aLS-Coop-Loc: Cooperative Combined Localization and Time-Synchronization in Underwater Acoustic Networks

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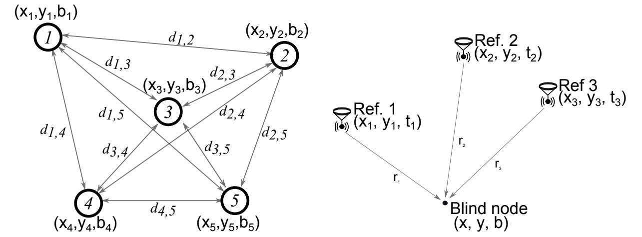
ABSTRACT

Traditionally, underwater localization and time-synchronization are performed separately. This, however, requires two-way ranging between nodes to determine propagation delays resulting in high power consumption and communication overhead. One-way ranging can be used by using a combined time-synchronization and localization approach. While such an approach exists for non-cooperative networks, to the best of our knowledge no such approach exist for cooperative networks. A cooperative approach has significant benefits in terms of number of reference nodes required, flexibility of reference nodes, and accuracy of localization and time-synchronization. Therefore, in this paper we propose a cooperative combined localization and time-synchronization for underwater acoustic networks.

We show our approach requires less communication and improves energy-efficiency of the ranging measurement phase, compared to existing Multi-Dimensional Scaling (MDS) approaches using two-way ranging or prior time-synchronization. Using simulation we evaluate the localization and time-synchronization accuracy of our approach and compare it with existing MDS approaches and a non-cooperative approach. Simulations shows that our cooperative approach outperforms non-cooperative approaches in terms of accuracy of localization and time-synchronization and is able to perform localization with fewer reference nodes. We also show that our approach outperforms MDS with prior time-synchronization in terms of accuracy.

1. INTRODUCTION

When measuring, it is important to know where and when the measurement was taken. Therefore, localization and time-synchronization play an important role in wireless sensor networks. Existing work on time-synchronization [5] and localization [2] consider these aspects separately. However combined localization and time-synchronization, similar to what is already done by Global Positioning System (GPS), allows the position and time to be simultaneously estimated using one-way ranging only. The significant benefit of one-way ranging is its lower communication overhead. With one-way ranging, broadcasts can be used, through which the number of packets required to be sent before localization is performed, is reduced from quadratic to linear complexity in number of network nodes. Because bandwidth is very limited in underwater acoustic networks and data rates [1] are therefore very low, localization and time-synchronization using one-way ranging becomes important. Another advantage offered by one-way ranging is reduction of energy consumption due to lower communication overhead offered by one-way ranging.



(a) Cooperative (b) Non-cooperative

Figure 1: Example of cooperative and non-cooperative localization. Cooperative localization uses all pair-wise measurements available, while non-cooperative localization uses only measurements between reference nodes and blind-nodes.

Figure 1 shows an example of cooperative and non-cooperative localizations. In cooperative localization all nodes cooperate to determine their position and all pair-wise distance measurements are used. This, potentially, increases the accuracy of cooperative localization and allows more flexible selection of the reference nodes.

To allow localization and time-synchronization using only one-way ranging, a combined localization and time-synchronization approach is required. Such a combined localization and time synchronization method already exists for non-cooperative localization approaches like GPS, however to the best of our knowledge no such approach exists for cooperative networks. We propose a cooperative combined localization and time-synchronization approach for underwater networks called Asynchronous Least-Squares Cooperative Localization (aLS-Coop-Loc).

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[1] Realistic data rates range between a few bits per second (long range, >1000 km) up to 10 kilobits per second (short range, <1 km)

This paper is organized as follows: In Section 2 we discuss related work on localization and time-synchronization. In Section 3 we introduce our cooperative combined localization and time-synchronization algorithm (aLS-Coop-Loc). In Section 4 we show our approach has significant benefits in terms of communication required compared to existing cooperative approaches. We compare the performance of non-cooperative and cooperative localization in simulation in Section 5.

2. RELATED WORK

In this section we review time-synchronization and combined localization and time-synchronization for non-cooperative and cooperative networks. Regarding cooperative localization, we will review the MDS localization approach. This approach is a commonly used approach for cooperative localization. It, however, does not incorporate time-synchronization.

2.1 Time-Synchronization

Time-synchronization is the process of synchronization of the clocks at different nodes such that an agreement is reached on what the current time is. This notion of 'time' does not necessarily have to be global (world time), as the nodes can agree on a local time for the complete network.

Let us consider a network of N nodes. Every node has a clock and all nodes are assumed to have the same frequency increment. The clock is modeled as a $\mathbb{R}$ variable, which increases continuously over time. We denote the clock of node i as ϕ_i. Every clock has a bias, this is an offset of the clock compared to another clock. We denote the bias of the clock as b_i. To synchronize a network of N nodes all biases of all the clocks should be calculated according to:

$$\phi_1 - b_1 = \phi_2 - b_2 = \cdots = \phi_N - b_N \tag{1}$$

Owing to the availability of low-drift clocks, we assume that the clock drift during range measurements is negligible and we therefore do not take clock drift into account in our model.

2.2 Non-cooperative Localization

A number of non-cooperative combined localization and time-synchronization already exist, an example of which is GPS. Figure 1(b) shows a non-cooperative localization and time-synchronization setup. All reference nodes have a known position (x_i, y_i) and are assumed to be synchronized, i.e. their clock biases are known. The reference nodes send out their position information (x_i, y_i) and the time when a message was sent (t_i). A blind node records the arrival time of the message (r_i) and is able to calculate the Time-of-Flight (TOF) of the message with a clock-bias of its local clock (b). The blind-node should estimate both its position (x, y) and clock-bias (b). This is done by minimizing the following cost function:

$$\min_{x,y,b} \sum_{i=1}^{N} \left(\sqrt{(x-x_i)^2 + (y-y_i)^2} - v \cdot (r_i - t_i - b)\right)^2, \tag{2}$$

where v is the propagation speed of the signal, which is commonly approximated to 1500 $^{\mathrm{m}}\!/\!_{\mathrm{s}}$ in water. Several methods exist to minimize the non-quadratic cost function (2). We use the Levenberg-Marquardt iterative optimization technique [4], which is well-behaved and a proven scheme.

2.3 Cooperative Localization

The MDS approach is a commonly used approach to cooperative localization, however it requires prior time-synchronization or costly two-way ranging.

An MDS localization algorithm calculates relative positions and works by measuring the distance between all pair of nodes in the network. The distance measured between a pair of nodes is placed in a dissimilarity matrix δ.

$$\delta = \begin{pmatrix} \delta_{1,2} & \delta_{1,3} & \delta_{1,4} & \dots & \delta_{1,N} \\ & \delta_{2,3} & \delta_{2,4} & \dots & \delta_{2,N} \\ & & \delta_{3,4} & \dots & \delta_{3,N} \\ & & & \dots & \dots \\ & & & & \delta_{N-1,N} \end{pmatrix}$$

The dissimilarity matrix is used to find the position vectors of the nodes $x_1 \dots x_N \in \mathbb{R}^3$. This is done by minimizing the following cost function [1]:

$$\min_{x_1 \cdots x_N} \sum_{i=1}^{N} \sum_{j=i+1}^{N} (\|x_i - x_j\| - \delta_{ij})^2, \tag{3}$$

where $\|x_i - x_j\|$ is defined as the Euclidian distance between vector x_i and x_j. Note that the upper triangle of the dissimilarity matrix is used, MDS assumes the dissimilarity matrix is symmetric.

MDS is a relatively straight-forward way of determining relative positions, however does require two-way ranging or prior time-synchronization, which introduces significant communication overhead.

3. ALS-COOP-LOC

In this section we introduce a combined localization and time-synchronization approach for cooperative networks. Our algorithm follows a similar approach as MDS. However, rather than just calculating the position (x, y) of nodes, also the unknown clock bias (b) is calculated. Although we describe our localization for a 2-dimensional setup, it can be easily extended to three dimensions.

Before we describe the localization algorithm, first we review how range measurements are calculated. Let us consider nodes are positioned in a D dimensional space, where $D = 2$ or 3. Let $\vec{x}_{i=1\dots N}$, $x_i \in \mathbb{R}^D$ be the vector or coordinates of node i and assume $b_i \in \mathbb{R}$ is the clock bias of node i.

Let us consider two nodes with index i and j out of a network of N nodes. If we define the transmission time of a message on node i as t_i and the reception time of the message as r_i and also consider the clock bias of both nodes b_i and b_j, we can measure the TOF between two nodes as follows:

$$(r_i - b_i) - (t_i - b_j) = tof_{i,j} \tag{4}$$

From the tof we can calculate the pseudo-distance between the two nodes (τ) by using the propagation speed v $\approx$ 1500 $^{\mathrm{m}}\!/\!_{\mathrm{s}}$. The measured pseudo-distance between nodes (denoted by $\tau_{i,j}$), measured during the operation of an underwater network, and the estimated distance between the nodes, calculated during the process of iterative optimization, should converge to the same value:

$$\tau_{i,j} = v((r_i - b_i) - (t_i - b_j)) \rightarrow ||\vec{x}_i - \vec{x}_j|| - v(b_i - b_j) \quad (5)$$

We measure these pseudo distances ($\tau_{i,j}$) between nodes using acoustic communication during the operation of the network and place them in a dissimilarity matrix similar as being done in MDS:

$$\tau = \begin{pmatrix} \tau_{1,2} & \tau_{1,3} & \tau_{1,4} & \dots & \tau_{1,N} \\ & \tau_{2,3} & \tau_{2,4} & \dots & \tau_{2,N} \\ & & \tau_{3,4} & \dots & \tau_{3,N} \\ & & & \dots & \dots \\ & & & & \tau_{N-1,N} \end{pmatrix}$$

However rather than measuring the actual distance between two nodes, we measure the distance between nodes with a clock bias error of the sender and a clock bias error of the receiver. After measuring the propagation delay between the nodes with the unknown clock biases, for every we estimate the position ($\vec{x}_i \in \mathbb{R}^D$) and clock-bias ($b_i \in \mathbb{R}$) by minimizing the following cost function:

$$cost = \min_{x_1 \dots x_N, b_1 \dots b_N} \sum_{i=1}^{N} \sum_{j=i+1}^{N} (\tau_{i,j} - ||\vec{x}_i - \vec{x}_j|| - v(b_i - b_j))^2 \quad (6)$$

Note that the upper triangle of the dissimilarity matrix is used, hence the approach uses one-way ranging.

3.1 Resolving ambiguity with references

The positions that are calculated using the cost function from Equation 6 fit the measured distance, but can be rotated or flipped in all dimensions. This means that they can be rotated in the space dimension ($\mathbb{R}^D$), which is similar to the ambiguity of the MDS approach, but it can also rotate or flip in the time dimension ($\mathbb{R}$). We call this problem the space-time ambiguity.

To add meaning to the results some reference measurements are required. For example to resolve the space-time ambiguity a measurement of the clock bias needs to be added. This can be done using a single round-trip measurement between only two nodes in the whole network or using an external time-synchronization such as a GPS receiver. This is a significant improvement compared with existing approaches, which require at least round-trip measurements between a reference nodes and all other nodes in the network.

Consider a set of nodes called ref_{time} for which we have the measured clock bias denoted as β_i. The cost function can now be extended with the following cost:

$$cost_{time} = \sum_{i \in ref_{time}} (\beta_i - b_i)^2 \quad (7)$$

The same can be done if we know or are able to measure the position or part of the position of a node. For example if the depth can be measured, the cost function can be extended with a cost for the depth. The set of nodes for which we have a reference is called $ref_{space,3}$ and we denote the measurement of the depth as $\vec{r_i}_{,3}$, we can now extend the cost function with:

$$cost_{space,3} = \sum_{i \in ref_{space,3}} (\vec{r_i}_{,3} - \vec{x_i}_{,3})^2 \quad (8)$$

Extending the cost function for other dimensions follows the same approach. If we know the x, y or *depth* of any node, we can extend the cost function with reference measurements. The set of reference nodes for dimension d is called $cost_{space,d}$. The complete cost function is now the basic cost function for fitting the distance measurements (Eq (6)) and all space (Eq (8)) and time (Eq (7)) cost functions:

$$cost_{overall} = cost + \sum_{d=1}^{D} cost_{space,d} + cost_{time} \quad (9)$$

To provide the absolute space-time coordinates some reference measurements are needed. To be able to at least split the results into space and time dimensions and to resolve the space-time ambiguity, the relative clock bias of two nodes in the network is required. To calculate an absolute position in 2 dimensions, 3 reference nodes in the network are required. Because the reference measurements can be split up into separate dimensions it is possible for example to measure the x, y position at surface nodes and assume the depth is 0, and to measure only the depth of a node that is submerged. This will allow the complete network to be absolutely positioned in 3 dimensions.

4. COMMUNICATION OVERHEAD AND POWER-CONSUMPTION

By looking at the amount of communication required to perform measurements we estimate the time required to perform ranging measurements and the power-consumption of nodes. Considering that an unsynchronized MDS approach requires two-way ranging between all pair of nodes the communication complexity of an MDS approach given the number of nodes in the network (N) is:

$$O\left(2N\frac{N-1}{2}\right) \quad (10)$$

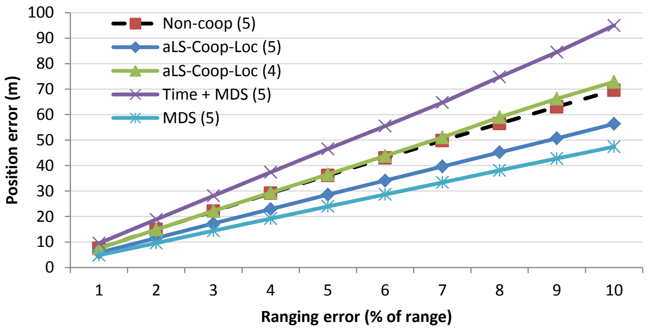
A better approach requiring less communication cycles would be to first synchronize all the nodes in the network to a single master using TPSN [3] and then performing ranging using broadcasts. All nodes first performs two-way ranging with a clock master ($O(N-1)$) and then broadcast a message to its neighbors ($O(N)$) which are also time-synchronized to perform ranging. The complexity of such an approach is:

$$O(2(N-1) + N) \quad (11)$$

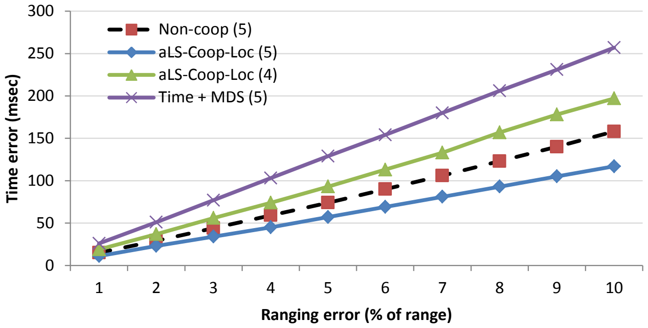
Our aLS-Coop-Loc approach requires broadcast messages only, and therefor the amount of communication required during the ranging phase of the localization and time-synchronization increases linear with the number of nodes in the network:

$$O(N) \quad (12)$$

The power-consumption required during the measurement phase is a linear function of the amount of communication required and therefor follows the same complexity. This shows our approach outperforms existing approaches in number of communication cycles required. Our approach reduces the energy consumed during the measurement phase, decreases the time required to perform measurements and improves reliability because fewer messages need to be received.



(a) Position error



(b) Time-synchronization error

Figure 2: The simulated time-synchronization and position error as a function of the ranging error.

5. SIMULATION

We evaluate the performance of our aLS-Coop-Loc, two-way ranging MDS, MDS with prior TPSN time-synchronization (Time+MDS) and non-cooperative localization approaches using simulation.

In the simulation eight nodes are randomly deployed in an area of 500x500 meters (our targeted deployment size for the system). Five reference nodes are added to the network and the position accuracy is evaluated for different ranging errors following a Gaussian distribution of $\mathcal{N}(0, 0 \ldots 0.1 \times range)$. We run this simulation for at least 100 deployments and evaluate the average accuracy of time-synchronization and localization. For aLS-Coop-Loc we run the algorithm centralized with 4 and 5 reference nodes in the network.

The result of the localization accuracy and time-synchronization accuracy are shown in Figure 2(a) and Figure 2(b), respectively. The two-way ranging MDS approach performs best in terms of localization accuracy, but does so at quadratic communication cost. Our aLS-Coop-Loc outperforms MDS with prior time-synchronization. Moreover our approach outperforms non-cooperative localization with the same number of reference nodes. This is due to the fact that the cooperative localization uses more measurements than non-cooperative localization. The cooperative localization approach uses all measurements available between all pair of nodes, while our non-cooperative localization uses only measurements between reference nodes and blind nodes. Moreover our cooperative localization approach is able to perform localization with fewer reference nodes compared to a non-cooperative localization approach.

6. CONCLUSION

Localization and time-synchronization are important aspects of underwater acoustic sensor networks, as they give meaning to sensor measurements by adding information on where and when measurements are taken. Localization and time-synchronization, however, are traditionally done separately.

When time-synchronization and localization are performed separate, two-way ranging is required. Two-way ranging poses a significant overhead in terms of communication and energy consumption. With very limited data-rates and battery capacity available in underwater acoustic networks this is not practical. One-way ranging is preferred because broadcasts can be used to perform the ranging and the amount of communication required is significantly decreased because not every link needs to be ranged separately.

In this paper we have shown how combined localization and time-synchronization can be performed for cooperative networks using a cost function which can fit both the position and clock bias of the nodes with the measured propagation delays. Reference nodes are required to remove space-time ambiguity. We have shown how to include reference information such as depth, position and clock-synchronization by extending the cost function. The algorithm is flexible in the reference positions and reference measurement can be used even if it is only one dimension.

Using simulation we have shown our cooperative combined localization and time-synchronization approach outperforms a non-cooperative approach when the same number of reference nodes are used. When four reference nodes are used, cooperative localization and time-synchronization is still able to calculate position and time, but does so with reduced accuracy. Two-way ranging outperforms all other approaches in terms of localization accuracy. Our approach does however require only one-way ranging reducing the amount of communication required from quadratic to linear complexity and provides both time-synchronization as well a positioning. Our approach outperforms MDS with prior time-synchronization.

Acknowledgment

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