Reprint Series **CMRE-PR-2019-018**

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Andrea Munafò, Jan Sliwka, Roberto Petroccia

May 2019

Originally presented at:

2018 OCEANS – MTS/IEEE Kobe Techno-Ocean (OTO)
doi: 10.1109/OCEANSKOBE.2018.8559127

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Localisation Using Undersea Wireless Networks

Andrea Munafò
Maritime Autonomous and Robotic Systems
National Oceanography Centre
Southampton, UK
andrea.munafo@noc.ac.uk

Jan Śliwka, Roberto Petroccia
NATO STO Centre for Maritime Research and Experimentation
La Spezia, Italy
{jan.sliwka, roberto.petroccia}@cmre.nato.int

***Abstract*—Underwater navigation for Autonomous Underwater Vehicles (AUVs) is a challenging task, requiring a trade-off between performance, costs and operational time. The project Network Long Base Line (Net-LBL) proposes a system for acoustic-based navigation that relies on the addition of localisation services to underwater networks. The localisation capability is added on top of existing networks, without imposing constraints on their structure or operation. All the nodes can act as transponders of a network baseline, with no need for dedicated instrumentation. This paper evaluates the Net-LBL system using an interval method-based navigation solution in a number of configurations, including the use of TDMA and CSMA MAC protocols, range-only and bearing-only measurements, and with different geometries. Results collected during the NETLBL17b sea trial, held in the Gulf of La Spezia, Italy, are presented and discussed.**

***Index Terms*—Underwater sensor networks, AUVs, Localisation, Navigation, Interval Methods**

I. INTRODUCTION

Localisation is essential to accomplish unmanned robotic missions as the value of collected data depends on the ability of the robots to accurately georeference the sampling locations. In terrestrial and aerial robotics, the problem of navigation is solved using GPS, a globally available and reliable positioning system. However, Autonomous Underwater Vehicles (AUVs) cannot benefit from GPS localisation underwater as the electromagnetic waves carrying the positioning information cannot properly penetrate the water column [1]. The constraints of the physical layer represent in fact the major challenges for underwater localisation. Underwater networks use in fact acoustics as the main means of communications, for any range longer than a few tens of meters. Several factors affect the acoustic communication performance, including a very limited bandwidth due to frequency-dependent absorption loss, multipath propagation, Doppler spread and long propagation delays due to the sound speed in water [2], [3]. The speed of sound is approximately 1500 m/s, but it varies with temperature, pressure and salinity. Additionally, the bit rates currently achievable underwater are quite limited, ranging between few hundreds of bits per second to few kilobits per second. Localisation methods for underwater networks should then ensure minimal message exchange, be robust against the unreliability of the communications, and explicitly keep into account the mobility of the underwater nodes.

To address these challenges, this work tackles the AUV localisation problem from a different perspective as the vehicles are considered mobile nodes of an underwater sensor network. In this scenario, the network itself is used to support the localisation of the nodes/AUVs. This work builds on our recent research on the implementation of acoustic network-based navigation systems [4]. Preliminary studies of the impact of different Medium Access Control (MAC) solutions on the network-produced range measurements were discussed in [5]. With respect to our previous work, this paper focuses on the robotic localisation problem and on the experimental results that were obtained during the NETLBL17b experimental activity conducted in September 2017 in the Gulf of La Spezia, Italy. More specifically, we evaluate the network-based localisation performance using a navigation system based on interval analysis [6] considering various configurations. The use of two MAC protocols, one based on Time Division Multiple Access (TDMA) and one based on Carrier Sensing Multiple Access (CSMA), is investigated. Additionally, range-only and bearing-only measurements are considered under different node geometries. Finally, the paper investigates the impact on the localisation of an increased packet loss, a situation which can be caused by poor communication conditions.

The rest of the paper is organised as follows. In Section II the network-based localisation layer, already presented in [4] and [5], is briefly reviewed. Section III details the AUV localisation problem. The experimental set-up is described in Section IV while the collected results are discussed in Section V. Finally conclusions are reported in Section VI.

II. NETWORK-BASED LOCALISATION

As described in [5] the acoustic network has a navigational layer that is able to add the relevant information (*i.e.* reception and transmission timestamps) to the acoustic messages and to propagate this information to the upper layers of the network stack. When a Ultra-Short Base Line (USBL) device is deployed, the bearing measurements are also made available to the network. No a priori infrastructure or synchronisation is assumed. The network is tasked to collect the locations of the various nodes and, depending on the application, to perform time synchronisation [7]. The underlying idea is to deploy this kind of self-organising network in the target area

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This work was supported in part by the NATO Allied Command Transformation (ACT) Future Solutions Branch under the Autonomous Security Network Programme and the Office of Naval Research Global under grant no. N62909-16-1-2095.

and to have it operating for several weeks, months or even years depending on their battery endurance and self-recharging capability (*e.g.* through docking stations [8]). Nodes cooperate and adjust their operations in order to support mobile nodes localisation and navigation. In the rest of the work we assume the nodes are not synchronised and that two-way Time Of Flight (TOF) measurements are obtained with a request-response mechanism.

A representation of the main elements of the acoustic network system and of their interaction is shown in Fig. 1. The Net-LBL module interacts with the other modules of the system to obtain the information needed to calculate a full localisation solution, including running the node navigation filters.

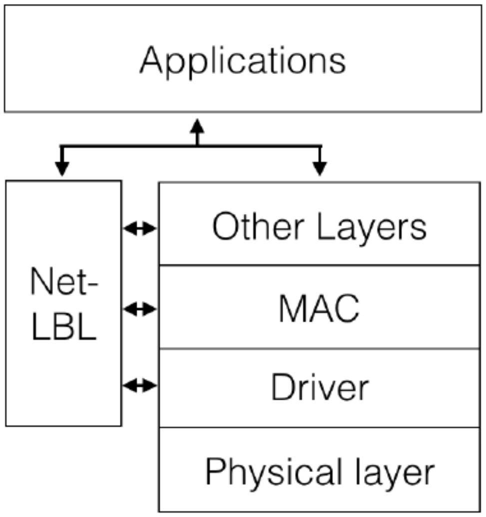

Fig. 1. Architecture of the network running on each node. The Net-LBL module interacts with the other modules of the system to obtain the information needed to calculate a full localisation solution. The navigation filter runs at the application level.

Using the proposed system, information is shared in the network in support to node localisation. Any node of the network can in fact obtain the range and bearing measurements with respect to other nodes, as well as the position of the remote nodes.

III. AUV LOCALISATION

The Net-LBL module (Fig. 1) implements a navigation filter which uses interval methods. Interval methods represent the uncertainty of the variables (*e.g.* measurements) using intervals of possible values (*e.g.* $x \in [x^-, x^+]$). When a measurement falls outside the specified interval it is simply considered an outlier. Intervals are then combined together using a continuous constraints satisfaction problem (CSP) solver, to provide the optimal solution set [6]. The input of the interval solver is a set of equations, also called constraints, which bind the unknown variables (in the case of vehicle localisation is the vehicle position), together with the known variables, namely the range measurements and the environmental variables (*i.e.* the sound speed). The solver returns the set of all possible positions ($\mathbf{x} \in \mathbb{R}^n$) of the localised node that satisfy the equations, originated by the measurements that are not considered to be outliers. The outliers are rejected by the solver. Interval methods can produce a solution set as soon as a first measurement is received. In fact, in the absence of outliers, when a range is measured, the first solution set is a ring with the diameter equal to the range measurement, and with a thickness equal to the range measurement uncertainty. When more measurements are received, possibly from different nodes, the solution quickly converges to a smaller set. When there are no more measurements, the size of the solution set grows with time as the movement of the localised node is uncertain.

A. Vehicle model

Denoting the position of the i-th vehicle at time t with $\mathbf{x}_i(t)$ and its velocity with $\mathbf{v}_i(t)$, we define the displacement function $\mathbf{f}_{i,t_a,t_b}$, which links the position of the node i at the time t_b with the position of the node i at the time t_a, as:

$$\mathbf{x}_i(t_b) = \mathbf{f}_{i,t_a,t_b}(\mathbf{x}_i(t_a), \mathbf{v}_i) = \mathbf{x}_i(t_a) + \int_{t_a}^{t_b} \mathbf{v}_i(t)dt. \qquad (1)$$

Whenever the vehicle receives a new measurement $\mathbf{v}_i(t)$ from its dead-reckoning system, it propagates its current estimate forward using (1).

It is worth pointing out that, depending on the available sensors on the vehicle, the measured velocity $\tilde{\mathbf{v}_i}$ might be measured with a substantial error $\mathbf{w}_i$ (*e.g.* DVL without bottom lock, low cost vehicles):

$$\tilde{\mathbf{v}_i} = \mathbf{v}_i + \mathbf{w}_i. \qquad (2)$$

B. Network localisation measurements

The network considered in this work is able to produce three possible types of localisation measurements:
Range: measurement calculated using a two way message exchange between network nodes. This is done recording the time of transmission t_{TX}, the time of reception t_{RX} and the turn-around-time δ. The sound velocity in water c_s is then used to transform the message round trip time into a distance [4]:

$$r_{i,j} = c_s \frac{(t_{RX} - t_{TX} - \delta)}{2} \qquad (3)$$

When a range measurement between node i and j with the timestamp t_r is obtained we have:

$$\|\mathbf{x}_i(t_r) - \mathbf{x}_j(t_r)\| = r_{i,j}(t_r). \qquad (4)$$

The localisation algorithm uses a window of several range measurements acquired in the past to computes the position $\mathbf{x}_i(t_p)$ at the time t_p. Assuming that $r_{i,j}(t_r)$ is one of these range measurements, the time at which the position is computed (t_p) is posterior to t_r. In order to use (4) at time t_p, the following constraint can be applied:

$$\left\| f^{-1}_{i,t_r,t_p}(\mathbf{x}_i(t_p),\mathbf{v}_i) - \mathbf{x}_j(t_r) \right\| = r_{i,j}(t_r). \quad (5)$$

The inverse of the displacement function (1) is used to map node i's position from measurement time t_r to t_p.

The positions of node j together with their timestamps are periodically updated on node i via acoustic communications. Node i then estimates the position of the node j at all times, and specifically at time t_r so that it can be used in (5).

Acoustic timings: in this case, the localisation system uses the reception and transmission timestamps directly. This makes it possible to take into consideration the relative movement between the vehicles and to explicitly consider how it affects the range measurement calculated based on the two-way TOF. This is especially important when the acquisition delay is high.

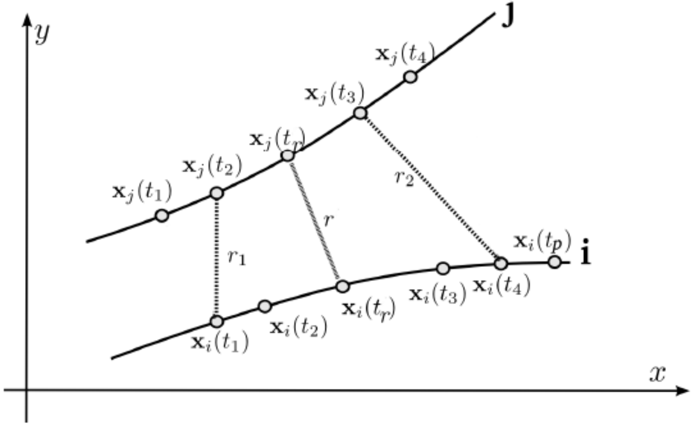

Fig. 2. Example of trajectories of the nodes i and j while they exchange messages. The positions at the times $t_1, .., t_4$ are highlighted.

Fig. 2 shows an example of movement of the nodes i and j while exchanging messages. In this context, a range at a specific time is not exactly what is measured by the Net-LBL system. More specifically, it is possible to express the two ranges r_1 and r_2 (see Fig. 2) as

$$\begin{aligned} r_1 &= c_s \cdot (t_2 - t_1) \\ r_2 &= c_s \cdot (t_4 - t_3). \end{aligned} \quad (6)$$

where t_1 is the transmission time of a range request at node i, and t_2 the reception time of the request at node j. Equivalently, t_3 is the transmission time of a range response at node j, and t_4 is the reception time of the response at node i.

In the case of non-synchronised nodes, it is not possible to measure either $t_4 - t_3$ nor $t_2 - t_1$ but their sum, the two-way TOF:

$$r_1 + r_2 = c_s \cdot (t_4 - t_3 + t_2 - t_1). \quad (7)$$

This leads to the following equation involving the positions of the nodes i and j, which generalises (4):

$$\|\mathbf{x}_i(t_1) - \mathbf{x}_j(t_2)\| + \|\mathbf{x}_i(t_4) - \mathbf{x}_j(t_3)\| = r_1 + r_2. \quad (8)$$

Finally, using the displacement function defined in (1), the position at time t_p can be estimated:

$$\begin{aligned} &\left\| f^{-1}_{i,t_1,t_p}(\mathbf{x}_i(t_p),\mathbf{v}_i) - \mathbf{x}_j(t_2) \right\| + \\ &+ \left\| f^{-1}_{i,t_4,t_p}(\mathbf{x}_i(t_p),\mathbf{v}_i) - \mathbf{x}_j(t_3) \right\| = r_1 + r_2. \end{aligned} \quad (9)$$

Similarly to the range measurement case, node i estimates the position of the node j at all time, and specifically at times t_2 and t_3.

Bearing: when the nodes are equipped with a USBL-capable device, it is possible to determine the direction of arrival of the incoming acoustic message. Denoting by $\theta_{i,j}$ the bearing of arrival of the message from node j, as measured by node i and expressed in the absolute frame of reference, the following measurement equation can be derived:

$$Arg(\mathbf{x}_i(t_4) - \mathbf{x}_j(t_3)) = \theta_{i,j}, \quad (10)$$

where $Arg(\mathbf{x}) = atan2(x_2, x_1)$, $\mathbf{x} = [x_1, x_2]$. The position at time t_p can be estimated using the constraint:

$$Arg(f^{-1}_{i,t_4,t_p}(\mathbf{x}_i(t_p),\mathbf{v}_i) - \mathbf{x}_j(t_3)) = \theta_{i,j}. \quad (11)$$

A similar equation can be obtained if the bearing measurement acquired by the node j and transmitted to the node i via acoustic communication.

IV. EXPERIMENTAL SET-UP

The NETLBL17b trial was conducted between the 25^{th} and the 29^{th} of September 2017, in the Gulf of La Spezia, Italy, in front of the NATO STO Centre for Maritime Research and Experimentation (CMRE) premises. The Littoral Ocean Observatory Network (LOON) [9] was used as the main network infrastructure. The LOON is composed of four acoustic modems, mounted on tripods and statically deployed on the sea bed. Fig. 3 provides an overview of the area along with the position of the fixed nodes.

The mobile node was deployed using a rubber boat where all the main electronics and the acoustic modem were installed. The acoustic modem was deployed from the front of the boat to minimise the bias between the modem position and the position of the GPS (located in the middle of the boat), when moving forward. The setup is shown in Fig. 4. The sound speed value was measured at 8 m depth and it was 1530.5 ± 0.5 m/s throughout the week. Two MAC protocols were used: one CSMA-based [10], the other one TDMA-based. The motivation to use two different MAC solutions is to be able to assess the impact each MAC protocol has on the quality of range measurements [5]. This has a direct impact on the performance of the localisation algorithm.

When using a TDMA-based approach, each node has to wait its own TDMA slot in order to transmit any ranging request/reply or Net-LBL data. No fixed transmission scheme is instead imposed by CSMA. Each node can more promptly

Fig. 3. Littoral Ocean Observatory Network (LOON) modem deployment (N1,N2,N4,N6). The picture also shows in green the desired trajectory for the mobile node on September 29^{th}.

Fig. 4. Acoustic modem deployed over the bow of the supporting rubber boat.

and freely transmit its own messages, thus enabling to also reduce delays in obtaining range updates.

Table I reports the average propagation delay calculated using the CSMA solution and the associated standard deviation over a 17 h test. In this configuration, with four static nodes, similar results are obtained using the TDMA approach. However, a higher variance is expected when mobile nodes are considered. Node 6 of the LOON was equipped with a USBL head and was able to provide the direction of the incoming messages. Table II shows the measured average bearings from Node 6 to all other nodes of the LOON, together with the associated standard deviation calculated during the same test.

TABLE I
AVERAGE PROPAGATION DELAY AND STANDARD DEVIATION BETWEEN ALL THE LOON NODES

	Node 1	Node 2	Node 6	node 4
Node 1	-	μ=0.29299s σ=1.3e^{-4}s	μ=0.20520s σ=1.4e^{-4}s	μ=0.32558s σ=1.0e^{-4}s
Node 2	μ=0.26300s σ=1.2e^{-4}s	-	μ=0.18325s σ=1.7e^{-4}s	μ=0.31775s σ=8.0e^{-5}s
Node 6	μ=0.20523s σ=1.4e^{-4}s	μ=0.18328s σ=1.7e^{-4}s	-	μ=0.15206s σ=2.5e^{-4}s
Node 4	μ=0.32559s σ=9e^{-5}s	μ=0.18328s σ=8e^{-5}s	μ=0.15206s σ=2.4e^{-4}s	-

TABLE II
AVERAGE USBL BEARING AND STANDARD DEVIATION FROM N6 TO THE OTHER LOON NODES

	Node 1	Node 2	Node 6	node 4
Node 6	μ=-78.20^o σ=0.19^o	μ=-164.55^o σ=0.15^o	-	μ=-52.39^o σ=0.28^o

V. RESULTS

As explained in Section III, the algorithm computes the position of the vehicles in the form of a set S of possible values. The solution set is then converted into a single point $p \in S$, which is the centre of the set. Two metrics are used to evaluate the solution:

- the ground truth localisation error, which is the distance of the centre p_c of the calculated set S (output of the interval solver) to the GPS position p_{GPS} (which is considered ground truth).
- the maximum localisation error, which is the maximum distance between the point p_c and any other point p of the solution set S: $e_{worst} = \max_{p \in S} ||p_c - p||$.
  In this respect, e_{worst} can also be considered as a representation of the localisation uncertainty (*i.e.* uncertainty of the solution p_c).

The first experiment performed compared the usage of range-only measurements to the usage of both range and bearing measurements, using only static nodes (Fig. 5). The experiment consisted on localising the central node of the LOON (N6) using measurements from the other nodes. Note that in the case of range-only measurements, once the interval solver converges, the localisation error converges as well to a constant value (all nodes are static). When the bearing is also considered, the maximum localisation error (uncertainty of the solution) decreases as more information is used to calculate the solution, but the average error increases. This was unexpected and attributed to a bias in the bearing measurements. The results in Fig. 5 refer to the case where CSMA was used, similar results were obtained using TDMA. These results were then used as the baseline to proceed with the more complex localisation of the mobile node.

The second experiment was carried out using the mobile node (node 10). When a moving node is considered, the uncertainties in the displacement function has an impact in (5). The input for the kinematic model (1) was the node

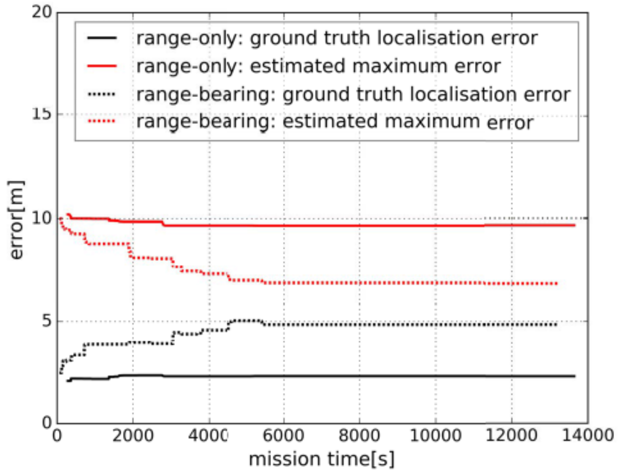

Fig. 5. Performance of static localisation of the node 6 using range-only (bold lines) and range and bearing (dashed lines) measurements to the other nodes of the LOON N1, N2 and N4.

velocity as obtained from the GPS receiver. This is shown in Fig. 6, where a varying value over time can be noticed. This variation impacts the uncertainty on the position computed by the localisation algorithm, because of the inaccuracy in the displacement function.

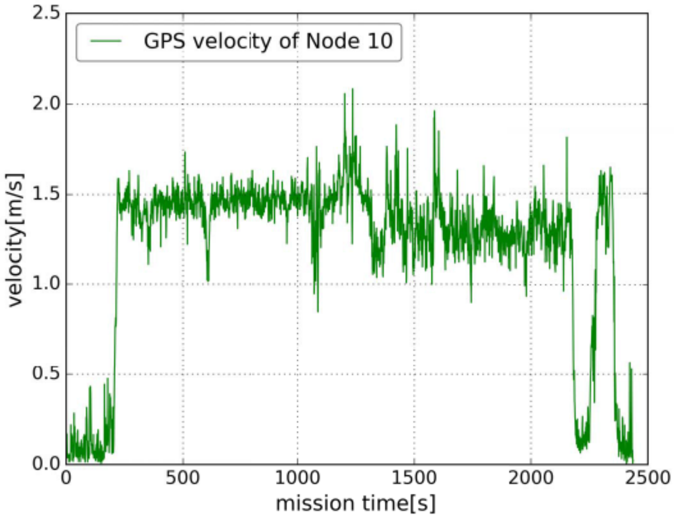

Fig. 6. Velocity of the mobile node as obtained through the GPS.

Results of the localisation are shown in Fig. 7 and in Fig. 8, in terms of trajectory estimation and localisation error.

The additional delays introduced by TDMA (with respect to CSMA) in collecting the range updates detrimentally impact the Net-LBL performance. Less accurate positions are computed with an increase in the uncertainty.

The interval solver is initialised without any a priori knowledge of the vehicle position resulting in the very big error at the beginning of the mission. From the operational point of view, this does not constrain a vehicle to start its mission from an a-priori known location (*e.g.* at the surface). It also proves that the vehicle can re-localise itself if it gets lost (*e.g.* in case of long periods of communications outage). As soon as ranges are collected the solver quickly reduces the error and the uncertainty of the solution. Except for the initial and transitory phase (first ∼ 400s), when using the CSMA protocol, the average error throughout the mission is about 10m, while the maximum error e_{worst} (representative of the size of the largest box calculated) is less than 50m.

When using TDMA, the average error increases to about 17m, while the maximum error is almost doubled with respect to the CSMA case.

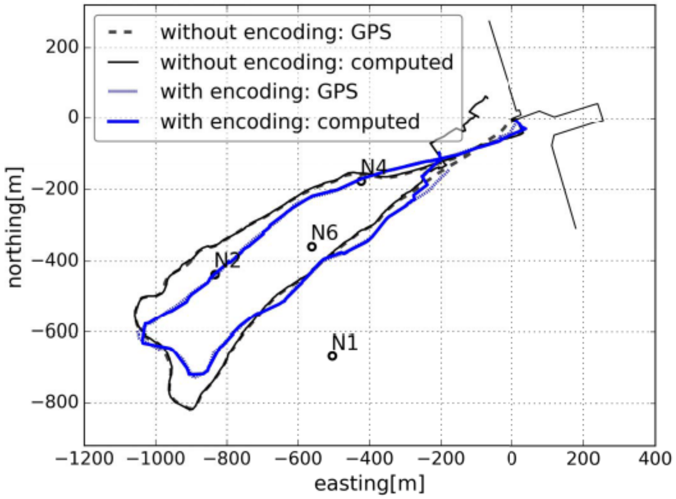

Fig. 7. GPS and network estimated trajectory of node 10 (rubber boat) when using range-only measurements, and CSMA (in black) or TDMA (in bold blue). The remaining black line represents the pier where the C2 was located and where the mission started.

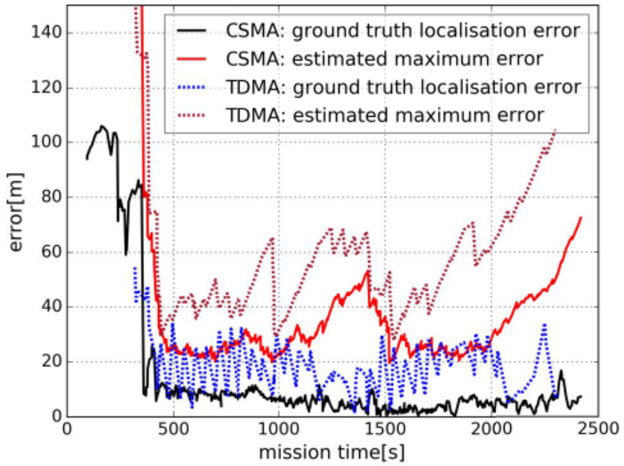

Fig. 8. Localisation error of node 10 (rubber boat) when using range-only measurements with CSMA or TDMA.

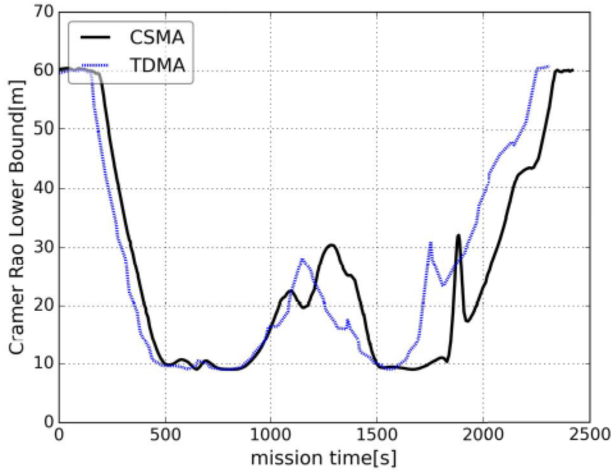

Fig. 9. Cramer Rao Bound for the trajectories reported in Fig. 7 when using CSMA (bold line) and TDMA (dashed line). The difference in the functions is due to the slightly different trajectories done by the mobile node.

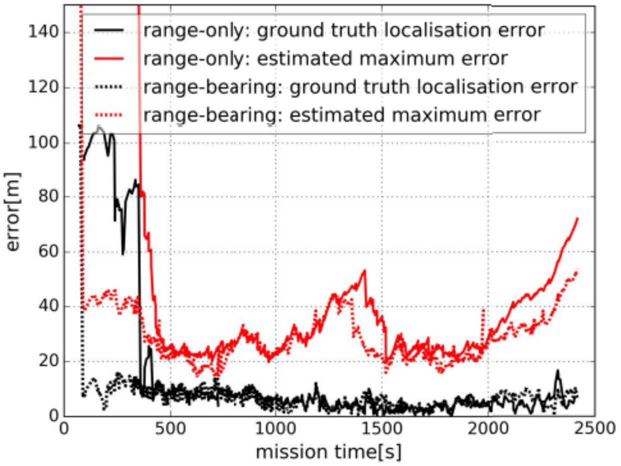

Fig. 10. Localisation error of node 10 (rubber boat) when using CSMA and range and bearing measurements. Note the decrease in the error that is obtained with respect to the range-only case.

As expected, using CSMA offers better localisation accuracy than TDMA.

Note that, depending on the geometry the uncertainty of the navigation increases. This is shown by the increase in the maximum localisation error (*i.e.* the uncertainty of the solution) corresponding to parts of the trajectories less favourable for the localisation. This is also represented by the increase in the Cramer Rao Bound (CRB) [11] as depicted in Fig. 9. As expected, there is correspondence between the CRB behaviour and the maximum solution uncertainty.

During the trial, the angle-of-arrival (bearing) of the messages transmitted from the rubber boat (node 10) was measured as received at node 6 using the USBL. In order to quantify the impact of using this data to improve the localisation performance, the interval solver was ran using both bearing and range measurements obtained using the CSMA MAC. A comparison between the resulting localisation error and uncertainty and the ones obtained in the range-only case is shown in Fig. 10. The USBL bearing measurements do not always improve the localisation considerably. On the other hand, most of the improvements are seen in cases where the geometry of the node constellation becomes less suitable for range-only localisation (as shown in the CRB plot of Fig. 9).

Fig. 11 shows the localisation error when considering only the angle-of-arrival measurements. In this case, node 10 is

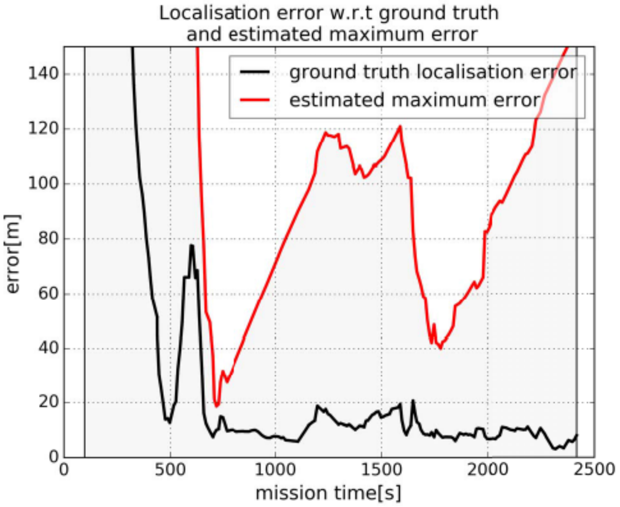

Fig. 11. Bearing only localisation error. In this case, node 10 is using only bearing data coming from the USBL mounted on node 6. Note how the error decreases when the vehicle is navigating tangentially to node 6.

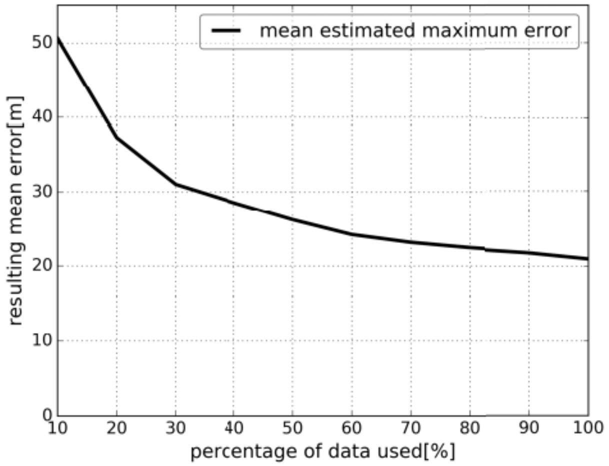

Fig. 12. Impact of an increase in packet loss (range measurements) on the performance of the localisation algorithm. The mean estimated maximum error is computed for different percentage of measurements used. Note that 100% of data available corresponds to using all the experimental data collected during the trial. As expected, the error decreases when more measurements are available but the decrease is not linear.

using only bearing data coming from the USBL mounted on node 6. As expected, the collected results show that bearing-only localisation is most favourable when node 10 is navigating tangentially to node 6.

Finally, depending on the quality of the acoustic channel and the distance between the nodes, the network might be subjected to an increase in the packet loss. This in turn results in less localisation measurements (range and/or bearing). Fig. 12 shows the impact of range measurement loss in the case of a range-only localisation. For that purpose, the mean estimated maximum error is computed using different percentages of range measurements. This has been done in post-processing, spanning from the case where the whole experimental dataset is considered (100% of the data) to the use of only 10% of the collected range measurements. The mean error was calculated from the time the algorithm converged till the end of the mission. As expected, the mean estimated maximum error decreases with good communication (when more measurements are available) but the decrease is not linear. In fact, using 50% of measurements, instead of 100%, only increases the mean localisation maximum error by 20%. This also suggests that the overall number of range requests could be optimised and possibly decreased.

VI. CONCLUSIONS

This paper presented a method to localise underwater mobile nodes using an acoustic network and interval methods. The proposed system can be used to support underwater navigation and data georeferencing for AUVs with poor dead reckoning capability (*e.g.* deep water scenarios, or no Doppler Velocity Loggers) and/or to improve the persistence of AUVs with good dead reckoning. The implemented solutions was tested and validated in operational conditions during the NETLBL17b sea trial conducted by CMRE and the National Oceanography Centre (NOC) in September 2017 in the Gulf of La Spezia, Italy. The collected results showed that, by sharing relevant information along with regular network messages, every node of the network was able to calculate its range to the neighbouring nodes. Performing concurrent communications and positioning, each node was also able to continuously and effectively correct its own position estimate. Additionally, the availability of bearing data, by at least some of the nodes in the network, enabled to decrease the localisation uncertainty. Two MAC solutions, TDMA and CSMA, were considered and their impact on the localisation performance was compared. The CSMA protocol was found to be more responsive and offering higher quality localisation data. Finally, the impact of the loss of localisation measurements was analysed.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Alberto Grati for his continuous and excellent support during the NETLBL17b trial.

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Document Data Sheet

Security Classification		Project No.
Document Serial No. CMRE-PR-2019-018	**Date of Issue** May 2019	**Total Pages** 7 pp.

Author(s)

Andrea Munafò, Jan Sliwka, Roberto Petroccia

Title

Localisation using undersea wireless networks

Abstract

Underwater navigation for Autonomous Underwater Vehicles (AUVs) is a challenging task, requiring a trade-off between performance, costs and operational time. The project Network Long Base Line (Net-LBL) proposes a system for acoustic-based navigation that relies on the addition of localisation services to underwater networks. The localisation capability is added on top of existing networks, without imposing constraints on their structure or operation. All the nodes can act as transponders of a network baseline, with no need for dedicated instrumentation. This paper evaluates the Net-LBL system using an interval method-based navigation solution in a number of configurations, including the use of TDMA and CSMA MAC protocols, range-only and bearing-only measurements, and with different geometries. Results collected during the NETLBL17b sea trial, held in the Gulf of La Spezia, Italy, are presented and discussed.

Keywords

Underwater sensor networks, AUVs, Localisation, Navigation, Interval Methods

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int