

# Localizing Autonomous Underwater Vehicles: Experimental Evaluation of a Long Baseline Method

Irene Tallini,<sup>\*†</sup> Luca Iezzi,<sup>\*‡</sup> Petrika Gjanci,<sup>‡</sup> Chiara Petrioli,<sup>\*‡</sup> Stefano Basagni<sup>†</sup>

<sup>\*</sup>Dipartimento di Informatica, “Sapienza” University of Roma, Italy

<sup>†</sup>The Institute for the Wireless Internet of Things, Northeastern University, USA

<sup>‡</sup>WSENSE Srl, Rome, Italy

**Abstract**—This work concerns underwater networking with mobile assets, like Autonomous Underwater Vehicles (AUVs), for advanced monitoring and exploration of submerged environments. Particularly, we are interested in enabling an AUV to localize itself while moving underwater by acoustically polling beacon nodes statically deployed at well-known location. Our method only relies on a model of the AUV dynamics, on an on-board depth sensor and on long baseline ranging information. The AUV applies an Extended Kalman Filter to estimate its position, without needing any further local measurements but those of depths. We have evaluated the accuracy of the proposed method via experiments at sea in the shallow waters around the Italian island of Ponza, computing the average distance between the estimated locations of the AUV and its positions as measured by GPS along its trajectory (localization error). In deployments with up to four beacons, our simple method enables AUVs to swiftly self localize with errors never exceeding 3.62m (using only two beacons), 2.65m (three beacons) and 2.45m (four beacons).

**Keywords**—Underwater acoustic networks, Autonomous Underwater Vehicles (AUVs), long baseline (LBL) localization.

## I. INTRODUCTION

Increasing commercial and strategic interests in the sustained and sustainable exploitation, preservation and regeneration of the marine environment has recently propelled the whole field of underwater communication and networking to unparalleled advances. The driving sectors of the *Blue Economy* [1], including tourism, climate change, renewable energy, aquaculture, waste management, security and maritime transport, now more than ever need the support of networking solutions at par with those available on earth, to ease swift data reporting, real-time monitoring, and other management operations. Many underwater applications require use of untethered devices that are capable of communicating wirelessly, thus offsetting the cost of deploying cables underwater that would be prohibitive for many applications, and that enable asset deployment in large geographical areas. Particularly, devices that can move, generically called Autonomous Underwater Vehicles (AUVs), are effective for decreasing costs, e.g., of experimental, surveillance, monitoring and exploration campaigns, for reducing human intervention in hazardous areas, and for extending network coverage. Over the recent years, a number of AUVs have been designed for fundamental applications for marine geoscience and ocean studies [2]–[4], inspection and maintenance of submerged infrastructures and search and rescue missions [5], and for harbor safety and

surveillance [6], [7], among many others.

*Localizing* AUVs, namely, providing the vehicles with the capability to determine their position while they move, clearly increases their usefulness for many applications. However, this is particularly challenging underwater, for the impossibility of relying on radio communication and especially on positioning system like the GPS. To solve this problem, a variety of technologies and techniques have been introduced, ranging from passive ones that are relatively inexpensive but inaccurate (e.g., dead reckoning and inertial navigation) to increasingly accurate ones, relying actively on communications, more expensive equipment, sophisticated on board sensors and requiring longer deployment and calibration times (e.g., acoustic or optical-based localization, and geophysical navigation) [8], [9]. *Underwater acoustic positioning systems* appears to be particularly suited to localize underwater assets, including mobile ones [10]. These systems measure positions by means of acoustic distance and direction measurements, and subsequent position trilateration. Some of these systems require acoustic transponders to be deployed on a ship or similar vessel (e.g., short baseline systems), while *long baseline systems* (LBL) determine asset locations relative to a framework of baseline stations, which must be deployed prior to operations, and whose positions needs to be precisely known [10] (Chapter 4). LBL systems are particularly known for their accuracy, and since they do not need to rely on ship support or on measurements from sensors on board of the AUV, they are suitable to be used for localizing mobile vehicles, especially those used in campaigns at sea, with small form factors and room for little payloads and very basic sensors (e.g., depth).

In this paper we aim at defining and testing an LBL-based localization methods for small, cost-effective AUVs that can be swiftly deployed along with the baseline stations, called *beacons*, to conduct missions of interest in selected underwater areas. In order to offset measurements errors in the deployment of the beacons and the ranging errors from acoustic communications, we supplement the LBL system with information on depth and from a predefined model of the AUV motion, all fused by an Extended Kalman Filter. Our method has been implemented on the commercial grade AUV *Zeno* (Zeno Environmental Nautical Operator) by MDM Team [11], [12]. We conducted a campaign of experiments to evaluate its accuracy in the shallow water off the coast of the island of Ponza, in central Italy. The LBL system is made

up of four baseline beacons, statically positioned at locations whose coordinates are determined by GPS. The beacon and the AUV are equipped with an acoustic modem and software by WSENSE, Srl. The method accuracy was assessed by measuring the average distance between the position estimated using our method and that obtained by “ground truth” measurements via the GPS module of Zeno. We performed localization experiments with range information from two, three and then from all four beacons, to evaluate the accuracy of our method and its robustness to limited information. Results show that our simple method enables the AUV to swiftly self localize with errors never exceeding 3.62m (experiments with two beacons), 2.65m (three beacons) and 2.45m (four beacons). These results compare favorably to those from similar works that use more sophisticated and costly equipment to improve calibration and measurements [13], [14] (see Section IV for a more detailed discussion of previous solutions). Considering also that the GPS module that we used to determine the ground truth trajectory of the AUV has an horizontal positioning error in the order of 2.5 m, we believe that our LBL-based localization method can be used confidently in multiple applications, especially when swift deployment is required of few beacons and “low cost” AUVs.

The rest of the paper is organized as follows. In Section II we provide the theoretical underpinnings of our method for localizing an AUV. The results of the performance evaluation of our method at sea are shown in Section III. In Section IV we describe similar work on experimental localization of AUVs. Finally, we draw our conclusions in Section V.

## II. SCENARIO AND LOCALIZATION METHOD

We consider an underwater scenario where  $N > 0$  baseline acoustic transponders, called *beacons*, are statically deployed to form a *long baseline* (LBL) acoustic positioning system [10] (Chapter 4). Beacons are positioned (semi-)permanently at locations whose geodetic coordinates are known. Each beacon knows its unique ID (a number  $i \leq N$ ) and its three geodetic coordinates. The purpose of the beacons is to communicate their ID and coordinates when requested. No assumptions need to be made about the locations of the beacons. In other words, the presented localization method does not require the beacons to be deployed according to specific or preferred geometric patterns, such as a grid, a line, etc. An *Autonomous Underwater Vehicle* (AUV) travels through this underwater scenario. The AUV is equipped with an accurate depth sensor, as those customarily used in underwater robots [12], [15], and with an acoustic modem compatible with those of the beacons. We assume that the AUV is not equipped with GPS or other sensors (e.g., Inertial Measurement Units and Doppler Velocity Logs) that could allow it to determine its location at a certain time while underwater. The AUV knows the unique ID of each of the beacons. We assume that wherever it is, the AUV is always within the (acoustic) communication range of all deployed beacons. Communications errors (e.g., corrupted or lost packets) are considered. A sketch of the considered scenario is depicted in Fig. 1.

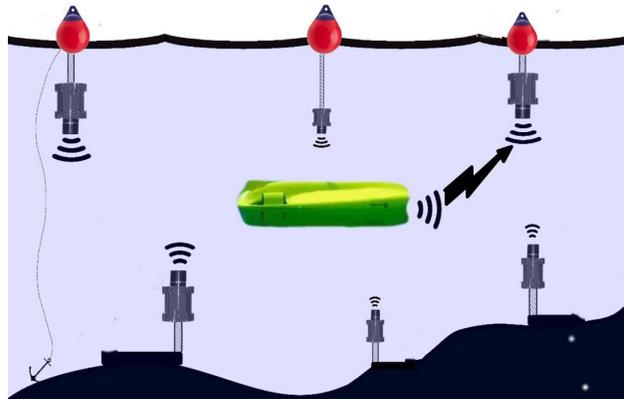


Fig. 1. An LBL-ready underwater scenario with an AUV and six beacons.

### A. The AUV localization method

The aim of the AUV is that of determining an accurate estimation of its position in 3D space in time. In an LBL system this requires the computation of its distance from the beacons. Particularly, the AUV polls one beacon at a time via a *location request packet*. Upon receiving a request packet, the polled beacon replies with a *location packet*, containing its own ID and its coordinates. The AUV can thus compute the distance from the beacon by dividing the round-trip time of the communication by two and multiplying it by the speed of sound in water [16].

To offset the inaccuracy of baseline ranging, we supplement the distance information with depth measurements, with information from a model of the AUV dynamics, and with the expected errors on both beacon positions and ranging, integrating all through an Extended Kalman Filter (EKF) [17].

A high level description of the localization process is the following, highlighting the joint use of information from the motion model and from the LBL system, at different time scales. After setting an initial estimate of its position, in time, the AUV estimates its coordinates by keeping executing the following two steps while it moves.

- 1) **Predict step:** With a frequency  $1/T$ , for a pre-defined  $T$ , the AUV computes a new position estimate using the model of its motion.
- 2) **Update step:** Every  $t$  seconds, for a pre-defined  $t$ , the AUV sets to collect location packets from the beacons. Once  $n \leq N$  location packets have been received, for a pre-defined  $n$ , the AUV updates the estimate produced in the Predict Step with ranges information.

In addition to the ranges from the LBL system and to the motion model, the AUV uses depth measurements from a pressure sensor. These sensors are notoriously accurate, providing depth information with very small errors (few centimeters). This way, the problem of localizing the AUV can be brought to two dimensions, reducing to the estimation of the AUV position on the sea surface plane.

We will now define the motion model and the equations for integrating range information to estimate the AUV position.

*Motion model.* The **state** of the AUV at time  $k$  is defined as  $x_k = [p_k, v_k]$ , where  $p_k = (p_{x,k}, p_{y,k})$  and  $v_k = (v_{x,k}, v_{y,k})$  are the position on the  $x, y$  plane and the velocity of the AUV, respectively. (Here round brackets indicate a vector and square brackets indicate the concatenation operator.) The planar position of beacon  $i$  is indicated with  $p^i = (p_x^i, p_y^i)$ .

We model the AUV dynamics using a constant velocity model, i.e., we assume that the vehicle is moving with constant velocity and with accelerations as Gaussian random variables with zero mean [17]. This is formalized by the following recursive equation (Dynamics Equation, [18]):

$$x_k = f(x_{k-1}) + r = \underbrace{\begin{pmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}}_F \begin{pmatrix} p_{x,k-1} \\ p_{y,k-1} \\ v_{x,k-1} \\ v_{y,k-1} \end{pmatrix} + \begin{pmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{pmatrix}$$

where  $r$  is a zero mean Gaussian random variable with the following covariance matrix:

$$R = a \begin{pmatrix} T^4/4 & 0 & T^3/2 & 0 \\ 0 & T^4/4 & 0 & T^3/2 \\ T^3/2 & 0 & T^2 & 0 \\ 0 & T^3/2 & 0 & T^2 \end{pmatrix}, \quad a \in R^+,$$

Where  $a$  indicates the amplitude of the acceleration.

*LBL measurements and position.* The distance  $d_k^i$  from beacon  $i$  is linked to the AUV state through the following equation (Measure Equation):

$$d_k^i = h(p_k, p^i, q_b) + q_r = \left\| [p_k - p^i + q_b, p_{z,k} - p_z^i] \right\|_2 + q_r,$$

where  $q_b$  is a Gaussian random variable representing the error of the beacon position and  $q_r$  is the ranging error. The overall error is indicated with  $q = [q_b, q_r]$  and its covariance matrix with  $Q$ . Moreover,  $p_{z,k}$  is the depth measured by the AUV depth sensor and  $p_z^i$  is the depth of beacon  $i$ . (As stated earlier, we consider depth measurements basically error free.)

The filtering procedure executed by the AUV for estimating its planar coordinates  $(p_{x,k}, p_{y,k})$  at time  $k$  is as follows.

- 1) **Base case.** The AUV sets an initial state estimation  $x_{0|0}$ , with relative covariance matrix  $P_{0|0}$ . At the end of this initial step the AUV state is  $x_k = x_{0|0}$ , whose first two elements are the estimated coordinates of the AUV.
- 2) **Predict step.** With a frequency of  $1/T$ , the AUV computes a new estimate  $x_{k|k-1}$ ,  $P_{k|k-1}$  using the Dynamics Equations. This is done through the Predict Equations of the EKF:

$$x_{k|k-1} = F \cdot x_{k-1|k-1} \\ P_{k|k-1} = F \cdot P_{k-1|k-1} \cdot F^T + R.$$

Here  $x_{k-1|k-1}$  is the output of the previous Update step (see below). At the end of this step the AUV state

is  $x_k = x_{k-1|k-1}$ , whose first two elements are the estimated coordinates of the AUV.

- 3) **Update step:** When the AUV determines  $n$  ranges it updates the estimate and covariance matrix produced in the Predict step with ranges information. This is done through the Update Equations of the EKF:

$$S_k = H_k \cdot P_{k|k-1} \cdot H_k^T + M_k \cdot Q \cdot M_k^T \\ K_k = P_{k|k-1} \cdot H_k^T \cdot S_k^{-1} \\ x_{k|k} = x_{k|k-1} + K_k \cdot (d_k^i - h(x_{k|k-1}, p^i, 0)) \\ P_{k|k} = (I - K_k H_k) \cdot P_{k|k-1}$$

Here  $H_k = \frac{\partial h}{\partial x_k} \Big|_{x_k=x_{k|k-1}, q=0}$ , is the Jacobian of  $h$  with

respect to the state and  $M_k = \frac{\partial h}{\partial q} \Big|_{x_k=x_{k|k-1}, q=0}$ , is the

Jacobian of  $h$  with respect to the error. At the end of this step the AUV state is  $x_k = x_{k|k}$ , whose first two elements are the estimated coordinates of the AUV.

It is worth noticing that the assumptions stipulated in the description of the localization method can be easily relaxed. For instance, it is not necessary for the AUV to know the ID of all beacons. Instead, beacons could periodically broadcast their ID and coordinates for the AUV to receive when they are in each other communication range. This approach would require the beacons to run a MAC protocol to ensure proper reception of ID and coordinates at the AUV. It would also impose higher energy consumption on the beacons. At the same time, this approach would also allow us to relax the assumption that the AUV is always capable of communication with all beacons. Finally, the proposed localization method clearly works also in the case of scenarios with multiple AUVs.

### III. EXPERIMENTAL EVALUATION

The performance of the proposed localization approach has been tested at sea in the shallow waters off the coast of the island of Ponza in central Italy. The system is made up of four beacons whose geodetic coordinates have been measured through GPS, and of the AUV. The AUV deployment area and the location of the four beacons are shown in Fig. 2. We have chosen a North-East-Down reference system with the origin in the lower left corner of the testing area.

- *Beacons.* Each beacon node is an acoustic transponder attached on one end to a floating buoy and on the other to an anchor placed on the seabed. We use a transponder and software by WSENSE [19]. The beacons are placed at a constant depth of 1.5 m.

- *The AUV.* We use the *Zeno vehicle* by MDM Team and the University of Florence as the AUV [11], [12]. Zeno runs the Robot Operating System (ROS) Melodic [20] as middleware for communication among its internal sensors and actuators. Zeno has been equipped with an intermediate-frequency modem by WSENSE that is compatible with the beacon transponders, whose nominal communication range is around 2 kilometers. We use the SUNSET Software Defined Communication Stack (S-SCDS) [19] as software for



Fig. 2. Testing area and location of the four beacons.

the modem. Communications between the WSENSE modem and Zeno happen through a TCP connection. The ranging information computed by the modem are received on a TCP port and re-published in ROS format for the AUV to use in the Update step of the localization method (Section II). Zeno and the integrated modem are shown in Fig. 3.



Fig. 3. The Zeno AUV with the WSENSE acoustic modem.

The depth of the vehicle is given by Zeno's pressure sensor, which is shared at a frequency of 10 Hz as a ROS message.

Throughout its journey Zeno's distance from any of the beacons never exceeds of 88 m. This way, the AUV is always in the communication range of any of them.

Zeno's journey took place on the water surface so to guarantee the availability of a GPS signal and trace its trajectory, which we use as ground truth to measure the localization error. For this purpose, we use the Ublox NEO-8T GPS module mounted on Zeno, whose estimated horizontal position error stands at 2.5 m. Zeno average speed throughout the experiment was 0.3 m/s. The vehicle was remotely controlled from a

nearby ship through RF communications, following a route determined in real time. Its traced trajectory is shown in Fig. 4.

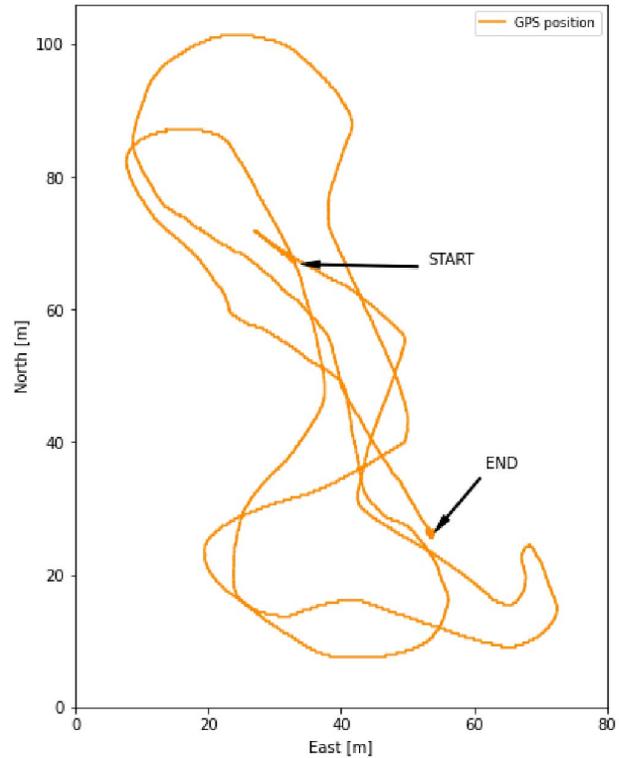


Fig. 4. Zeno's GPS-based trajectory.

- *Experimental results.* The experiment starts with Zeno reporting a starting position with coordinates different from the actual ones, to test the method resilience to misplacement of the AUV and the convergence time to GPS-measured positions. Specifically, the initial position of the AUV was set some 20 m away from its GPS-measured initial position. The starting velocity  $v_0$  is set to 0.3 m/s. The initial covariance matrix of the EKF is set to the identity matrix.

While traveling, Zeno keeps executing the Predict and Update steps of our localization method described in Section II.

The first step is executed with frequency  $1/T$ , with  $T = 0.1$ . We set the amplitude parameter  $a$  to 0.1.

For the Update step, Zeno's modem polls the beacons for coordinates and computes distances, sending location request packets and receiving location packets back. Polling happens in round robin fashion, from beacon 1 to beacon 4. If a beacon does not reply within 1 s, its location packet is considered lost, and the following beacon is polled, if any. As soon as  $n$  ( $n = 2, 3$ ) location packets have been received and the corresponding distances have been computed, the AUV proceeds to adjust its position estimates using the EKF (Update Equations; Section II). If less than  $n$  packets have been received, this Update step is skipped. For this step, the standard deviation of the beacon placement error  $q_b$  is

set to 6. The standard deviation of the ranging error  $q_r$  is instead set to 3. All components of the overall measurement error  $q$  are considered uncorrelated. Update steps are executed every  $t = 8$  s.<sup>1</sup>

All our experiments concern evaluating the accuracy of our localization method. We define the *localization error* as the Euclidean distance between the estimated position and the position measured using the GPS, measured each time a new estimate is computed. We use its average as an indication of the goodness of our approach.

We tested the method in three different scenarios, distinguished by the number  $N$  of beacons used in the LBL system. We considered (i) a scenario with a total of four active beacons, with (ii) three active beacons, and with (iii) only two active beacons. In fact, we run only one experiment with four active beacons. Results with two and three beacons have been obtained by post-processing the measurements collected during that experiment.

The whole experiment lasted nearly one hour and a half, including the time for deploying the beacons and to start up the AUV. Measurements were collected for about 50 minutes. The average values reported below do not include data collected in the first 30s (transient state).

#### A. Scenario with four beacons ( $N = 4, n = 3$ )

Fig. 5 shows the GPS-based trajectory of Zeno (in orange; see also Fig. 4) compared to the one estimated using our method, in purple (EKF-based). The red crosses indicate the update checkpoints. The location pointed to by START indicates the GPS-based initial position of the vehicle, while the yellow square is where we set the starting coordinates for the model. We observe that the filter estimates form a path quite close to the GPS-based one throughout the entire course of the experiment, achieving an average accuracy of 2.45 m.

In Fig. 6 we provide an indication of the goodness of our method by depicting the localization error in time. We start by noticing its resilience to the initial misplacement of the AUV: It took less than 5 seconds for the error to decrease from over 20 m to around 2.5 m. We also observe that the error remains centered around 2.5 m for the rest of the time, indicating consistency of results. The spikes correspond to the times when the Update step was skipped for lack of the necessary number of ranging measurements ( $n = 3$ ).

#### B. Scenario with three beacons ( $N = 3, n = 3$ )

For this test we considered only ranging measurements from beacons 2, 3 and 4. Results are shown in Fig. 7.

Similar to the case with four beacons, the estimated trajectory follows the GPS-based one quite closely. We notice a higher number of missing updates, resulting in higher localization error, due to the higher probability of not receiving the

<sup>1</sup> The process of polling the four beacons in the selected testing area, including the 1 s time outs, takes well below 8 s. The reason this wider time interval  $t$  has been chosen concerns the use of the AUV for a mission beyond localization, which includes the use of another AUV and the use of the modem for acoustic communication other than that with the beacons.

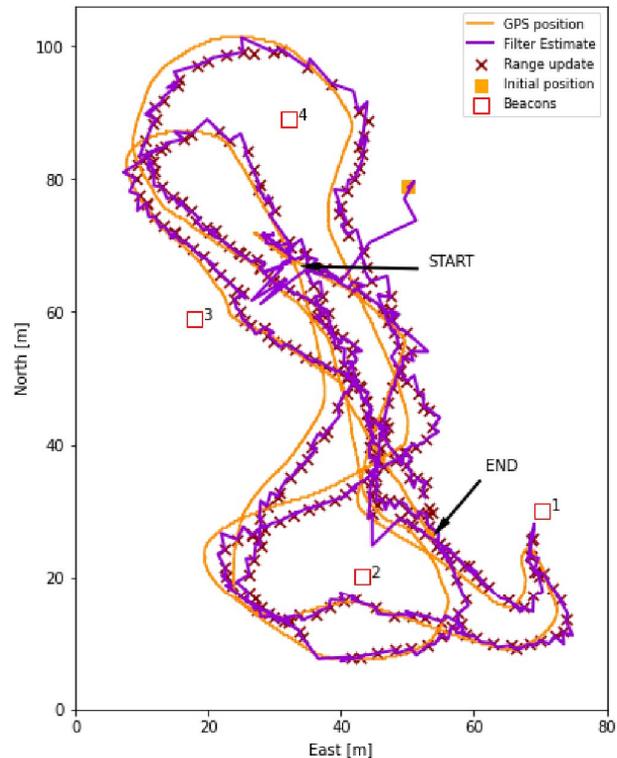


Fig. 5. GPS-based and EKF-based localization with four beacons.

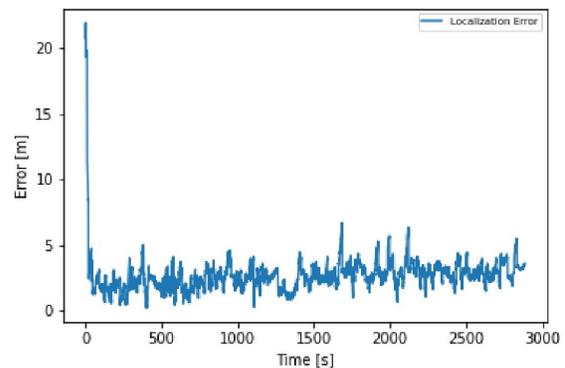


Fig. 6. Localization error in time using four beacons.

necessary number  $n = 3$  of ranging measurements. Nonetheless, the average localization error in this case is 2.65 m, just slightly higher than for the scenario with four beacons.

The localization error in time is depicted in Fig. 8. It takes only a few seconds for the model to reduce the initial misplacement error to values close to the average value, which is then kept for the rest of the time. The higher number of spikes than in the case of four beacons confirms the higher number of missing updates.

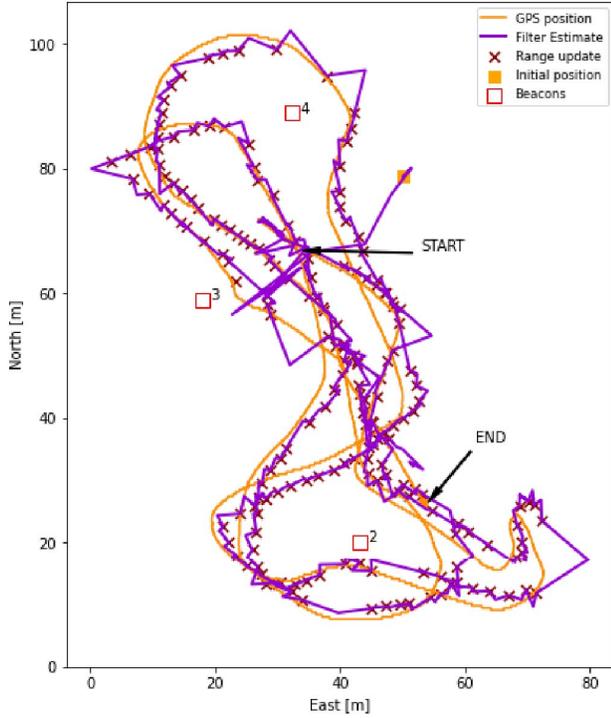


Fig. 7. GPS-based and EKF-based localization with three beacons.

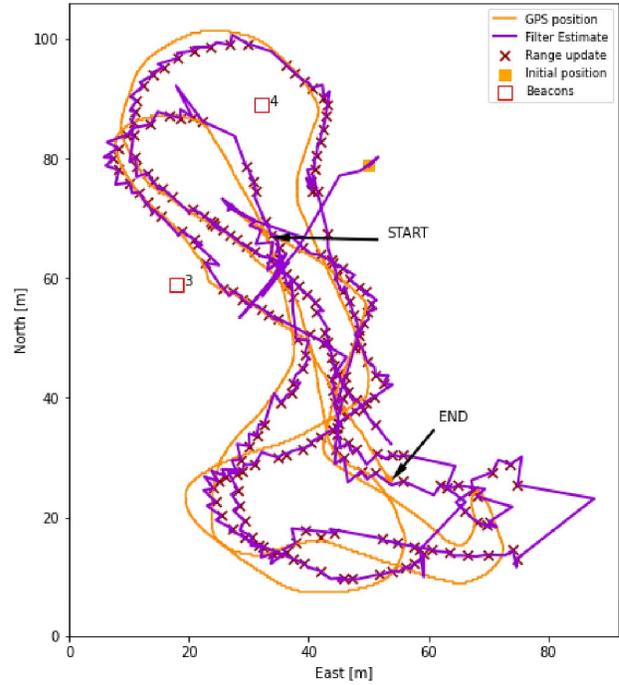


Fig. 9. GPS-based and EKF-based localization with two beacons.

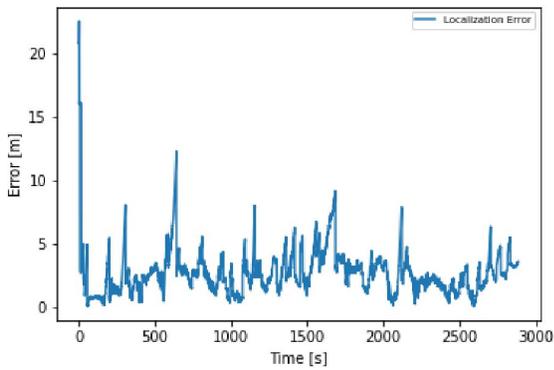


Fig. 8. Localization error in time using three beacons.

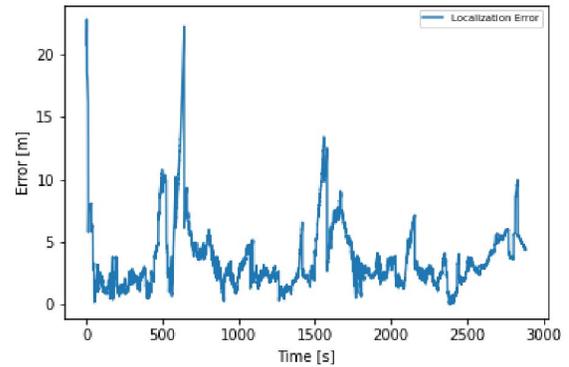


Fig. 10. Localization error in time using two beacons.

### C. Scenario with two beacons ( $N = 2, n = 2$ )

In this test we consider only measurements from beacons 3 and 4. While deviating more noticeably from the GPS-based, Zeno still follows the benchmark route quite closely (Fig. 9), incurring an average localization error of 3.62 m.

Fig. 10 confirms the trends from the previous scenarios. We notice, again, that it takes only a few seconds to decrease the localization error from the misplaced initial position to a much smaller value around the average, which is then kept through the end of the experiment. We also observe that even if the number of LBL-based updates performed in this scenario

is higher than that of the scenario with three beacons (252 vs. 228, respectively), the average localization error in this case is higher than before (3.62 m vs. 2.65 m, respectively) because the amount of information provided by two beacons to the EKF is less precise than that from three beacons.

By way of conclusion, we notice that independently of the number of beacons considered, the obtained average localization errors (2.45 m, 2.65 m and 3.62 m) are comparable with the location error of the AUV GPS module (2.5 m).

Overall, our results show that by using reliable underwater modems with good ranging accuracy it is possible to deploy basic LBL localization systems that can provide the needed accuracy for AUV navigation.

#### IV. PREVIOUS WORK

The problem of localizing underwater assets has been investigated for decades, being this critical for military, civilian and commercial applications [21]. For the specific problem of localizing mobile vehicles the reader is referred to the several recent surveys illustrating a wide variety of technologies and techniques that have been used to solve this problem [8], [9].

In this section we report on works concerning the implementation and testing at sea of methods for localizing AUVs based on LBL measurements, whose aims and purposes are similar to ours, namely, evaluating the localization error of the proposed method. These works can be broadly divided into those that are mainly based on LBL ranging like ours, and those who supplement LBL measures with information from sensors on board of the AUV.

Li et al. propose an LBL-based approach that achieves remarkable accuracy, with a mean localization error in the order of few centimeters [13]. The accuracy of their results stems from a long calibration phase and precise determination of the coordinates of the beacon, resulting in extremely accurate ranging. Their method also take into account the different values of the speed of sound in water, depending on the depth of the AUV. The coordinates of the actual trajectory of the AUV is determined through differential GPS, which produces geodetic measurements that are within very few centimeters from the actual ones. This enables a very precise determination of the localization error. Similarly, Han et al. obtain a mean localization error never to exceed 1 m [14] due to a ranging equipment that is capable of extremely accurate LBL measurements and to accurate GPS readings. These two methods achieve greater accuracy through the use of costly equipment that is not easy to deploy.

Among the works where the localization of an AUV is performed by supplementing ranging with measurements from sensors on board of the AUV, the method by Wang et al. add heading measures from an Inertial Measurement Unit (IMU) and velocity from a Doppler Velocity Log (DVL) [22]. Their method, however, achieves a reported accuracy around 4 m, which is inferior to the one that we have obtained without using those additional measurements. In the work by Bernardi et al. a system is defined and implemented in support of divers and multimedia networking that uses Zeno and three beacons for localization [23]. The method uses LBL and the measurements from an on board IMU. Based on the reported results, our method outperforms theirs by producing an average localization error that is at least 80 cm smaller. Other localization methods worth mentioning in this category of works includes those by Techy et al. [24], Wolbrecht et al. [25] and by Singh et al. [26]. These methods, however, do not evaluate the accuracy of the localization of the AUV, focusing instead on the goodness of the trace of the covariance matrix of the filter they define. As such, these approaches cannot be directly compared to ours.

By way of conclusion, we observe that while supplemental information from on board sensors might increase localization

accuracy, their use could be prohibitive for certain AUVs, especially for those with small form factors, in terms of cost and payload. The distinguished contribution of our paper is that of achieving high localization accuracy without requiring expensive payloads and costly and complex deployment or calibration operations.

#### V. CONCLUSIONS

We present and evaluate the performance of a method for the swift and accurate self-localization of AUVs. The method is based on a long baseline system of pre-deployed beacons that the AUV queries for coordinates while it moves. Our method only relies on a model of the AUV dynamics, on an on-board depth sensor and on LBL ranging information, all fused together by an Extended Kalman Filter. We have evaluated the accuracy of the proposed method via experiments at sea in the shallow waters of the island of Ponza, in central Italy, comparing the estimated locations with those measured by on board GPS. In deployments with up to four beacons, our simple method enables AUVs to swiftly self localize with errors never exceeding 3.62m (using only two beacons), 2.65m (three beacons) and 2.45m (four beacons), which are consistent with the horizontal location error of the GPS module on board of the AUV (2.5 m).

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