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Bandwidth Efficient Concurrent Localisation and Communication in Underwater Acoustic Networks

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Abstract—**Localisation is essential for an Autonomous Underwater Vehicle (AUV) to perform its mission and to georeference any data acquired during the dive. When the AUV is part of a heterogeneous underwater acoustic network (UAN), concurrent communications and localisation can be exploited to support AUV operations. However, since acoustic communication is low bandwidth there is the need to reduce the overhead required to exchange localisation data. This paper presents a novel method to efficiently encode and decode localisation information. This results in a lower overhead without impacting the localisation performance. Results are presented from the CommsNet17 sea trial where a network consisting of up to eleven nodes was deployed, including static and mobile nodes.**

Index Terms—**Underwater Sensor Networks, Acoustic Communication, AUVs, Localisation, Navigation, Interval Methods, Bandwidth Efficient, Low Bandwidth, Data Compression**

I. INTRODUCTION

Underwater navigation is essential for Autonomous Underwater Vehicles (AUVs) to perform their mission. In some scenarios, the AUVs are part of a larger system, namely an underwater acoustic network (UAN), where the cooperation of multiple nodes and vehicles can be exploited to enhance the localisation capability of each node. Acoustic messages can be exchanged in the network while obtaining range measurements [1]–[3] and other useful data for localisation, such as the positions of the nodes and/or the angle-of-arrival of the incoming acoustic packets. However, acoustic communication is very low bandwidth [4]. Keeping the overhead introduced by the localisation data exchange limited is therefore important.

Although some of the current approaches quantify the bandwidth required for the ranging protocol [1], [5], most of the research does not focus on reducing the required overhead. One way to tackle this problem is using a data compression algorithm at the bit-level. The authors in [6] exploit statistical redundancy to represent data without losing any information. Data compression is largely used in the computer domain and many algorithms have been proposed, especially for what related to video and audio (*e.g.* MPEG, MP3, FLAC). In the acoustic communications domain, one of the existing solutions is the Dynamic Compact Control Language (DCCL) [7]. In this scheme, compression gain is achieved by enforcing bounds on minimum and maximum values of the datum and by setting a fixed numeric scale[1] for the encoded value. In this paper a complementary approach is described to efficiently encode and decode localisation specific messages. As opposed to a bit-level compression, data reduction is performed at the information-level. Less information is transmitted which is then recovered at the receiving side exploiting domain-specific knowledge of such information. The algorithm in fact builds on the fact that the transmitted data is then used to solve the problem of localisation. By solving this problem, the loss of information is recovered. The overall objective is thus to reduce the number of bits used to encode the intended information while maintaining a desired accuracy in the localisation. The selection of the number of bits to use and localisation performance are tied together. This selection is thus set accordingly to the mission profile and the quality of the sensors. At the receiving node, a concurrent decoding and localisation method is applied, based on interval methods [8], [9], to compute the node position. The proposed strategy can be combined with any bit-level compression solution to achieve a higher compression rate. Experimental results, collected during the CommsNet17 trial, shows that the proposed solution was able to reduce the number of transmitted bits by more than 50% with little effect on the localisation performance.

The rest of the paper is organised as follows. Section II describes the localisation data exchanged in the network. Section III reports the method used to encode and decode the localisation information, while Section IV details about the processing performed on the received data. Experimental results are presented in Section V. Finally, Section VI concludes the paper, presenting also possible future activities.

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[1] The numeric scale is the number of digits after the decimal point.

II. LOCALISATION DATA

Localisation is essential to accomplish unmanned robot navigation and to support various operations, such as georeferencing of the data collected for monitoring applications. In the terrestrial domain the problem of navigation is solved using GPS, a globally available and reliable positioning system. Such a solution is not available underwater since the electromagnetic waves carrying GPS data do not properly penetrate the water column [10].

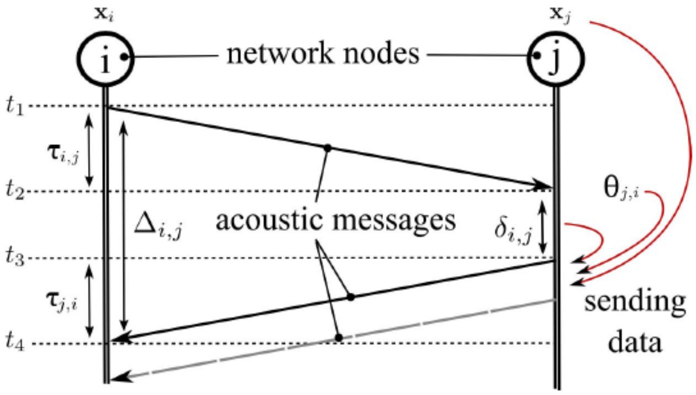


Fig. 1. Principle of acoustic network based localisation by exchange of localisation information between Nodes i and j. Here Node i is the node acquiring the localisation information from Node j.

Various strategies have been proposed for underwater localisation, including on-way Time Of Flight (TOF), two-way TOF and angle of arrival estimation.

Figure 1 shows a two-way message exchange between Node i and Node j, where Node i is getting localisation information from Node j.

Possible localisation data to be exchanged includes:

- the position of Node j, $\mathbf{x}_j$;
- the waiting time between the reception and transmission of the reply message, $\delta_{i,j}$;
- the angle of arrival $\theta_{j,i}$ measured by Node j, this could be measured using a Ultra-Short Base Line (USBL) system;
- the timestamps of the data transmission/reception.

When enough information is received by Node i, the distance to Node j can be computed using the received data. A possible way to compute this distance $r_{i,j}$ could be:

$$r_{i,j} = c_s \frac{(t_4 - t_1 - \delta_{i,j})}{2}$$

where c_s is the sound velocity in water and t_1, t_4 are, respectively, the time of emission and time of reception of the ranging messages [11] (see Figure 1).

III. REDUCING THE OVERHEAD: ENCODING LOCALISATION DATA

This Section describes the mathematical formulation behind the proposed strategy to perform encoding and decoding of the localisation data.

A. Encoding

We denote by $y(t) \in [y_{min}, y_{max}]$ one of the values to be encoded (*e.g.* $\delta_{i,j}$, $\theta_{j,i}$, components of node position $\mathbf{x}_j$) at the time t. Denote by H_c the encoding function used to compute the natural number $y_c(t)$ which is to be transmitted in the network. In this work, the H_c function is formed using quantisation and modulo

$$y_c(t) = H_c(y(t), u, n) = [\frac{y(t) - y_{min}}{u} + \frac{1}{2}] \pmod{2^n} \quad (1)$$

where [] is the integer value operator used to obtain a quantised value of $y(t)$. The H_c function has two parameters u and n which are set by the user. The parameter u is the selected unit to represent the data (similar to the resolution metric) and n, is the number of bits used to encode the value.

The encoding used in the DCCL [7] can be seen as a special case of this implementation. In the DCCL case, u is set to 10^{-q}, q being the desired numeric scale. More importantly, when using DCCL, the number of bits n must be enough to encode any value of y from $[y_{min}, y_{max}]$ with the given precision and without ambiguity. Consequently, in the DCCL case, the modulo in (1) never affects the resulting encoded value.

In this paper, the number n is set below the minimum number of bits used to encode the largest value y_{max} that $y(t)$ can have. This translates to the following equation:

$$[\frac{y_{max} - y_{min}}{u} + \frac{1}{2}] \geq 2^n \quad (2)$$

In this case, encoding the value using (1) reduces the required number of bits but also creates ambiguities when trying to decode it.

B. Decoding

On the receiver side, we define the decoding function as the function linking the encoded value $y_c(t)$ and the original value $y(t)$. The decoding function can be obtained based on (1). More specifically, the definition of the modulo ensures the existence of $p \in \mathbb{Z}$ such that

$$y_c(t) = [\frac{y(t) - y_{min}}{u} + \frac{1}{2}] + p * 2^n. \quad (3)$$

Also, the definition of the integer operator ensures the existence of $w \in [0, 1]$ where

$$\frac{y(t) - y_{min}}{u} + \frac{1}{2} = [\frac{y(t) - y_{min}}{u} + \frac{1}{2}] + w, \quad (4)$$

hence

$$y_c(t) = \frac{y(t) - y_{min}}{u} + \frac{1}{2} - w + p * 2^n, \quad (5)$$

hence

$$y(t) = y_{min} + y_c(t) * u + p * u * 2^n + (\frac{1}{2} - w) * u. \quad (6)$$

Finally, by defining $\varepsilon = (\frac{1}{2} - w) * u$, the decoding function H_d is obtained as:

$$y(t) = H_d(y_c(t), u, n, p, \varepsilon) = y_{min} + y_c(t) * u + p * u * 2^n + \varepsilon, \quad (7)$$

where $\varepsilon \in [\frac{-u}{2}, \frac{u}{2}]$ is the error due to the quantisation by u, and $p \in \mathbb{Z}$ is the modulo quotient. From here on we denote $a = u * 2^n$ as being the ambiguity resulting from the modulo operation in (1). For simplicity of notation, one can also consider $y_0(t) = y_{min} + y_c(t) * u$, thus obtaining the following simpler equation

$$y(t) = y_0(t) + p * a + \varepsilon. \tag{8}$$

Both ε and p are unknown to the receiver. As such, $y(t)$ can only be estimated with an quantisation error ε and an ambiguity a.

In what follows an example of this uncertainty and ambiguity produced by the encoding is provided. Let us suppose that a bearing measurement $\theta = 321^o$ has to be transmitted and (1) is applied. We have $\theta \in [0, 360] = [\theta_{min}, \theta_{max}]$. Assuming a quantisation unit $u = 1^o$ and a number of bits $n = 5$, applying (2) it is clear that not all the values of bearing can be encoded without ambiguity. After applying the encoding function we obtain $\theta_c = 1$. On the decoding side, since there is an ambiguity $a = 32$, all possible values which correspond to the encoded value of θ and still fall within the interval $[0, 360]$ are $\{1, 33, 65, 97, 129, 161, 193, 225, 257, 289, \mathbf{321}, 353\}$. The resulting quantisation error is $\varepsilon \in [-0.5, 0.5]$.

In the next section we show how to resolve the ambiguities in the case of the localisation problem.

IV. RESOLVING AMBIGUITIES - USING DOMAIN SPECIFIC KNOWLEDGE

A. The ambiguous localisation problem

In this section we rely on domain-specific knowledge of the localisation problem to resolve the ambiguities created at the time of transmission. More specifically, we consider a dynamic localisation problem using range and bearing measurements to node with known locations [8], [9], [11]. In this case, the position of a node is estimated fusing a number of past range and bearing measurements with the velocity measurements of the node.

Note that, this localisation problem can be solved by a number of methods such as Particle Filters, Extended Kalman Filter [12] or Interval methods [13].

Consider a pair of nodes i and j where node i is receiving localisation data from node j with the aim of using it to localise itself. When no encoding is used, the range equation for node i can be written as

$$\|\mathbf{x}_i(t_r) - \mathbf{x}_j(t_r)\| = r(t_r), \tag{9}$$

where $\mathbf{x}_{i/j}(t_r)$ is the position of a node at timestamp t_r and $r(t_r)$ is the range from nodes i to node j at t_r.

Similarly, the bearing measurement equation can be written as:

$$Arg(\mathbf{x}_i(t_\theta) - \mathbf{x}_j(t_\theta)) = \theta(t_\theta), \tag{10}$$

where $\theta(t_\theta)$ is the absolute bearing between node i and node j at the timestamp t_θ.

When range and bearing are instead encoded using (1), using the simple formulation in (8), the new (ambiguous) range measurement equation can be written as:

$$\|\mathbf{x}_i(t_r) - \mathbf{x}_j(t_r)\| = r_0(t_r) + p_r * a_r + \varepsilon_r, \tag{11}$$

where $r_0(t_r)$ is a value obtained from the encoded value, a_r is the range ambiguity and ε_r is the quantisation error for the range.

Similarly, the new bearing (ambiguous) measurement equation can be written as:

$$Arg(\mathbf{x}_i(t_\theta) - \mathbf{x}_j(t_\theta)) = \theta_0(t_\theta) + p_\theta * a_\theta + \varepsilon_\theta, \tag{12}$$

where $\theta_0(t_\theta)$ is a value obtained from the encoded value, a_θ is the bearing ambiguity and ε_θ is the quantisation error for the bearing. Substituting the regular range and bearing measurements with ambiguous measurements, the localisation problem translates into a new problem which can be named *ambiguous localisation problem*.

B. Solving the ambiguous localisation problem

To solve this new problem, interval methods are used. These methods enable the creation of solvers for the non-linear sets of equations [14]. The obtained solution is in form of a set of points that satisfy all these equations, or a portion of the equations if there are some inconsistencies caused by outliers in the data. The output set can be disjoint, *i.e.* in our case represent multiple possible subsets. Interval methods were chosen as they deal well with ambiguity. In fact, in the case of an ambiguity between two equations, *i.e.* when only one of them is satisfied, the solution is the union of the solution sets for each one of these equations independently. Figure 2 shows an example of localisation using two ambiguous range equations and one ambiguous bearing equation. The set of points which satisfy an ambiguous range measurement equation is a set of concentric rings. This set is the union of the sets of points which satisfy each of the possible ranges (*i.e.* for every value of p_r in (11)). Similarly, the set of points which satisfy an ambiguous bearing measurement equation is a set of eccentric pie slices.

If the node is not moving, the solution is the intersection of these sets. In the example in Figure 2, this intersection lead to many "ghost" solutions. For the problem to be properly solvable, the encoding should be parametrised in a way to make these ghost solutions not overlap with the true solution. This in turn depends on the quality of the sensors. For example, more uncertainty in range lead to wider rings which imposes a larger ambiguity so that the rings do not overlap.

C. Operational considerations

We can define two operational scenarios, one where the localising node knows its starting position (*e.g.* GPS fix on the surface), the other one when it does not have this knowledge, *e.g.* when the vehicle loses track of its position in the case of no fixes for long time.

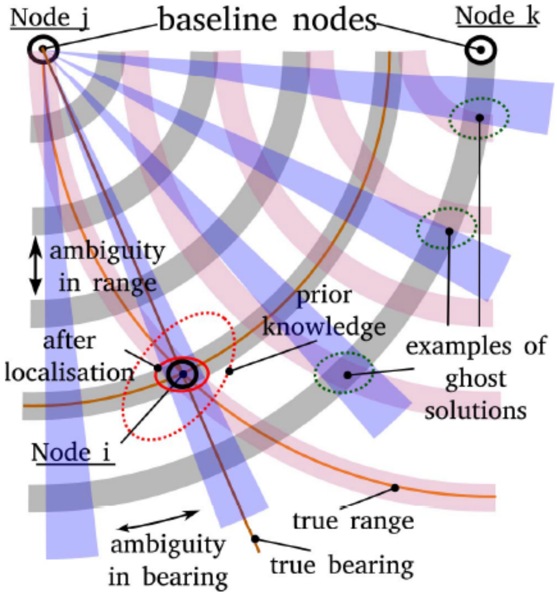


Fig. 2. Example of localisation using two ambiguous range measurements and one ambiguous bearing measurement. Using ambiguous localisation data leads to multiple possible solutions (intersection of the areas consistent with the measurements). Tracking the solutions is one possible approach for disambiguation since, if the multiple solutions are not overlapping, there are no local ambiguities.

The ambiguous localisation problem solver can be applied in both these scenarios. These two cases are however different. The first case (local resolution) is not affected by the ambiguity assuming that the ambiguous solutions do not overlap. It is therefore possible to track the mobile vehicle position distinguishing between the true solution and the "ghost" solutions. When using local resolution, the performance of the localisation is no different than when using encoded data without the modulo.

The second case (global resolution) instead is more challenging as the algorithm has to resolve the ambiguities first. After this the same approach as in the first case can be applied.

Both these scenarios are possible in underwater acoustic networks and are discussed in the next Section. More specifically we focus on the second scenario since it combines both cases.

V. EXPERIMENTAL RESULTS

A. *CommsNet17 trial*

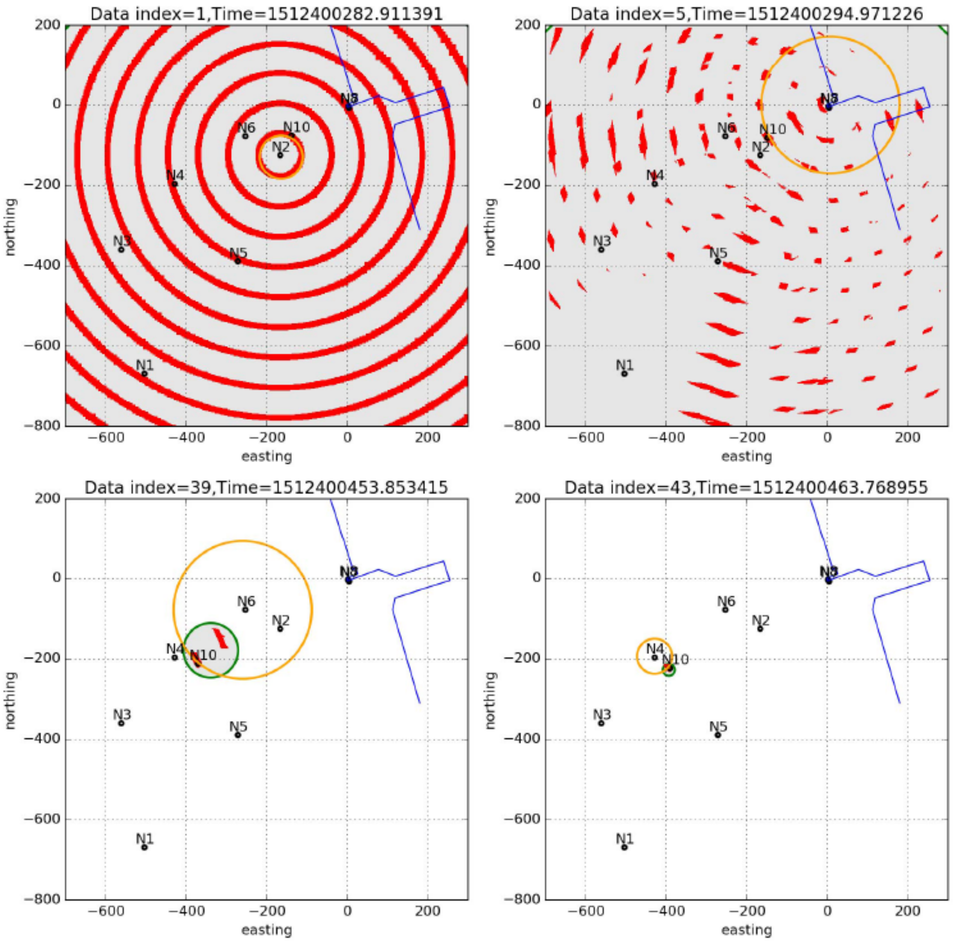
The CommsNet17 trial [15] was organised by the NATO Centre for Maritime Research and Experimentation (CMRE). It was held from the 27^{th} of November to the 6^{th} of December in the Gulf of La Spezia, Italy, close to the CMRE premises and consisted in deploying a persistent underwater acoustic network composed of up to eleven nodes (static and mobile). The nodes were heterogeneous and included one AUV, one USV, one portable gateway buoy, 4 cabled nodes part of the CMRE Littoral Ocean Observatory Network (LOON) [16], 4 portable nodes and a docking station to recharge the AUV and offload the data. Figure 3 shows the Gulliver USV and one of the portable nodes on the bottom-left corner. The Gulliver was equipped with precise Differential GPS (DGPS) positioning and its acoustic modem was deployed on a rigid retractable pole thus obtaining a precise ground truth for the modem position.

B. *Encoding settings and efficiency*

The CommsNet17 experiment was conducted sending the localisation data without the proposed encoding. The $\delta_{i,j}$ (see Figure 1) and bearing measurements were transmitted. The modulo and quantisation were then investigated in post processing and compared with the original data. This was done to validate and evaluate the performance of the proposed strategy. Using the solution proposed in this paper, the number of bits and the quantisation unit were set up in a way to have a small impact on the performance of the localisation algorithm while allowing to save several bits of information. The $\delta_{i,j}$ was originally encoded using 19 bits using a unit of 10^{-4} seconds. Considering that the uncertainty on range measurements was of several meters, in the proposed approach the quantisation unit was changed to 8×10^{-4} seconds leading to a quantisation error for the range measurement of about ±0.5 meter. This action saved 3 bits. Using $n = 7$ as the number of bits to encode the data, the use of the modulo enables to save 9 bits. When using both modulo and quantisation the total bit saving is of 12 bits (63% less bits are transmitted). The pure gain of the modulo, *i.e.* when applied on already quantised data, is of 56%

Similarly, the bearing was originally encoded using 19 bits with a quantisation unit of 10^{-3} degree. Considering that the uncertainty on bearing measurements was of several degrees, the quantisation unit was changed to 1 degree. In this case, the resulting quantisation error is about ±0.5 degrees. This action saved 10 bits. Using $n = 5$ as the number of bits to

Fig. 3. The USV Gulliver used as a node of the underwater acoustic network as well as one portable node in the bottom-left corner. The Gulliver had the id=10 and is the target of localisation in our paper.



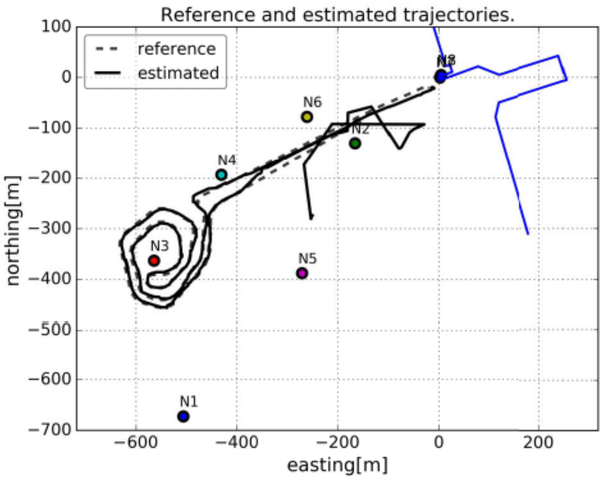
Data index=1,Time=1512400282.911391

Data index=5,Time=1512400294.971226

Data index=39,Time=1512400453.853415

Data index=43,Time=1512400463.768955

Fig. 4. The results of range-only localisation of USV (label N10) using ambiguous range measurements. The image at range data index 1 (top left) shows the solution set in the form of concentric rings. At the next range data index, one can see several disjoint solutions. At the next range data index, most of the ambiguities have been resolved. Finally, at the last data index, the algorithm has converged and is able to properly track the solution.



Reference and estimated trajectories.

Fig. 5. The resulting computed trajectory against the ground truth. At the beginning there is ambiguity in the solution causing the estimated trajectory to be offset by a large amount. After resolving all of the ambiguities, the solver was able to properly track the position until the end of the mission.

encode the data, the use of the modulo enables to save 4 bits. When using both modulo and quantisation the total bit saving is of 14 bits (76% less bits are transmitted). The pure gain of the modulo, *i.e.* when applied on already quantised data, is of 44%.

C. Localisation results

In what follows the results for the range-only and bearing-only cases are presented. The USV (node with id=10, labelled as N10) is used as the target node localising itself. The algorithm is set to solve the problem globally, *i.e.* with no prior knowledge of the position of the node. In this configuration, the algorithm first resolves the ambiguities and then tracks the solution till the end of the mission.

Figure 4 shows the resulting solution set of the ambiguous localisation problem using range-only measurements and solving the problem globally. The results are showed at four different snapshots of the system (data index 1, 5, 39 and 43). Each snapshot corresponds to a different set of collected range measurements. When the first range data is received (index = 1, in Figure 4), the set of possible solutions is in a form of a set of concentric rings. The range data received at index 5 is

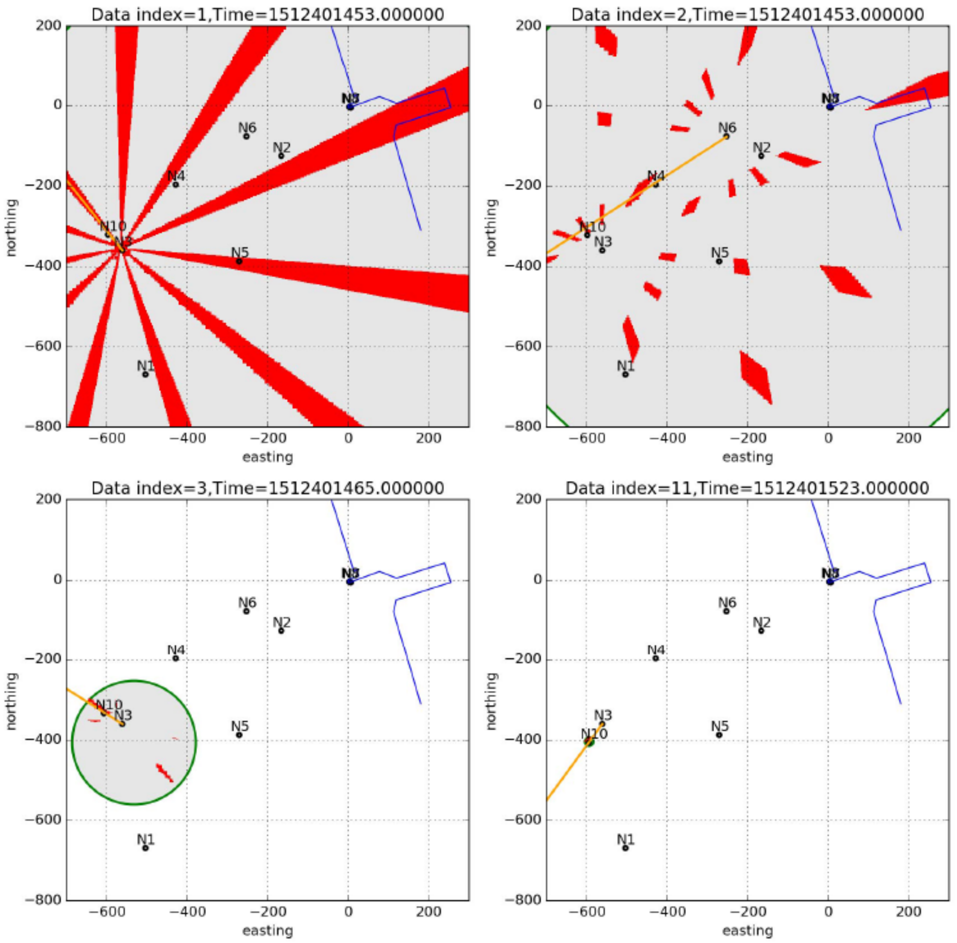


Fig. 6. The results of bearing-only localisation of USV (N10) using ambiguous bearing measurements. The image at bearing data index 1 (top left) shows a solution set in the form of eccentric pie slices. At the next bearing data index, one can see several disjoint solutions. At the next bearing data index, most of the ambiguities have been resolved. Finally, at the last data index, the algorithm has converged and is able to properly track the solution.

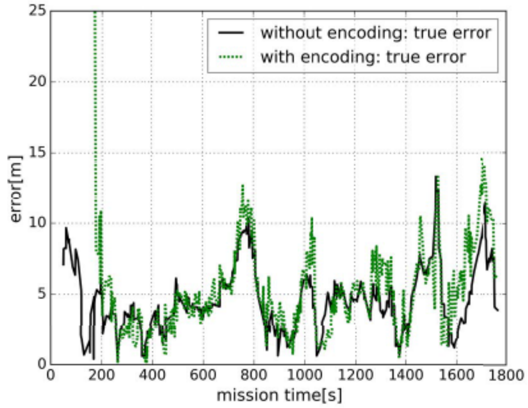


Fig. 7. Comparing localisation errors resulting in the execution of the localisation algorithm with and without using the encoding. At the beginning, when using the encoding, the algorithm takes time to solve the ambiguities in the solution which causes the uncertainty to be off the scale. When the algorithm converges, there is a slight difference in the localisation error caused by the use of a coarser quantisation.

still not sufficient to uniquely localise the node since several non-overlapping areas in which the USV may be can still be identified. At data index 39, we see that most of the ghost solutions have been eliminated. Finally, at data index 43, there is only one solution remaining.

Figure 5 shows the resulting computed trajectory against the ground truth which shows that after converging the algorithm kept tracking the solution properly. Thus validating both the global and local solution of the problem.

The localisation error obtained by the algorithm with and without the proposed encoding is displayed in Figure 7. This error is computed as the distance between the centre of the solution set given by the localisation algorithm and the USV GPS ground truth. One can see that at the beginning, using the proposed encoding approach, the uncertainty is off the scale because of the multiple ghost solutions. When the algorithm converges, the localisation error is not much affected by the encoding.

Figure 6 shows the resulting solution set of the ambiguous localisation problem using bearings-only and solving the problem globally. The results are showed for four selected snapshots of the bearing measurements (data index 1, 2, 3, 11). When the first data is received (index=1, Figure 6), the set of possible solutions is this time is in a form of a set of eccentric pie slices. The subsequent bearing measurement still defines several non-overlapping areas in which the node may be. USV position is among those areas. At data index 3, we see that most of the ghost solutions have been eliminated, and, finally, at data index 11, there is only one solution remaining. When both range and bearing measurements are combined the algorithm is expected to converge faster.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we presented a method to reduce the bandwidth required by localisation specific messages in an underwater acoustic network. The paper presented specific information-level encoding and decoding functions based on quantisation and modulo. The method was validated using experimental data obtained during the CommsNet17 trial for range-only and bearing-only scenarios. The node was able to successfully resolve the ambiguities and localise itself globally. It was then able to properly track the position until the end of the mission. Future work includes the study of the optimal parameters for the encoder to ensure minimal bandwidth requirements. Considering the efficiency of the method, next step is to also investigate other applications (other than localisation) where this strategy could be used.

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Title

Bandwidth efficient concurrent localisation and communication in underwater acoustic networks

Abstract

Localisation is essential for an Autonomous Underwater Vehicle (AUV) to perform its mission and to georeference any data acquired during the dive. When the AUV is part of a heterogeneous underwater acoustic network (UAN), concurrent communications and localisation can be exploited to support AUV operations. However, since acoustic communication is low bandwidth there is the need to reduce the overhead required to exchange localisation data. This paper presents a novel method to efficiently encode and decode localisation information. This results in a lower overhead without impacting the localisation performance. Results are presented from the CommsNet17 sea trial where a network consisting of up to eleven nodes was deployed, including static and mobile nodes.

Keywords

Underwater Sensor Networks, Acoustic Communication, AUVs, Localisation, Navigation,
Interval Methods, Bandwidth Efficient, Low Bandwidth, Data Compression

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