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UKF-based Navigation System for AUVs: Online Experimental Validation

Riccardo Costanzi**
Francesco Fanelli*
Enrico Meli*
Alessandro Ridolfi* (*IEEE Member*)
Andrea Caiti** (*IEEE Fellow*)
Benedetto Allotta* (*IEEE Member*)
*Department of Industrial Engineering, University of Florence (UNIFI), Florence, Italy
ISME - Interuniversity Center of Integrated Systems
for the Marine Environment
**Dipartimento di Ingegneria dell′Informazione and Centro di Ricerca "E. Piaggio" -
Università di Pisa (UNIPI), Pisa, Italy
ISME - Interuniversity Center of Integrated Systems
for the Marine Environment
Email: riccardo.costanzi@unipi.it, Email: a.ridolfi@unifi.it

Abstract

Modern Autonomous Underwater Vehicles (AUVs) are currently involved in complex tasks and scenarios, and require accurate and robust navigation systems to estimate their position. However, since the Global Positioning System (GPS) cannot be exploited underwater, the AUV position is not directly measurable in real-time (unless using dedicated acoustic-based sensors), making the availability of a reliable navigation system even more crucial. In this context, the main role is played by the filter used to estimate the AUV motion, usually relying on simple kinematic vehicle models and equations linearization.

A navigation strategy specifically thought for AUVs and based on the Unscented Kalman Filter (UKF) is proposed and experimentally validated by the authors. Preliminary tests of the developed strategy have been carried out by running the navigation filter on experimental data acquired during the FP7 European ARROWS project. This initial validation has been performed totally offline. The AUVs navigated in dead-reckoning without using navigation filters whereas the proposed strategy has been compared to standard Extended Kalman Filter (EKF)-based ones, highlighting encouraging performances.

To further validate the proposed navigation system, suitable sea tests have been performed. The navigation filter has been implemented online on an AUV and the vehicle controller relied only on it to navigate. The new validation procedure, whose results are reported in this paper, showed again the good performance of the chosen strategy, yielding satisfying results in terms of accuracy of vehicle position estimation.

I. Introduction

Currently, Autonomous Underwater Vehicles (AUVs) are broadly employed in several industrial applications (especially in the Oil&Gas industry), scientific tasks (archaeological exploration and surveillance), military reconnaissance and patrolling missions, search and rescue duties, etc.

An accurate, efficient and robust navigation system, including the suitable hardware and software needed to get a real-time estimation of the vehicle pose, is mandatory for all these kinds of applications [1], [2], [3], [4]. Due to the strict requirements of the modern AUV tasks, involving both single and multiple vehicles [5], [6], [7], [8], [9], precise motion estimation represents the key point in AUV navigation, along with a good trade-off between accuracy and numerical efficiency. Good performance of the navigation system is crucial not only for the results of the mission (e.g. position and attitude errors between desired and real paths, etc.) but also to georeference the experimental data coming from onboard acoustic or optical payload. Furthermore, the Global Positioning System (GPS) information cannot be exploited underwater, complicating both the vehicle localization and the motion estimation, and increasing the importance of an accurate and robust navigation system.

Nowadays, the Kalman Filter (KF) [10] and the Extended Kalman Filter (EKF) (nonlinear KF version) [11], [12], [13] are the main filters exploited for AUV motion estimation. To reach a satisfying trade-off between accuracy, efficiency and memory consumption and to be effectively used in real-time applications, this kind of filters is usually based on simplified kinematic models of the AUV.

An alternative to the EKF is a filtering approach based on the Unscented Kalman Filter (UKF), [14], [15]. Being it computationally affordable by today's AUV hardware and, most of all, derivative free (characteristic that allows it to cope with the difficulties arising using, e.g., the EKF on nonlinear, stiff and non-differentiable systems such as AUVs), it theoretically represents a valid alternative to the most commonly used filters. In recent literature several contributions regarding the use of the UKF in the marine fields can be found. In [16], for example, the authors simulate the behavior of two different real world AUVs during the execution of an autonomous underwater task. Both vehicles are dynamically modeled, and their control loops close on an UKF navigation filter exploiting inertial, velocity and (acoustic) position measurements. The presented results suggest that the UKF may constitute a reliable strategy to estimate the state of a vehicle in the underwater field. In [17], instead, an UKF is used to estimate the kinematic state of an AUV in case of unreliability of sensor measurements. The structure of the filter is suitably modified in order to be able to react to faulty sensor readings, and simulations show the increased robustness of the proposed approach.

In addition, in [18], a comparison between the EKF and the UKF is proposed: both filters are used to estimate online the state of a kinematic and dynamic model of an AUV. The state of the system is then augmented to include the unknown hydrodynamic coefficients of the vehicle. Simulation results show that the UKF performs better in estimating both the kinematic state of the vehicle and the unknown coefficients, highlighting the problems faced by the EKF in case of highly nonlinear systems.

Despite the encouraging simulation results documented in literature (e.g. the above-mentioned references), to the authors' knowledge, UKF-based approaches have not yet been extensively exploited in practical applications in the underwater field. This led the authors to propose an UKF-based navigation filter specifically developed for AUVs. The algorithm relies on the information coming from sensors usually available onboard AUVs (as for instance linear velocity, and depth sensors [19], [20]) and on a mixed kinematic and dynamic AUV model suitably developed and validated, able to provide accurate results if used in conjunction with estimation filters, but not too heavy from a computational viewpoint [21], [22].

In previous works, preliminary tests of the UKF-based approach have been carried out by the authors by running the navigation filter on experimental data acquired during the FP7 European ARROWS project [23], [24]. This initial validation has been performed completely offline: sensor data have been used to perform a comparison between an EKF-based navigation filter and the proposed UKF-based one, highlighting the better performance of the latter, especially under critical operating conditions (for instance, with a reduced set of available sensors) [21], [22]. For the sake of clarity, the authors published, till now, intermediate research steps that have been fundamental to reach the actual use in real time of the UKF strategy, which is the achieved final research step described and reported in the present paper. The manuscript is thus not intended to provide a performance comparison with algorithms proposed in the works previously published by the same authors. The navigation strategy here presented is the updated one with a reduced state vector: this is the scheme implemented on board the AUV. The paper is intended as an experimental validation of a navigation system that exploits, as fundamental constituent elements, the most important results achieved and demonstrated in the previous works.

After the encouraging results obtained during the first phase of offline validation, subsequent sea tests have been executed in order to validate the proposed approach in a realistic scenario. Different sea test campaigns have been carried out in order to evaluate the performance of the UKF-based navigation filter online: the controller of the vehicle relied only on the filter to navigate. In particular, the results obtained during two sea test campaigns are reported in this paper.

After a description of a state-space model of the vehicle given in the following Section, the results obtained during the two above-mentioned sea test campaigns, which took place in Sicily, Italy, in June 2015 and in La Spezia, Italy, in November 2015, are presented in the final Section.

II. NAVIGATION FILTER

In order to exploit a recursive discrete estimation filter, a suitable discrete state-space formulation of a model of the vehicle must be derived in the form:

$$\begin{cases} \mathbf{x}_k = \mathbf{f}_{k-1}(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}) + \mathbf{w}_{k-1} \\ \mathbf{y}_k = \mathbf{h}_k(\mathbf{x}_k) + \mathbf{v}_k \end{cases}, \tag{1}$$

in which $\mathbf{x}_k$ is the state vector at the k-th instant, $\mathbf{u}_k$ and $\mathbf{y}_k$ are the system inputs and outputs, and $\mathbf{w}_k$ and $\mathbf{v}_k$ are additive process and measurement noises, respectively. The first equation in (1) is the *system evolution equation* while the second one is the *measurement equation*.

The starting point is the complete 6 DOFs dynamic vehicle model proposed by [1]. Then, in a previously published work by the authors [22], this model has been suitably simplified, taking into account only longitudinal dynamics, to derive a mixed kinematic and dynamic model; this model would constitute a convenient trade-off between accuracy and computational load. In [22], the state vector was a twelve-dimensional vector including all the kinematic variables of the AUV (pose and velocity, both linear and angular).

At the same time, the authors developed an efficient attitude estimation filter [25], which is able to estimate the orientation of the vehicle even in presence of magnetic disturbances, hence removing the need of estimating the attitude and the angular velocity of the AUV within its navigation filter. For this reason, the authors decided to reduce the dimension of the state vector with respect to [22], considering attitude a time-varying input instead of a state component; i.e. in the real scheme implemented on board the AUV, the authors use algorithms dedicated to the estimation of the vehicle orientation and this is the reason why it is possible to use the AUV angles as inputs for the UKF-based position estimation. The UKF position estimation algorithm is a good choice for the non-linear behaviour of the AUV. The used orientation estimator [25] is useful during real missions at sea because it is able to face the quite common magnetic disturbances present in the environment. From the application point of view, the authors thus believe that both algorithms (UKF and attitude estimation algorithm) are important for high performance navigation systems.

Taking into account the above-mentioned considerations, and using SNAME notation [1], the resulting state vector can be properly defined as:

$$\mathbf{x} = \begin{bmatrix} \boldsymbol{\eta}_1 \\ \boldsymbol{\nu}_1 \end{bmatrix} \ . \tag{2}$$

where the state vector $\mathbf{x}$ is composed of Earth-fixed position $\boldsymbol{\eta}_1$ and body-fixed linear velocity $\boldsymbol{\nu}_1$ of the AUV. The discrete-time system state evolution equation is given by:

$$\begin{aligned} \begin{bmatrix} \boldsymbol{\eta}_1 \\ \boldsymbol{\nu}_1 \end{bmatrix}_k &= \begin{bmatrix} \boldsymbol{\eta}_1 \\ \boldsymbol{\nu}_1 \end{bmatrix}_{k-1} + \\ &+\Delta T \begin{bmatrix} R_B^N \left((\boldsymbol{\eta}_2)_{k-1} \right) (\boldsymbol{\nu}_1)_{k-1} \\ \begin{bmatrix} \frac{\tau_{1x}(\boldsymbol{\nu}_{k-1}, \mathbf{u}_{k-1})}{m} + \frac{F_1(\boldsymbol{\nu}_{k-1})}{m} \\ 0 \\ 0 \end{bmatrix} \end{bmatrix} + \mathbf{w}_{k-1} \ , \end{aligned} \tag{3}$$

where $R_B^N(\boldsymbol{\eta}_2)$, function of the orientation of the vehicle $\boldsymbol{\eta}_2$, is the rotation matrix from a fixed *North-East-Down* (NED) frame N to the body-fixed frame B, $\tau_{1x}(\boldsymbol{\nu}, \mathbf{u})$ is the force acting on the vehicle longitudinal axis as a nonlinear function of its velocity and of the rotating speeds of its propellers $\mathbf{u}$, m is the mass of the vehicle, ΔT is the fixed filter sampling time, and $F_1(\boldsymbol{\nu})$ is the hydrodynamic damping force acting on the longitudinal degree of freedom, given by:

$$F_1(\boldsymbol{\nu}_{k-1}) = -\frac{A_f C_u \rho \left(\nu_{1x}\right)_{k-1}^2 sgn(\nu_{1x})_{k-1}}{2} \ , \tag{4}$$

being A_f and C_u the "reference frontal area" of the AUV and the longitudinal drag coefficient [26]. For a detailed derivation of the terms of (3), including the propulsion system modeling, please refer to [22], [27].

For what concerns the measurement equation, the available physical quantities are the sensors outputs:

$$\mathbf{y}_k = \left[\eta_{1x}^{GPS} \ \eta_{1y}^{GPS} \ \eta_{1z}^{DS} \left(\boldsymbol{\nu}_1^{DVL} \right)^T \right]_k^T \ , \tag{5}$$

where the GPS (on surface) and the depth sensor (DS) are used to measure $\boldsymbol{\eta}_1$, while the Doppler Velocity Logger (DVL) is used to measure $\boldsymbol{\nu}_1$. Please refer to table I for the main characteristics of the considered vehicle, including a sensor list.

(5) highlights that the measurement equation is affine. More particularly, the measurement function $\mathbf{h}_k(\cdot)$ can be expressed through a matrix H_k containing only 1 or 0 elements:

$$\mathbf{y}_k = H_k \mathbf{x}_k + \mathbf{v}_k \ . \tag{6}$$

The size of the matrix H_k may vary over the time. In fact, the vehicle sensors are characterized by different working frequencies but the filter sample time ΔT is fixed. Consequently, since each sensor is queried for a new measurement at each sampling period, if such measurement is not available, the corresponding rows of H_k must be deleted. In the proposed navigation strategy, the GPS is used for the correction step each time it is available. I.e. GPS data are always used for the correction when the vehicle is on surface, while instead they are not available when the AUV is navigating underwater.

Considering Equations (3)-(4), the resulting vehicle model is highly nonlinear and non-differentiable; for this reason, linear filters, such as the standard Kalman Filter [10], cannot be used to estimate the state of the vehicle. Additionally, even strategies based on the Extended Kalman Filter [11], [12], [13] could lead to important accuracy problems. These reasons motivated the authors to investigate alternative estimation strategies. A navigation filter based on the Unscented Kalman Filter [11], [14], [15] has then been chosen, since it is completely derivative free and the hardware which is today present on AUVs is able to efficiently handle the required computational load. However, despite the above-mentioned advantages, the authors could not find in literature extensive sources of its exploitation in practical underwater operations; for instance, taking into account the state of the art of the last years, analyzed in the Introduction, only completely simulated results or offline simulations exploiting experimental sensor data can be found.

At first, after developing the vehicle model described in [22], the authors performed an offline comparison between the proposed UKF-based strategy and an EKF-based navigation filter (exploiting real sensor data acquired during experimental missions), highlighting the advantages of the UKF, especially when the sensor set is reduced. The results of such tests can be found in [21], [22]. The positive outcomes of this preliminary comparison encouraged the authors to test the UKF-based strategy online, simplifying the original vehicle model as described at the beginning of this Section and implementing the filter onboard. Then, suitable experimental tests have been carried out in order to evaluate the online performance of the proposed solution in a real scenario. The obtained results at sea are reported in the following Section.

III. EXPERIMENTAL TESTS AND VALIDATION

This Section reports the results obtained during two different test campaigns, which took place, respectively, in June 2015 and in November 2015. The UKF-based navigation filter described in the previous Section has been integrated within the control architecture of the vehicle, which is based on ROS (*Robot Operating System*); the performed tests aimed at validating online the proposed strategy.

The used vehicle is the Typhoon AUV, developed and built by the Department of Industrial Engineering of the University of Florence (DIEF) during the THESAURUS Tuscany Region project [28] and the European ARROWS project [23] (Figure 1). The main features of the vehicle are given in Table I. Both the missions presented in the paper, starting from the first waypoints WP1, are performed underwater (the AUV is at a certain depth); thus, GPS data are not available from WP1 till the end of each mission - final resurfacing (no other resurfacings are present) - and cannot be used for the correction step. In the remaining of this

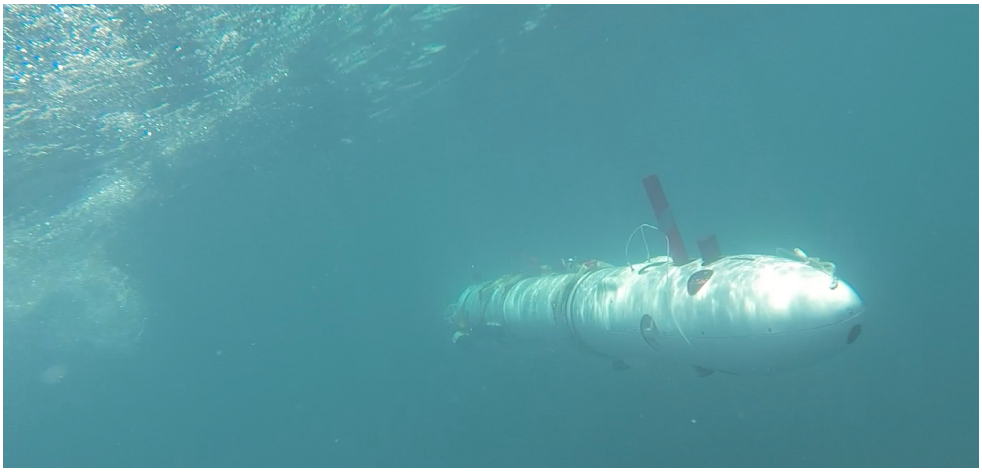

Fig. 1: Typhoon AUV

Typhoon AUV main characteristics	
Size [mm]	3600×350 (diameter) approx.
Mass [kg]	130-180 (dep. on payload)
Max speed [kn]	5-6
Max depth [m]	300
Autonomy [h]	8
Navigation sensors	GPS, IMU, FOG, DVL, depth sensor, acoustic modem
Payload	cameras, 2D forward-looking sonar, side-scan sonar

TABLE I: Typhoon AUV physical data, payload and performance

Section, the results obtained during the two test campaigns are analyzed in details.

A. *Sicily, Italy, June 2015 test campaign*

This experimental campaign was performed near the *Cala Minnola* wreck (Levanzo, Aegadian Islands, Sicily, Italy) during the first final demonstration of the ARROWS project (May 25 - June 5, 2015, [23], [24]). Typhoon AUV was required to autonomously follow the transept-shaped path shown in Figure 2. The path consisted of 16 waypoints (from WP1 to WP16) and its sizes were about 27 m per 55 m (total length equal to about 464 m); the GPS coordinates of the point WP1 are $37.9891°$ N and $12.3547°$ E. The AUV navigated underwater at a depth of about 25 m and at a constant altitude of 2 m from the seabottom whereas the longitudinal speed was controlled at 0.5 m/s. A non-negligible sea current was present during the test day, approximately directed in North-South direction. An Ultra Short BaseLine (USBL) transducer was mounted

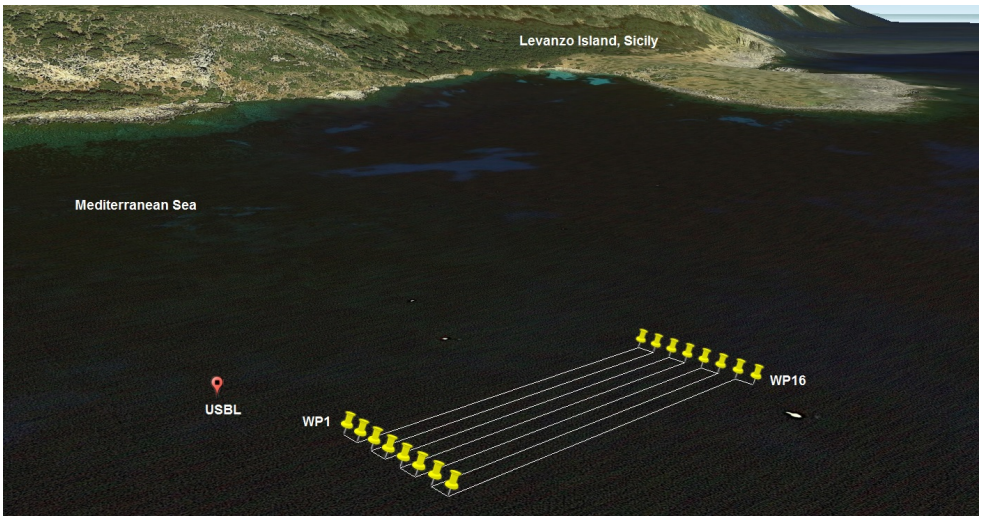

Fig. 2: The transept-shaped path followed by the Typhoon AUV during the sea tests near the *Cala Minnola* wreck (Levanzo, Aegadian Islands, Sicily, Italy)

on a support ship near the planned path, as shown in Figure 2, and was used for mission monitoring. The measured AUV position, not used as a correction term within the filter, can be considered the ground truth. The position of Typhoon was measured through such sensor and its data were made available to Typhoon through acoustic communication. It is worth noting that thus the USBL orientation was not constant and this may affect the localization measurement accuracy. For the sake of clarity, this measurement system suffers from a certain error due to the combination of: the intrinsic measurement error of the USBL device itself, the measurement error of the GPS and the measurement error of the IMU mounted on the buoy, the possible synchronization error of these onboard (on the buoy) data, [29]. Nevertheless its outputs, given in Figure 5, were consistent with similar results reported in literature (see for example [30]). In Figure 3, the vehicle position estimated by the navigation algorithm $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$ is reported and compared to the

ideal vehicle position based on the predefined waypoints $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$. Although the disturbance due to the sea current is visible during the first legs of the transept and no current estimators are exploited into the navigation filter, the results are quite encouraging and highlight the goodness of the proposed approach. The good estimation of the vehicle position provided by the navigation algorithm allowed, among the other

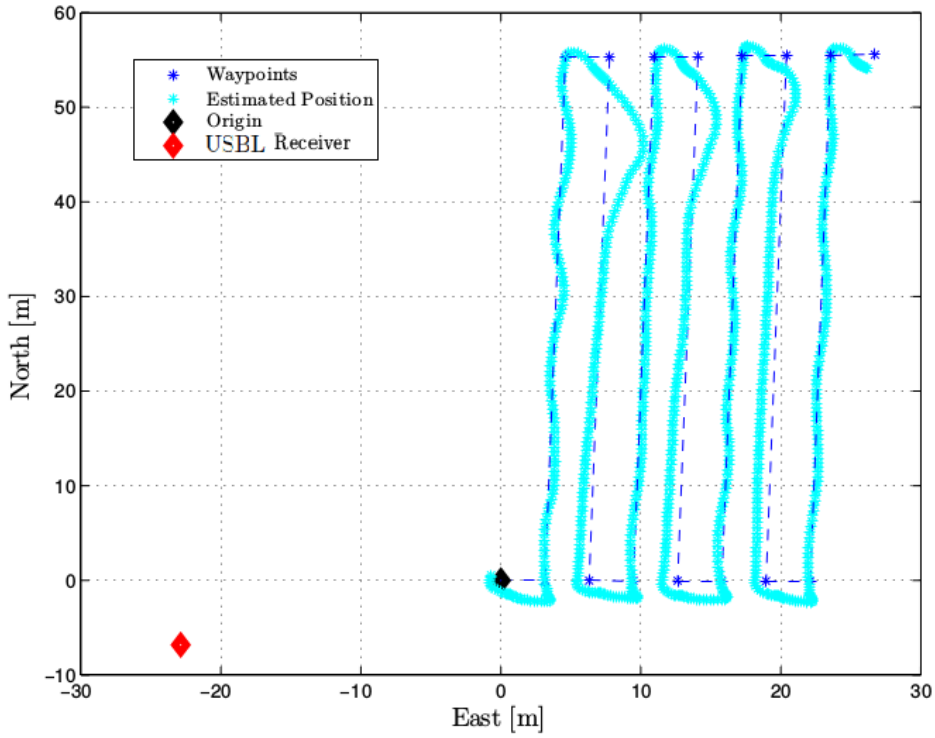

Fig. 3: Comparison between the vehicle position estimated by the navigation algorithm $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$ and the ideal vehicle position based on the predefined waypoints $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$

benefits, the accurate mapping and reconstruction of the archeological site of the *Cala Minnola* wreck ([23], [24]). As an example, an optical frame captured by the vehicle during the mission is reported in Figure 4. Some of the obtained 3D reconstructions are available on the ARROWS project website [23].

From a quantitative point of view, the estimation errors $||\boldsymbol{\eta}_1^{UKF} - \boldsymbol{\eta}_1^{USBL}||$ between the vehicle position estimated by the navigation algorithm and the vehicle position provided by the USBL are summarized in Figure 5, in correspondence of the USBL fixes. The USBL fixes are quite numerous and uniformly distributed in time, allowing a reliable assessment of the performance of the navigation algorithm. The error trend here reported is associated with the vehicle navigating underwater; i.e. the origin of the time line of Figure 5 coincides with the AUV immersion phase. Thus as concerns the time slot of the error trend, GPS data are not available (the AUV is at depth) and cannot be used for the correction step. Despite

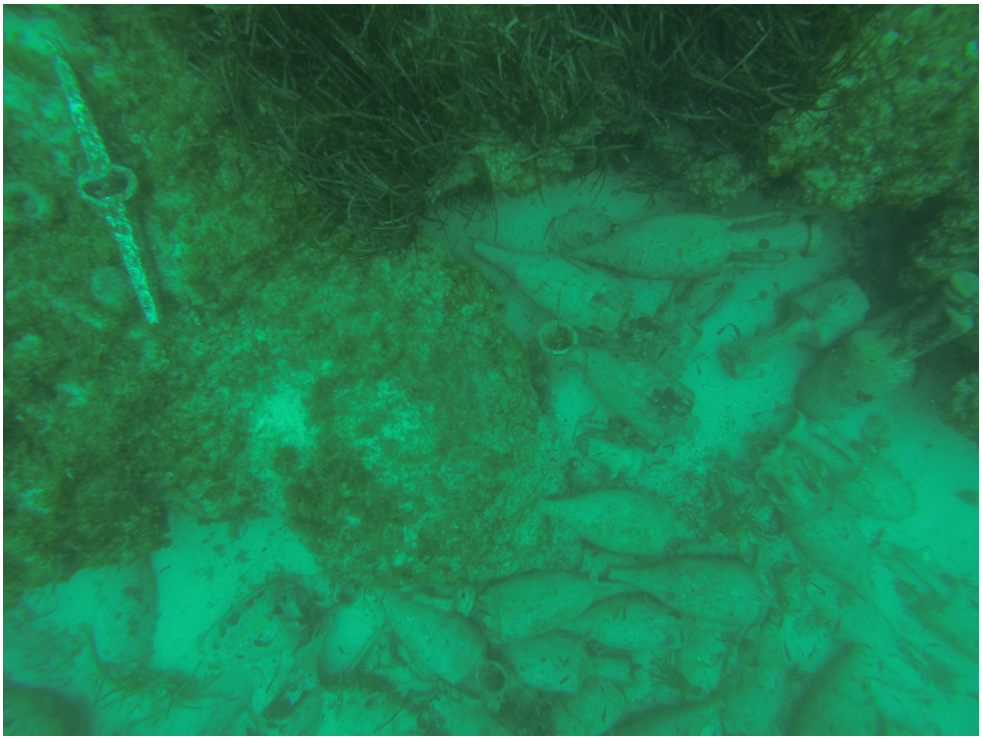

Fig. 4: An optical frame captured during the mapping of the archeological site of the *Cala Minnola* wreck (Levanzo, Aegadian Islands, Sicily, Italy)

the uncertainty affecting the USBL measurements, the error caused by the USBL sensor (see for example [30]) and the effect of the sea currents, the global estimation error is limited (less than 5 m), highlighting the good performance of the navigation algorithm.

B. La Spezia, Italy, November 2015 test campaign

The second test campaign presented in this paper was carried out on November 19, 2015 in a sea basin in the harbor of La Spezia, Italy. During the mission, Typhoon autonomously performed the transept-shaped path shown in Figure 6. The ideal trajectory was composed of 8 different waypoints (from WP1 to WP8) and its sizes were about 10 m per 80 m (total length equal to about 350 m); the GPS coordinates of the point WP1 are 44.09468695° N and 9.862218645° E. While executing its task, Typhoon navigated underwater (depth of about 3 m) at a fixed desired longitudinal speed equal to 0.5 m/s. Close to the mission path, a fixed reference buoy (Figure 6) equipped with an USBL transducer, an Inertial Measurement Unit (IMU) and a GPS (to estimate its own pose) was placed on the water surface. The buoy (GPS coordinates 44.09506073° N and 9.86148400° E) transmitted the data needed for mission monitoring directly to the shore through a proper a WiFi access point. The USBL sensor allowed to determine the AUV position at

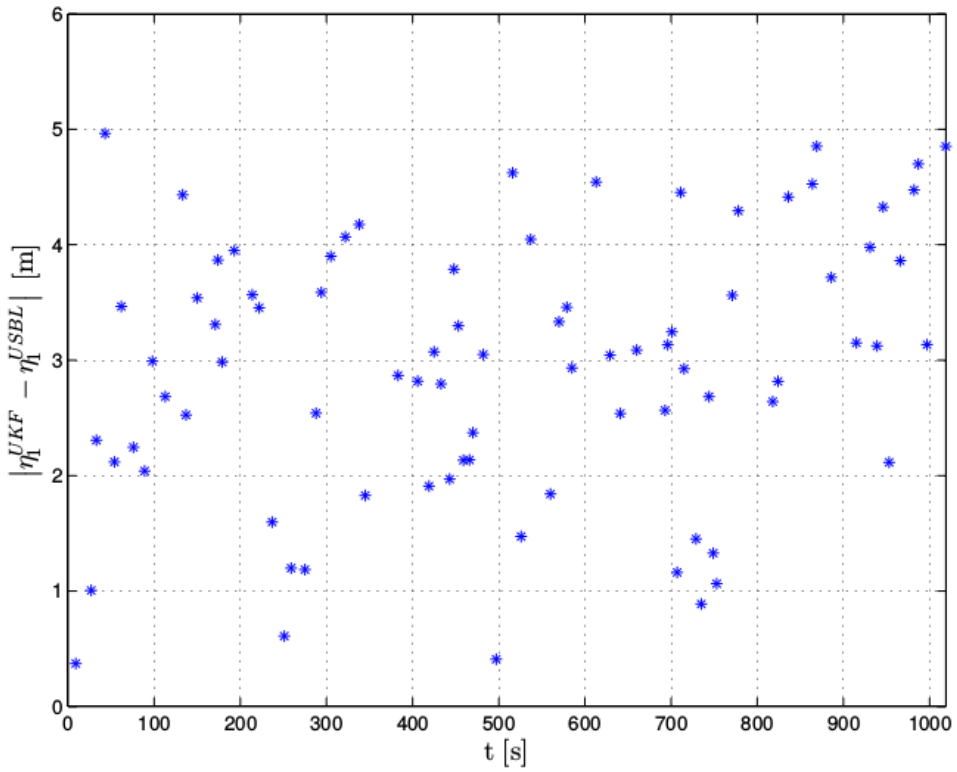

Fig. 5: Estimation errors $||\boldsymbol{\eta}_1^{UKF} - \boldsymbol{\eta}_1^{USBL}||$ between the vehicle position estimated by the navigation algorithm and the vehicle position provided by the USBL (in correspondence of the USBL fixes)

high rate and sent an acoustic ping after each vehicle localization. Thanks to the USBL, the trajectory of the AUV was measured according to the accuracy of the sensor. Similarly to the previous test campaign, such measurement was then exploited as ground truth to investigate the performance of the UKF navigation algorithm implemented into the AUV motion controller.

It is important to point out that the USBL pose was not exactly constant. This may negatively influence the accuracy of the USBL measurements; however, the quality of the data provided by the USBL during the experimental campaign (see Figure 9) turned out to be numerically similar to those of other studies present in literature [30].

The AUV position provided by the navigation filter $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$ and the reference AUV trajectory obtained connecting the desired waypoints $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$ are compared in Figure 7. A specific zoom of the estimated and ideal vehicle positions $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$, $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$ near to the waypoints WP6 and WP7 is highlighted in Figure 8. As for the first test campaign, even if the system is characterized by several sources of uncertainty (e.g. error on the USBL sensor positioning due to residual motions of the reference buoy and the intrinsic error of the USBL sensor), the resulting online AUV position estimation error is

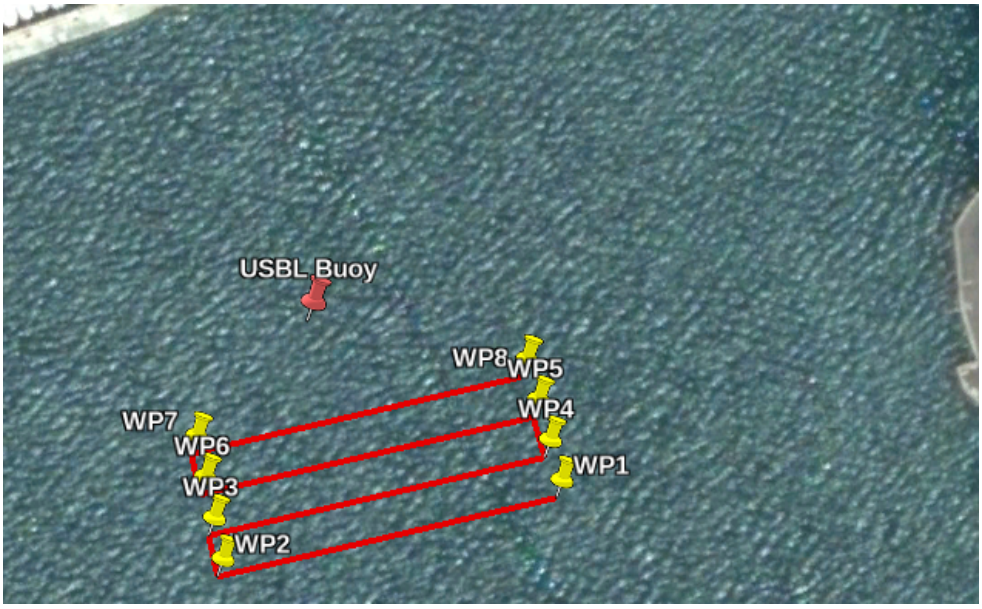

Fig. 6: The transept-shaped path followed by the Typhoon AUV during the sea tests in La Spezia, Italy

quite limited, confirming the satisfying performance of the proposed navigation filter shown in previous tests.

Finally, the authors would like to highlight that in the two missions proposed in the paper (error results given in Figures 5 and 9) it is hard to appreciate the increase in the position error drift, even if present for sure. This is due not only to the adopted ground truth but also because the strategy/system illustrated in the paper exploits a quite performing sensor set, e.g. a DVL and a FOG on board (please refer e.g. to [31] to see that with good sensors the error can be very limited even with just a dead reckoning navigation strategy); the error thus does not grow quickly during time. If the error grows slowly it is not simple to appreciate its drift in the time slots related to the experimental campaigns at sea made here in Italy and reported in the paper. However, the slowly growing error achieved in both the mission is a good point because the AUV is not obliged to perform frequent resurfacings to get the position reset. These results have the aim to validate the UKF navigation strategy, not too much widespread in the underwater robotics field nowadays, and considering this aim they are consistent and satisfying.

IV. Conclusion

In this paper, the authors studied and validated an UKF-based navigation algorithm especially developed for AUVs. The navigation algorithm has been experimentally tested directly online on the Typhoon AUV, developed and built by the University of Florence in the framework of the Tuscany Region THESAURUS

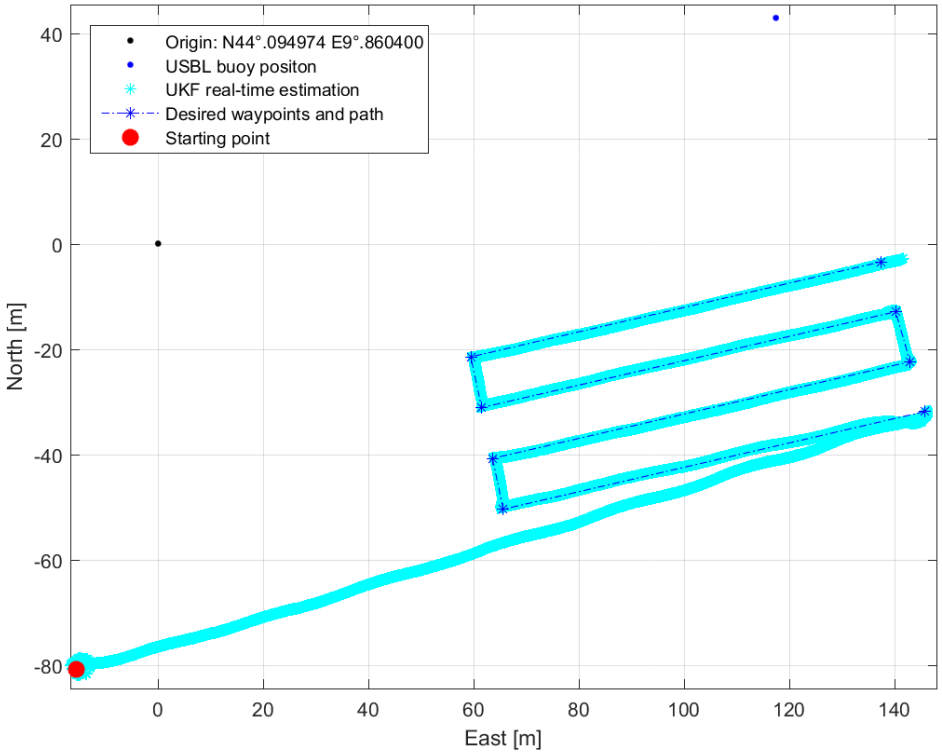

Fig. 7: Comparison between the vehicle position estimated by the navigation algorithm $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$ and the ideal vehicle position based on the predefined waypoints $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$ (the GPS coordinates of the point WP1 are $44.09468695°$ N and $9.862218645°$ E)

project [28] and of the FP7 European ARROWS project [23], [24]. Suitable experimental tests have been carried out to validate online the proposed strategy, and this paper reports the results obtained during two of these test campaigns.

This first online validation of the navigation system yielded satisfying results. The navigation algorithm showed good accuracy in estimating the vehicle position, even in presence of environmental disturbances such as sea currents which may deeply influence the navigation system accuracy. The complete navigation algorithm performs a real-time (the algorithm here proposed is implemented online within the motion control loop) pose (both position and orientation) estimation that contemporarily exploits the positive results achieved in previous works by the same authors, and till now validated only singularly and off-line through post-processing analysis of data logged in various experiments of the past. In addition, it is worth pointing out that the results presented in this manuscript did not highlight discrepancies with respect to what was obtained in the previous works; on the contrary, the online experimental validation of the proposed algorithm, that combines the approaches of position and orientation estimation within a whole strategy (based on the

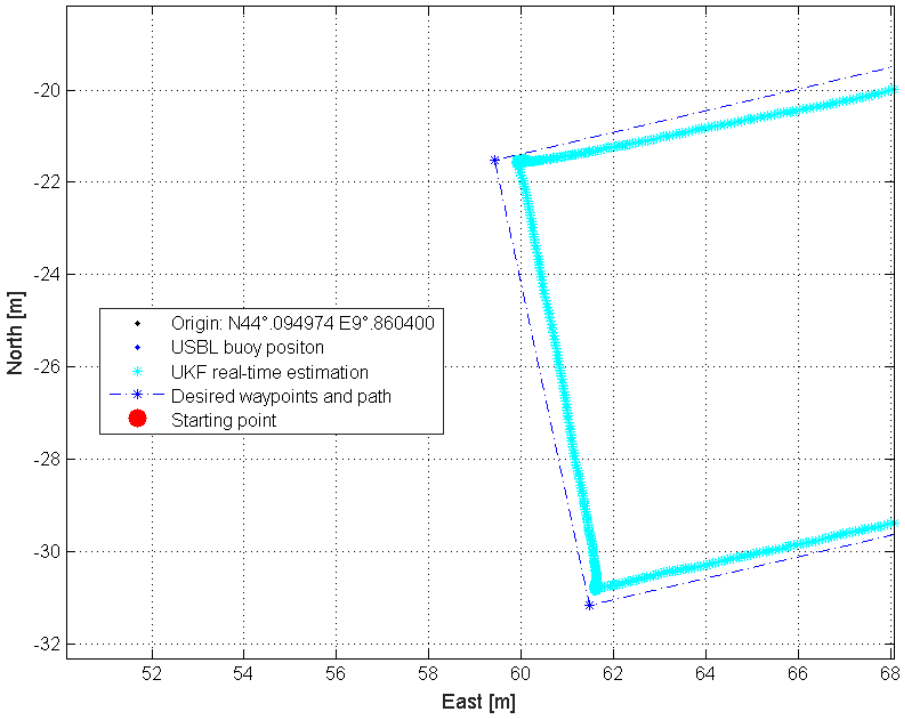

Fig. 8: Zoom of the estimated and ideal vehicle positions $\left[\eta_{1x}^{UKF}\ \eta_{1y}^{UKF}\right]^T$, $\left[\eta_{1x}^{ID}\ \eta_{1y}^{ID}\right]^T$ near to the waypoints WP6 and WP7

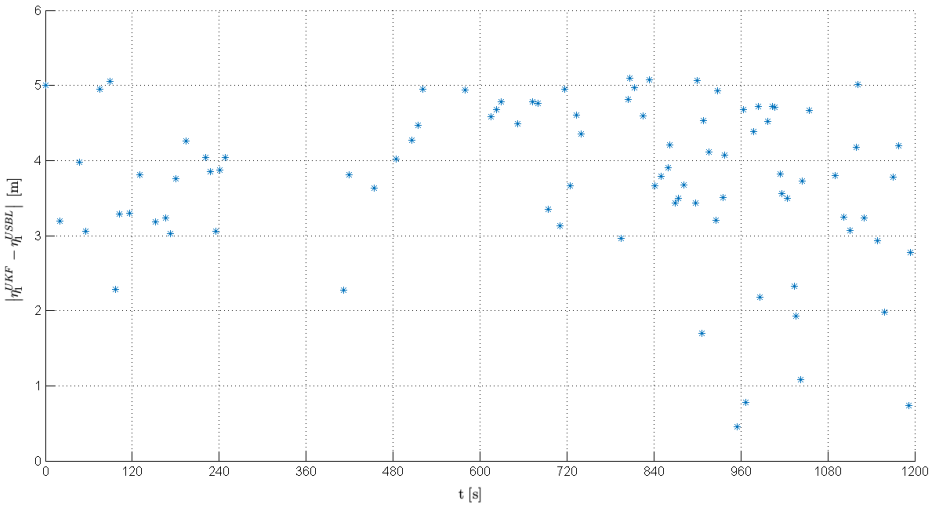

Fig. 9: Estimation errors $||\boldsymbol{\eta}_1^{UKF} - \boldsymbol{\eta}_1^{USBL}||$ between the vehicle position estimated by the navigation algorithm and the vehicle position provided by the USBL in correspondence of the USBL fixes

267 described new, modified version of UKF), provided results coherent with them. The navigation algorithm
268 allowed the vehicle to navigate underwater without problems related to its own pose estimation.
269 As regards the further developments of this research activity, the UKF-based navigation filter will be

validated again on different AUVs belonging to the University of Florence in more complex tasks. This way, the reliability of the proposed navigation strategy will be better investigated. Subsequently, sea current estimators will be studied and implemented on the AUVs and tested online to further improve the filter robustness and to better understand the influence of the sea currents on the AUV dynamics.

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