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Andrea Munafò, Thomas Furfaro, Gabriele Ferri, João Alves

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Supporting AUV localisation through next generation underwater acoustic networks: results from the field

Andrea Munafò[1], Thomas Furfaro[1], Gabriele Ferri[1] and João Alves[1]

Abstract— **This work describes how the localisation of autonomous underwater vehicles can be supported through networked acoustic communication. The localisation approach includes timing information within acoustic messages to create an interrogation scheme similar to that of long-baseline methods, but realised at the application level of the network. In this way, the network itself is able to provide vehicle localisation information, reducing the needs for additional on-board sensors or dedicated deployed platforms/transponders. The aim of this work is to report at sea localisation results as obtained in two completely different application scenarios. The first one is represented by the FP7 MORPH project (HORTA15 sea trial) where the proposed approach has been applied to support navigation of a fleet of AUVs in a tight formation and in very shallow waters. The second application is represented by the NATO STO CMRE multistatic network demonstrator with the acoustic network used to support navigation of AUVs working in large operational areas. In this latter case, results are given from the COLLAB–NGAS14 experimental campaign.**

I. INTRODUCTION

The ability of Autonomous Underwater Vehicles (AUVs) to accurately move in the environment (underwater navigation), is still a challenging task [13]. The usual approaches rely on 'proprioceptive information' usually obtained from Inertial Navigation Systems (INS) or deploying static beacons with known locations that act as external references. There are characteristic limitations and constraints associated with these traditional approaches, which often require a trade-off between performance and cost. Commercially available INSs range from very expensive systems with a cost of over 1 Million USD with drifts of less than 1800 metrs per day, to more economic systems with drifts as high as 60 metres per minute [3]. To compensate for the unavoidable INS drift, a typical underwater navigation mission requires periodic resurfacing to acquire GPS fixes, which involves interrupting the task and, in sensitive scenarios, risking detection while on surface, hence reducing the underwater vehicle effectiveness and stealthiness. Requiring a vehicle to surface is an operation that takes more time the deeper the vehicle has to work and also incurs an energy expense. The use of static and dedicated beacons as in the case of Long BaseLines (LBL) [9] avoids the problem of cumulative drift, but imposes constraints on the operational area. Depending on the scenario, this might be incompatible with the higher-level mission requirements, as in the case of operation in denied areas, or when the vehicles need to be data driven. To obtain a good navigational fix from beacons, multiple dedicated beacons must be deployed around each mission area. Deploying beacons, and navigating them in to provide a known location, requires a great deal of instrumentation to be deployed and calibrated at each site. This is impracticable for many operational scenarios. Recently, there has been a significant effort to reduce some of these limitations. Examples of such efforts can be found in [6], [5], [16], [8], where some of the leading manufacturers of acoustic modems focus on making the acoustic modems themselves able to produce localisation data. The new generation of acoustic modems are in fact almost always able to provide the distance with their communication counterpart, given a message exchange. This kind of information, which, in this paper we call localisation data, can be used to determine the position of a vehicle in space, as for instance using triangulation or trilateration [5]. An alternative approach has been investigated at CMRE, where preliminary studies done in recent experimental campaigns have shown that when the underwater vehicles are part of a network, the inclusion of localisation data together with normal traffic can be instrumental in enhancing AUV navigation even at long ranges and with sporadic communication [12]. In parallel, a first implementation [7] was deployed within the CMRE Littoral Ocean Observing Network (LOON) [1]. This first deployment focused on proving the feasibility of the interrogation scheme in real-time with real data, but only with static nodes. The work described herin expands the previous work, demonstrating the usage of the proposed network interrogation scheme to support navigation of AUVs in real scenarios, explicitly including moving nodes.

The proposed method makes it possible for the system to have heterogeneous capabilities (when a node joins the network it can also receive localisation data, together with the normal network traffic), mixed navigational fusing (integration of additional devices that might be available on some of the assets), applicability to a range of modems and to be explicitly tailored to software defined-modems [14].

The proposed navigational service does not rely on specific hardware requirements or on stable-precision clock. This is particularly convenient for inexpensive vehicles, and in scenarios where there is the need to limit costs. The approach

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[1]Andrea Munafò, Thomas Furfaro, João Alves and Gabriele Ferri are with the NATO STO Centre for Maritime Research and Experimentation (CMRE), La Spezia, Italy [andrea.munafo, thomas.furfaro, joao.alves, gabriele.ferri]@cmre.nato.int *(Andrea Munafò and Thomas Furfaro are co-first authors.*

is independent from the specifics of the implemented acoustic network, and it readily scales with the number of nodes. The price to pay is that local clock data must be added to each (localisation) packet, slightly increasing the communication overhead. The system can be exploited by less capable vehicles that need navigational aides to compensate the measurement drift of their inexpensive on-board inertial sensors, reducing total system cost. It may also be exploited by more capable AUVs, increasing their persistence, improving their performance, and/or to enlarge their area of operation. Of particular interest for the authors is the possibility to augment the navigation performance of systems operating in deep water where some traditional tools are not available (e.g. DVL).

The position uncertainty of multiple AUVs can be reduced using localisation aware networks. For instance, in [17] less capable vehicles acoustically measure their ranges, and integrate received external fixes from better-navigated nodes to increase their navigation ability. In this case however, there was no network involved and the ranging system was based only on what was made available directly at physical level. Additionally the inter-node ranging utilises synchronised one way time of flight measurements. The exchange of measurements with a network can be beneficial, it runs the risk of using the same data more hence running the risk of estimate overconfidence. Navigation systems that rely on collaborative measurements are at risk of producing overconfident measurements. This overconfidence is an artefact of implicitly reusing the same data. For this reason, a great deal of effort has been put in distributed multi-robot localisation algorithms for underwater scenarios. In [2] consistent cooperative navigation was performed, explicitly filtering measurements that would lead to cross-correlation. More recently, [13] proposed a method for AUV trajectory estimation that explicitly tackles the limitations of the underwater communication channel (i.e. unreliability, limited bandwidth, high latency), and reduces the localisation uncertainty and hence the number of GPS surfacing manouevres that are required to achieve a target navigation accuracy. The network-based interrogation scheme proposed herein can be used within these frameworks as the information provided by the network can be seamlessly fused within the AUV navigation system.

The system has been shown effective for two very diverse applications. The first one is represented by the multistatic active CMRE experimental network demonstrator which consists of two Ocean Explorer AUVs, gateway buoys and wave gliders [4], collaborating together in operational areas, oftentimes, of more than $100\,\mathrm{km}^2$. Within this demonstrator the AUVs are capable of working together to search and prosecute underwater targets utilising underwater network communication protocols to exchange information. In this scenario, the addition of localisation data to the normal network traffic must not interfere with the normal network operation (e.g. data on detected contacts, tracks, etc.) and must make minimal use of acoustic communication for the purpose of navigation. The second application is represented by the system developed in the framework of the FP7 EU-funded project MORPH [10]. The MORPH project developed a cooperative fleet of heterogeneous marine vehicles to perform detailed 3D imaging and sonar surveys of topologically complex environments. This fleet is composed of 5 autonomous platforms, including one surface vehicle and 4 AUVs, collaborating in a tight formation where the vehicles are spaced on the order of 10's of meters apart. In this case, the formation control and coordination rely heavily on the communication system, which augments the navigational capabilities of each node, providing a method by which the AUVs can measure their position with respect to the others. Together with a description of the proposed network-based localisation method, we report at-sea results for both application scenarios, showing how the system was effective in enhancing the navigation capability of the underwater nodes. More in particular, results are reported as obtained at-sea during the COLLAB–NGAS14 campaign, conducted in October 2014 by NATO STO CMRE, and from the HORTA15 sea trial.

The remainder of this paper is organised as follows: Section II gives details on the inclusion of localisation services into networked acoustic communications. Section III describes results from the HORTA15 and the COLLAB–NGAS14 experimental campaigns, where the proposed algorithm was tested in very different operational conditions. Finally, Section IV draws some conclusions.

II. LOCALISATION SERVICES IN UNDERWATER NETWORKS

This section describes the integration of localisation data together with normal network traffic so that the resulting network is able to provide localisation as a service to connected nodes. This integration has been based on the software-defined communication system implementation efforts at CMRE during the last years [14]. Such architectures are meant to be flexible workspaces that provide standardised interfaces and interactions between specific communications building-blocks, paving the way for adaptive and cognitive stacks that may react to sensed or learned changes in the environment. Open and modular architectures are an attractive solution since they allow the reuse of already developed modules to enhance new components in a given architecture. In this respect, the developed localisation architecture is designed to provide a module that can be incorporated into such a software-defined architecture.

A. Theory of operation

Most acoustic ranging systems are based on measuring, at the physical layer, the two-way time-of-flight (TOF) between transponders, and converting this duration into distance using measured or estimated sound speed values. For this to work, an acknowledgement is required to be sent from all the receivers to the transmitter, taking care that such replies do not interfere. It is typical that this acknowledgement is immediate, with an internal turn-around time that is known *a priori*. While no absolute precision-clock is required for

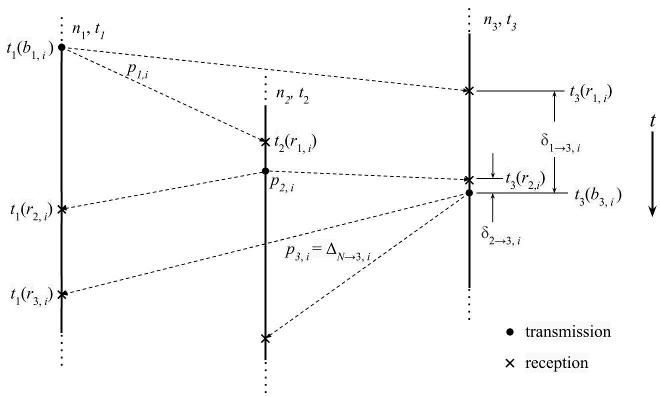

Fig. 1. Network-based two-way message exchange or message round trip between three nodes.

TOF measurements, the disadvantage is that in this 'all-ask-all' scheme the overall update rate for each vehicle decreases as $1/N$ in an N vehicle environment: each node must interrogate the network in order to obtain a two-way TOF measurement between it and all replying nodes. Furthermore, when a Time Division Multiple Access (TDMA) Medium Access Control (MAC) scheme is used in the network with fixed acknowledgement turn-around, the all-ask-all method becomes extremely inefficient as it becomes necessary to allocate additional guard times for the transmission of the reply (or of an acknowledgement) from the interrogated node to the interrogator. Note that this approach becomes more inefficient with inter-node distance as it takes more time for the acknowledgement to get back to the interrogator. This limits the types of localisation devices that can fit within such a communication network: for example, USBL devices which rely on acknowledgements to calculate their distance from a remote transponder, cannot be used. The usage of synchronised clocks scales to a multi-node environment (all listeners can calculate the TOF with the interrogator at once). The price to pay in this case lies in the need for dedicated and high-precision clocks, and for a synchronisation procedure.

The approach proposed in this work uses a third alternative, based on the asynchronous exchange of acknowledgements for two-way measurements. In scheme, synchronised clocks are not required, and the acoustic modem must be able to provide the time of transmissions and receptions. Fig. 1 shows a simple three node network, with multiple two-way message exchanges between nodes n with local clocks t_n. At time $t_1(b_{1,i})$, node n_1 transmits a message, $b_{1,i}$ to the other nodes n_2 and n_3, which each saves the time of reception in their local time frame $t_n(r_{1,i})$, at cycle index i. These other nodes wait until their appropriate time to transmit, e.g. determined by a MAC, at $t_n(b_{n,i})$. When these messages are sent, they include in the payloads sufficient data to reconstruct the turn-around delay, for a set of previously received messages. In the case of the implementation from COLLAB–NGAS14, this payload data includes the time of transmission of the reply, $t_n(b_{n,i})$, and the time of reception for a set of messages received within a fixed window (duration T), $t_n(r_{j,i})\left\{i \mid t_n(r_{j,i}) > t_n(b_n j,i) - T; j \mid j \neq n\right\}$. Conversely in the implementation of HORTA15, the delays are sent, and only from the previous cycle, $\delta_{j\to n,i} = t_n(b_{n,i}) - t_n(r_{j,i})\left\{i \mid t_n(r_{j,i}) > t_n(b_{n,i-1}); j \mid j \neq n\right\}$. This method, dubbed Distributed Long BaseLine (DLBL) is more fully described in [7]. Finally, at time $t_1(r_n, i)$, node n_1 receives this deferred acknowledgement with the transmitted payload data. At this point, n_1 can calculate the two-way travel time, $rtt_{1,n}$, to the remote node n_n:

$$
\begin{aligned}
rtt_{1,n} &= t_1(r_{n,i}) - t_i(b_{1,i}) - [t_n(b_{n,i}) - t_n(r_{1,i})] = \\
&= t_1(r_{n,i}) - t_1(b_{1,i}) - \delta_{1\to n,i}. \quad (1)
\end{aligned}
$$

Combining this information together with a measurement or an estimation of the sound velocity profile of the local water column makes it possible to calculate the range. The key component that addresses the scheme's scalability is that whenever a node transmits, it transmits *all* of the accumulated arrival timing information. With this payload data, all nodes (who presumably have transmitted in the past) will receive the broadcast message have a piece of data that allows them to calculate the range between themselves and the transmitter. The network scale has an impact on communications overhead (in terms of payload size), as the timing information needs to be included. For example, in HORTA15, 24 bit are used per delta encoded, with a resolution of 1 µs, so a network of size N would require $(N-1)\times 24$ bit. Similarly, in the COLLAB–NGAS14 implementation, each time-stamp (which is absolute, not relative) uses 32 bit for the same resolution, and additionally includes the time-stamp of transmission, so the localisation component of the payload is $(N)\times 32$ bit.

For some scenarios, e.g. when localisation has secondary priority to other responsibilities, this communication overhead might have too great an impact on the effective network capacity. One possible option, such as in the case of COLLAB–NGAS14, is to only send one absolute time-stamp of 32 bits and then to encode relatively each preceding piece of information, or to use data compression as shown in [15]. However, because this scheme is sufficiently flexible to be overlaid on top of the infrastructure and not tightly tied to the physical layer, the localisation data size and time of transmission can be adjusted according to priority (possibly dynamic), data availability, or even localisation accuracy.

Remarks

- The hardware requirements on the modem include (1) the ability to register the time of arrival of incoming packets, where the precision and accuracy are related to the ranging estimation error and (2) to be able to send messages synchronously.
- This scheme is implemented at the packet level, meaning that, given the above requirements are met, there aren't any additional implications on the modulation and coding scheme.
- When the transmission of the reply (see Fig. 1) at time $t_n(b_{n,i})$ can be done right after the reception of the

request, the method reduces to something similar to a traditional LBL implementation.

- The resolution of the range measurements is limited by the relative clock drift within a network-based two-way message exchange, and depends on the available hardware. In the general case where standard embedded computers are used (no high precision clock), this drift could be as high as $60\,\mathrm{ms\,h^{-1}}$ [18], leading to a resolution of 1.5 m in the case of a TDMA-based network with a 60 s frame.
- When the nodes are mobile the time required for an acoustic packet to go back and forth introduces a ranging error due to the movement of the vehicles. This depends on the relative motion between the nodes and may increase with the time necessary to reply to an interrogation $(t_n(b_{n,i}) - t_n(r_{j,i}))$. In this case, the inclusion of the dynamic model of the mobile nodes might be used to reduce the error, or Doppler information that may be available from the acoustic hardware.
- Each range measurement is associated to the time of reception of the reply from the interrogated node $t_n(r_{j,i})$ (end of the corresponding message round trip). Note that in general there is no single range-time association due to the very nature of the proposed interrogation scheme, and different choices might lead to different time association errors (e.g. another option might be that of using the average between the transmission $t_n(b_{n,i})$ and the reception $t_n(r_{j,i})$).
- The ranging measurement as presented does not itself compensate for multipath or ray bending; such compensation could be made with additional physical layer information, but this implies more requirements on the hardware (e.g. the ability to estimate multi-path).

III. FIELD RESULTS

The proposed localisation system has been tested through several sea trials within the FP7 MORPH project and the NATO ACT Anti-Submarine Warfare experimental campaigns. This paper focuses on two of such experiments where the proposed concept has been used as an operational service of the acoustic network.

A. HORTA15: short range localisation

The HORTA15 sea trial was held from September 1 to September 11, 2015, near the island of Faial in the Azores archipelago (Portugal). This was the final demonstration and validation of the MORPH achievements, the major goal of which is to produce high resolution fully 3D multi-modal maps of underwater structures, via a system of distributed heterogeneous underwater vehicles flying in formation [10], [11]. The communications system provides the backbone for the exchange of command and control (C2) and inter-node collaboration information, as well as the relative ranging mechanism upon which the formation control mechanisms actuate. The nodes of the so-called 'MORPH Supra-Vehicle' (MSV) work in close proximity (~ 10 m), using formation control mechanisms to adaptively modulate the MSV shape

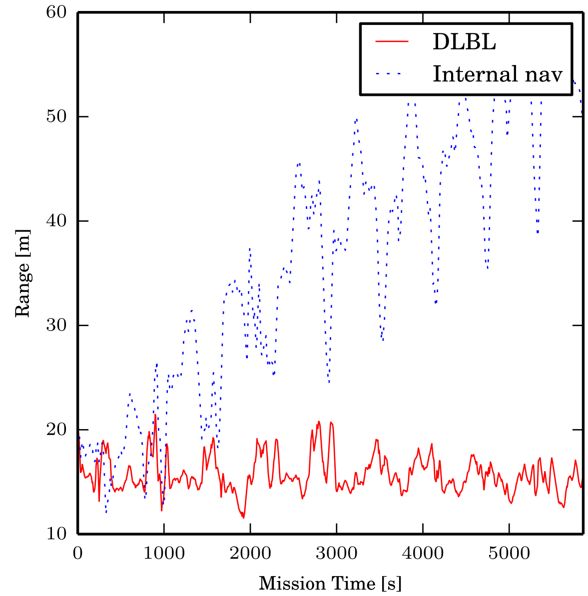

Fig. 2. Inter-node range measured between a GPS-fixed node (mblack) and a submerged node (sparus), via internal navigation (blue dotted lines) and DLBL ranges (red solid lines).

with respect to survey surfaces. The network in MORPH uses TDMA as the MAC mechanism, with 1 s-long slots (including guard time), for a total frame length of 5 s. In effect, for the DLBL algorithm described and in a perfect scenario, each node would receive a range update to each other node sequentially per slot, with a global update completed every frame. The packet lengths in this case range from 14 B to 25 B, which are 290 ms to 413 ms in real ensonified duration, leaving a minimum guard time of ~ 600 ms. The nodes in the MORPH fleet typically have more economical navigation systems, and are not equipped with low-drift timing hardware. The extra guard time accommodates for fluctuations in the system clocks during the mission progression.

1) Results: The results described here are excerpts from a 100 min mission performed on September 11, 2015. Fig. 2 shows an example of range measured between a surface vehicle with GPS visibility (Medusa$_S$ from IST) and a submerged vehicle (Sparus from UdG) that has a significant navigation offset (no DVL fix), comparing the acoustically estimated range and the range calculated by the difference of local navigation solutions. In this kind of situation, the necessity and advantage of acoustic localisation services is very clear, providing a zero-drift measurement of inter-node position.

Fig. 3 shows the range error between a different node-pair, where one vehicle has GPS visibility (Medusa$_S$) and the other is submerged (another Medusa$_S$), but has a significantly lower drift than the previous example. Here the range error has little to no drift with a mean around 0 m, though because of the relative movement of nodes during the message exchange, there can still be some non-trivial residual. In both

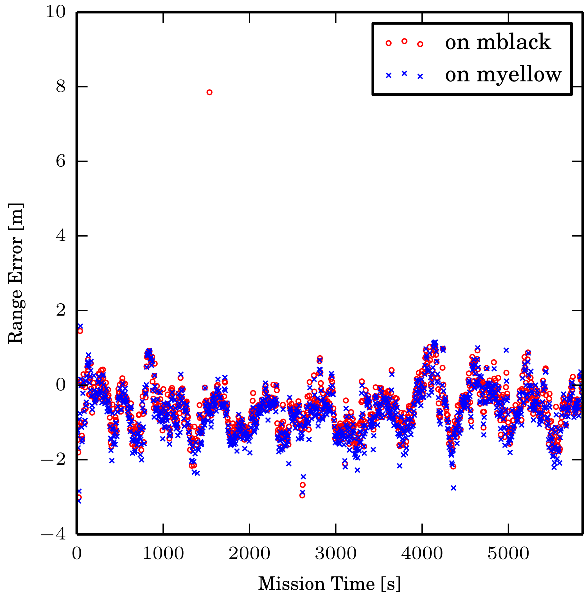

Fig. 3. Inter-node range error between vehicles with stable navigation solutions (mblack on surface with GPS and myellow underwater), comparing the internal navigation solution and the acoustic range on each node.

scenarios, as the typical range rate is close to the same order of magnitude as the typical range compared to the distance, $0.3\,\mathrm{m\,s^{-1}} \approx 5\,\mathrm{m}/5\,\mathrm{s}$, the noise effect of relative node velocity is high, in particular when the inter-node range rate is non-zero (e.g., in turns).

B. COLLAB–NGAS14: experimental results in long-range navigation

The second trial presented in this work is the COLLAB–NGAS14 sea trial. This was conducted from October 19, 2014 to October 31, 2014, off the West coast of Italy. For the purpose of this work, we restrict our focus on the activities of October 31.

The deployed network was composed of six nodes: one moored gateway buoy, two Wave Gliders (Lisa and Carol), the NRV *Alliance* and two CMRE Ocean Explorer (OEX) AUVs (named OEX Groucho and OEX Harpo), which navigated inside an area of approximately $60\,\mathrm{km}^2$. The water depth went from around 25 m to more than 60 m. This was convenient as it made possible to bottom lock the DVL, hence providing a navigation solution that can be used as ground truth for performance comparison. A fair water current of about $0.5\,\mathrm{m\,s^{-1}}$ was present in the area, moving from north to south. The sound speed profile was approximately constant in the water column [18]. The acoustic network was run using a Time Division Multiple Access protocol for the nodes to access the acoustic channel. The TDMA cycle is composed of one slot per node, with the AUVs slots of length 12 s to permit the transmission of 5 messages of 64 bytes up to a distance of 8 km, and shorter slots of 6 s allocated to the Command and Control (C2) on the NRV *Alliance* to send mission commands to the vehicles, and to Gateways and

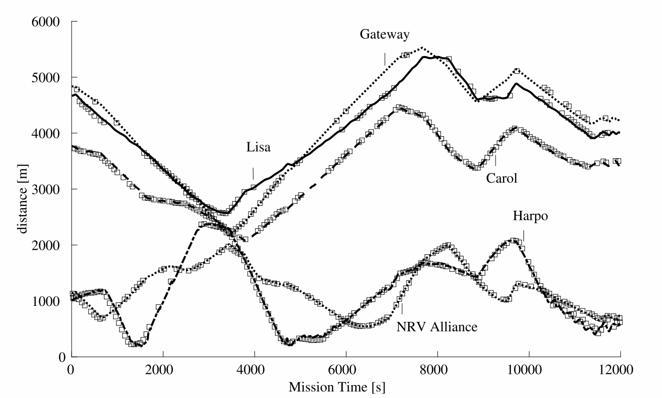

Fig. 4. Computed distance versus ground truth between OEX Groucho and the other nodes of the network on October, 31, 2014. Note how the ranging performance varied with time and with the nodes.

Wavegliders, which mainly need to send their position to the vehicles. The overall TDMA was 66 s, including gap periods to allow for the acoustic signal to travel to all destinations. Note that the TDMA length has a direct effect on the range measurement error as the current implementation does not correct for node movement during the time between the request and the reply.

1) Results: This section describes localisation and navigation results obtained on OEX Groucho, on October 31, 2014, during a 3 h mission. The distance calculated applying the proposed approach between OEX Groucho and the other five nodes is shown in Fig. 4. Continuous lines represent ground truth calculated using GPS when possible (i.e. for surface assets) and the inertial navigation with DVL measurements for the AUVs. The network-based range measurements are shown as squares.

OEX Groucho's ranging performance depended on node with which it was able to complete a network interrogation cycle. On average it went from about -9 m when pinging Wave Glider Carol (standard deviation of 27 m) to 2 m when pinging the NRV *Alliance* (standard deviation of 30 m). The maximum range measurement error was about 90 m. OEX Groucho EKF navigation error is shown in Fig. 5. The navigation error is defined as the error in position obtained comparing the EKF position estimate $p = (x, y)$ to that obtained running a inertial navigation system with DVL readings.

The effect of the network aided navigation system in keeping the navigation error bounded is visible, with drops in the error when new range measurements were received. Note that, running the same EKF filter, without network range measurements would lead to an ever growing navigation error which is around 1.5 km at the end of the mission ($\sim 25\%$ of the distance traveled).

IV. CONCLUSIONS

This paper described an acoustic network-based system to support underwater navigation of AUVs. The approach is based on the addition of localisation services to networked

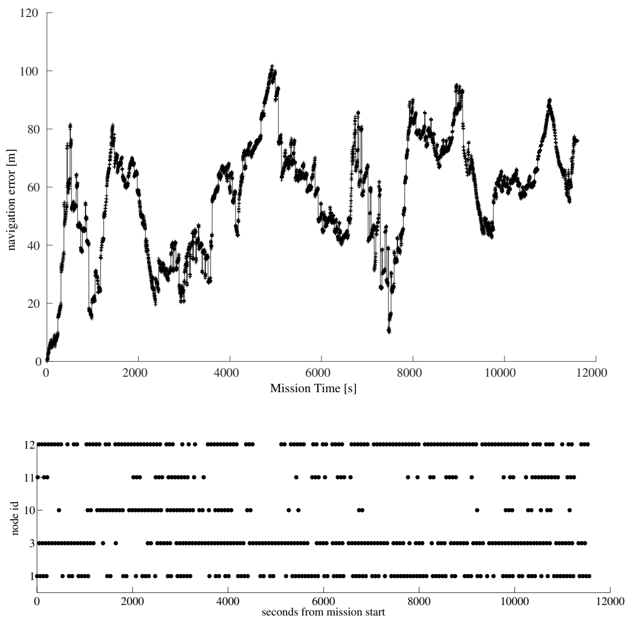

Fig. 5. Top: OEX Groucho navigation error on October, 31, 2014. Bottom: node number with which a network interrogation cycle was completed. NRV *Alliance* is node 1, OEX Harpo is number 3, Gateway is node 10, Wave Glider Lisa is number 11, and Wave Glider Carol number 12.

acoustic communications using the software-defined communications architecture paradigm. Traditional approaches to AUV navigation such as LBL and/or USBL methods, require the AUVs to query one or more modems/transponders while measuring the two-way travel time of the acoustic packets. Although these methods have been integrated together with communication devices, this has been usually done at the level of the acoustic modem. In this respect, the approach proposed herein is more generic: the localisation data is synthesised directly with regular communication traffic, and is designed to be applicable to generic, including software-defined, modems.

Results from the deployment of the system during two sea-trials have been shown. Results have shown how the proposed interrogation scheme is effective in limiting the navigation error, both at short and long ranges and even with sporadic communication. In the case of the COLLAB–NGAS14 experiment, with nodes kilometers away, the TDMA-based MAC layer of the network played a big role in determining the overall localisation performance. Future work will investigate how the usage of different MAC layers impacts on the ability of the network to provide the range measurements. Work is also on-going to support One-Way-Travel-Time (OWTT) implementations and to take advantage of multi-user waveforms and real-time channel analysis.

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Author(s)

Munafò, A., Furfaro, T., Ferri, G., Alves, J.

Title

Supporting AUV localisation through next generation underwater acoustic networks: results from the field.

Abstract

This work describes how the localisation of au-tonomous underwater vehicles can be supported through net-worked acoustic communication. The localisation approach in-cludes timing information within acoustic messages to create an interrogation scheme similar to that of long-baseline methods, but realised at the application level of the network. In this way, the network itself is able to provide vehicle localisation information, reducing the needs for additional on-board sensors or dedicated deployed platforms/transponders. The aim of this work is to report at sea localisation results as obtained in two completely different application scenarios. The first one is represented by the FP7 MORPH project (HORTA15 sea trial) where the proposed approach has been applied to support navigation of a fleet of AUVs in a tight formation and in very shallow waters. The second application is represented by the NATO STO CMRE multistatic network demonstrator with the acoustic network used to support navigation of AUVs working in large operational areas. In this latter case, results are given from the COLLAB–NGAS14 experimental campaign.

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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