters L, Liu H, Tiltman C, Brown D (2008) Navigation technologies for autonomous underwater vehicles. Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on 38(4):581–589, DOI 10.1109/TSMCC.2008.919147

Walls JM, Eustice RM (2014) An origin state method for communication constrained cooperative localization with robustness to packet loss. The International Journal of Robotics Research 33(9):1191–1208, DOI 10.1177/0278364914532390

Webster S, Walls J, Whitcomb L, Eustice R (2013) Decentralized extended information filter for single-beacon cooperative acoustic navigation: Theory and experiments. Robotics, IEEE Transactions on 29(4):957–974, DOI 10.1109/TRO.2013.2252857

Whitcomb L, Jakuba M, Kinsey J, Martin S, Webster S, Howland J, Taylor C, Gomez-Ibanez D, Yoerger D (2010) Navigation and control of the Nereus hybrid underwater vehicle for global ocean science to 10,903 m depth: Preliminary results. In: Robotics and Automation (ICRA), 2010 IEEE International Conference on, pp 594–600, DOI 10.1109/ROBOT.2010.5509265