Collaborative Relative Positioning in Underwater Environments Using Acoustic Communication and Two-Way Ranging

Semir Cömertpay[1], Gerhard Bauch[1], Dennis Galsdorf[2], Ivor Nissen[2]
[1] *Hamburg University of Technology, Institute of Communications, Germany,*
e-mail: {bauch, semir.coemertpay}@tuhh.de
[2] *Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71), Germany,*
e-mail: {ivornissen, dennisgalsdorf}@bundeswehr.org

Abstract

This study explores the feasibility of using acoustic communication and two-way ranging for relative positioning in underwater navigation applications which use the GUWMANET® protocol. Propagation time estimations were gathered between multiple nodes in a heterogeneous mobile ad-hoc network during a series of sea trials, which employed two different physical layer methods along with double-sided two-way ranging (DS-TWR). Following this data collection, multidimensional scaling was applied to the estimated propagation-time matrix to generate relative positions in Euclidean space, resulting in a topology that was subsequently compared to GPS data for validation purposes. In order to enhance the accuracy of the topology estimation process, the classical multidimensional scaling algorithm was adapted to incorporate extrinsic information, such as the known depths of surface vehicles. The real-world performance is compared to the performance of the system achieved through simulations using the DESERT underwater network simulator. Furthermore, the limitations of the acoustic communication schemes are derived to provide valuable insight into the feasibility of real-time navigation in complex underwater environments.

Introduction

During the annual *Robotic Experimentation and Prototyping using Maritime Unmanned Systems* (REPMUS) exercise, hosted by the Portuguese Navy and the European Defence Agency, the available acoustic communication network was utilized to test and validate the acoustic propagation time estimation capabilities. The present acoustic communication network uses the *Gossiping Underwater Mobile Ad-Hoc Network* (GUWMANET®) network protocol, which was jointly developed by the *German Maritime Research Department* (WTD 71) and *Fraunhofer Institute for Communication, Information Processing, and Ergonomics* (FKIE) [1] in 2012. GUWMANET® is not based on any widespread radio-frequency network protocol and was designed from scratch to meet the needs of an underwater acoustic network. Key features of the resulting GUWMANET® protocol are its modular structure and its cross-layer design approach concerning the conventional ISO/OSI communication layers [2]. This cross-layer approach allows the design of a communication stack capable of adapting its medium access or physical layer standard depending on the application message. Such behavior is implemented in the NaviPAS module inside GUWMANET® by evaluating messages coming from the top layers and starting propagation time estimate messages whenever an application message conveys navigational intent.

Real-world Underwater Networks

The underwater acoustic communication network used during the REPMUS 2024 exercise was based on software and hardware from the WTD 71 and its partners from the *European Defence Agency* (EDA) developed during the *Smart Adaptive Long-and Short-range Acoustic Networks* (SALSA) project. The available communication stack consisted of the following elements:

- Application layer:
  - GUWAL messages [3]: To actively initiate the NaviPAS module.
  - NaviPAS messages: Intra-swarm communication to gather the propagation time estimates. Packet length is shorter than a GUWAL message.
- Network layer: The GUWMANET® protocol with its cross-layer design approach [1]. GUWMANET® interfaces with the NaviPAS module and enables the module to schedule messages for propagation time estimation using different multiple access schemes (MACs).
- Physical layer:
  - JANUS [4]: Open underwater signaling standard standardized in STANAG 4748.
  - FRSS [5][6]: Proprietary physical layer standard developed during the EDA-SALSA project.

The network used for experiments evaluated in this paper consisted of a total of four heterogeneous acoustic communication nodes. Three of the nodes are equipped with a modem capable of using the physical layer standards *JANUS* and *FRSS*, while the remaining bottom node only supported *FRSS*. All multimodal nodes were equipped with a *NaviPAS* module which is able to schedule messages for propagation time estimation. Acoustic and mobility capabilities of the nodes are summarized in table 1. All four nodes log their GNSS position and depth

Table 1: Overview of acoustic communication and mobility capabilities of all nodes. Mob. stands for mobile and Sub. for fully submerged communication nodes.

		Capabilities			
		JANUS	FRSS	Mob.	Sub.
Nodes	AUV	✓	✓	✓	✓
	Gateway 1	✓	✓	✓	✗
	Gateway 2	✓	✓	✓	✗
	Bottom node	✗	✓	✗	✓

internally and are equipped with local clocks which are not synchronized.

JANUS is an open and simple underwater signaling standard designed by the NATO Centre for Maritime Research and Experimentation (CMRE) [4][7]. The standardized modulation scheme is Frequency-Hopped Binary Frequency-Shift Keying (FH-BFSK), which allows for simple transmitter and receiver implementations [8]. For channel coding, a convolutional encoder of rate $r = 0.5$ is used, enabling robust communication even in harsh channel environments. FRSS stands for Frequency-Repetition Spread Spectrum which is the transmission technique of a proprietary physical layer standard developed during the EDA-SALSA project.

The used frequency band 4 kHz – 8 kHz of the FRSS scheme is larger than the used JANUS band B: 4.96 kHz – 7.04 kHz. The packet duration of a packet containing 128 bit is $T_{FRSS} = 1.42\,\mathrm{s}$ while a baseline JANUS message with 64 bit has a duration of $T_{JANUS} = 2.2\,\mathrm{s}$. Since both GUWMANET® and the NaviPAS module are designed to be flexible with regards to the physical layer standard, all procedures of the NaviPAS module—i.e., the propagation time estimation and message scheduling—are intended to function independently of the used physical layer standard. Differences in propagation time estimation accuracy and varying robustness against environmental noise are expected as well as permitted due to the different bandwidths of the physical layer standards.

GUWMANET® is designed to enable network communication between nodes without a direct link via multi-hop messages. Network routes are established using a restricted flooding algorithm and yield an *enlarged route corridor* in which neighboring nodes forward messages if the previously designated route fails to route a message [1]. Routes are adapted as soon as the network topology changes, provided that a neighboring node observes a mismatch between the expected and actual routing behavior. During the REPMUS exercise, all network nodes had a direct link to one another. Additionally, all nodes maintained a line-of-sight (LOS) connection.

The Generic Underwater Application Language (GUWAL) [3] message is used to initiate the NaviPAS module, triggering propagation time estimation to another node via a selected physical layer standard. NaviPAS messages are primarily used for intra-swarm acoustic communication. NaviPAS payloads are 34 bit long, allowing them to fit within the application data block of a JANUS baseline message. As NaviPAS messages are always navigation-related, they assume a direct link between sender and receiver, without intermediate relay nodes.

Propagation Time Estimation

Collaborative navigation of a swarm of vehicles requires the topology estimation, i.e. the relative coordinates of all vehicles in the swarm, to be locally available at each individual vehicle. A network $\mathcal{N} = \{N_1, N_2, ..., N_M\}$ consisting of $M = |\mathcal{N}|$ nodes generates the propagation time estimate matrix $\mathbf{T} \in \mathbb{R}^{M\times M}$, where the elements $\hat{t}_{i,j} = 0$ for $i = j$ and $\hat{t}_{i,j} = \hat{t}_{j,i} \neq 0$ for $i \neq j$ denote the estimated propagation times between nodes N_i and N_j. Each individual propagation time estimate during the REPMUS experiments, is generated by performing double-sided two-way ranging (DS-TWR) [9]. DS-TWR is a ranging method which measures the round-trip time between two communication nodes in unsynchronous networks as shown in Figure 1. The locally measured round-trip time for the active communication nodes N_1 and node N_2 amounts to the difference of the receive time of the response message to the transmit time of the initiation message for the node which initiates the DS-TWR process: $T^{(1)}_{rtt,12} = t^{(1)}_{Rx,Resp.} - t^{(1)}_{Tx,Init.}$. Since the round-trip time $T^{(1)}_{rtt,12}$ is estimated using the local oscillator of node N_1, no prior synchronization between nodes is required. The propagation time estimate is calculated as $\hat{t}_{1,2} = \frac{T^{(1)}_{rtt,12} - T_{p,2}}{2}$, where $T_{p,2}$ is the processing time of node N_2 and is transmitted within the response message from node N_2. Similarly, the locally measured round-trip time for node N_2 amounts to $T^{(2)}_{rtt,21} = t^{(2)}_{Rx,Fin} - t^{(2)}_{Tx,Resp}$ and is likewise only measured using the local clock $t^{(2)}$. A third, passive node N_3 can infer the propagation time between N_1 and N_2 by tracking the receive time estimates $t^{(3)}_{Rx,Init.}$ and $t^{(3)}_{Rx,Fin.}$. The calculation of the propagation time $\hat{t}_{1,2} = t^{(3)}_{Rx,Fin.} - t^{(3)}_{Rx,Init.} - T_{p,1} - T_{p,2}$ requires either an unencrypted communication or prior encryption key exchange within the network, since the processing times are encoded in the response messages. The blue arrows in figure 1 illustrate the passive propagation time estimation by node N_3. The NaviPAS module automatically schedules DS-TWR messages and calculates a propagation time matrix locally whenever a new NaviPAS message is received. Since the NaviPAS module is designed to be flexible regarding the physical layer standard, transmitted information such as the processing time $T_{p,i}$ has to be highly quantized to fit into the smallest supported application data block. Additionally, the processing time $T_{p,i}$ has to be long enough to allow for accurately timed transmissions. In practice, acoustic modems operate in half-duplex mode, and switching between transmission and reception depends on the modem used and the physical layer standard [11].

Topology Estimation

For the relative topology estimation, the estimated propagation time matrix $\mathbf{T}$ is used to generate the relative positions of all nodes using *Multidimensional Scaling*

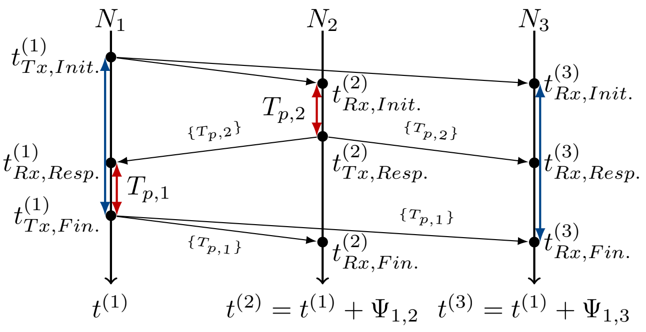

Figure 1: Time diagram of double-sided two-way ranging (DS-TWR). All nodes are able to measure the round-trip time without prior clock synchronization.

(MDS) [10]. MDS is a technique for reducing the dimensionality of a dataset while preserving the pairwise distances between data points. To estimate topology in Euclidean space, the MDS algorithm can be directly applied to the estimated propagation time matrix $\mathbf{T}$ to determine the relative positions of all nodes in the network. The MDS algorithm can be applied even when the estimated propagation time matrix $\mathbf{T}$ is corrupted by noise or incomplete, as demonstrated in [10]. Algorithm 1 presents the classical MDS algorithm used for the localization which assumes a complete Euclidean distance matrix is present.

Algorithm 1 Classical Multidimensional Scaling

```
Input: $\mathbf{T} \in \mathbb{R}^{M \times M}$                ▷ Prop. time matrix
Output: $\mathbf{P} \in \mathbb{R}^{M \times d}$                    ▷ Position est.
  function MDS($\mathbf{T}$, $d$)              ▷ $d$ dim. of output space
    $\mathbf{J} \leftarrow \mathbf{I} - \frac{1}{M}\mathbf{1}\mathbf{1}^\top$               ▷ Geometric centering
    $\mathbf{G} \leftarrow -\frac{1}{2}\mathbf{J}\mathbf{T}\mathbf{J}$                        ▷ Gram matrix
    $\mathbf{U}, \mathbf{\Lambda} \leftarrow \mathrm{EVD}(\mathbf{G})$                ▷ Eigenvalue decomp.
    $\mathbf{P} \leftarrow \mathbf{U}_d \mathbf{\Lambda}_d^{\frac{1}{2}}$
    return $\mathbf{P}$
  end function
```

Classical MDS was applied to the data gathered during the REPMUS exercise. The calculated relative positions of the nodes are not directly comparable to the GNSS positions, as the MDS embedding, $\mathrm{MDS} : \mathbb{R}^{M \times M} \to \mathbb{R}^{M \times d}$, may be subject to translation, rotation, or reflection relative to the GNSS coordinates. To evaluate the embedding, pairwise distances between the estimated positions are calculated and compared to those between the GNSS positions. To convert the propagation times $\mathbf{T}$ to Euclidean distances in space $\mathbf{D} = c_0 \cdot \mathbf{T}$, a speed of sound estimate c_0 is aquired by the sound velocity probe of the AUV.

Field Experiments

The REPMUS exercise was conducted in the Atlantic Ocean near the coast of Portugal. The communication nodes were spaced up to 1,000 m apart. The nodes were deployed in a line-of-sight (LOS) configuration. The GNSS positions of the Gateway 1 and Gateway 2 nodes were continuously monitored, as the nodes were moving on the water surface. The AUV tracked its GNSS position using dead reckoning assisted by a built-in DVL, thus providing an estimate of its position as well. The Bottom node's coordinates were captured during deployment at the surface, but they are subject to errors, as underwater currents can move the Bottom node while sinking. A rule of thumb is that the Bottom node is off by 1 m for every 10 m of depth. The Bottom node's depth was $d_B = 110\,\mathrm{m}$. The estimated GNSS coordinates of the nodes are shown in figure 2 as red dots. Since the propagation time estimates are calculated by the NaviPAS module, which interfaces with the built-in acoustic modems, the accuracy of the time estimates is limited by the resolution of the receive time of the acoustic modems. At the time of the REPMUS exercise, the acoustic modems had a resolution of 1 ms, meaning the resolution in space is 1.5 m, given a speed of sound of $c_0 = 1,500\,\mathrm{m/s}$. Given multiple measurements between two stationary nodes, N_1 and N_2, which are 300 m apart, the propagation time estimate $\hat{t}_{1,2} = \frac{\hat{d}_{1,2}}{c_0}$ has a mean error of $\mu_e = 5.34\,\mathrm{ms}$ and a standard deviation of $\sigma_e = 3.72\,\mathrm{ms}$ when compared to the GNSS positions using the speed of sound estimates c_0 gathered by the AUV. c_0 was in the range of $1,505 - 1,517\,\mathrm{m/s}$. As expected, the propagation time estimates $\hat{t}_{1,2}$ and $\hat{t}_{2,1}$ exhibit strong reciprocity. The mean timing difference observed by the acoustic modem is $\mu_t = 0.5\,\mathrm{ms}$, with a standard deviation of $\sigma_t = 1.25\,\mathrm{ms}$.

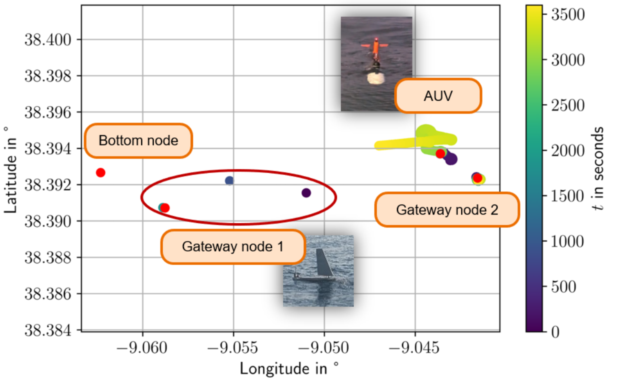

Figure 2: True GNSS positions of the nodes over time. The red dots depict the GNSS positions of the nodes during the propagation time estimation.

Figure 2 shows the true GNSS positions of the nodes over time. The AUV can be identified by its continuous movement trajectory in the northeast of the operating region. The Gateway 1 and Gateway 2 nodes log their GNSS positions at 15-minute intervals. It can be observed that Gateway 2 was almost stationary to the southeast of the AUV trajectory. Gateway 1 was moving westward, but remained stationary once the NaviPAS experiments were conducted. The stationary Bottom node is the westernmost of the nodes.

The propagation time estimates were initiated by sending GUWAL messages via LTE from a ship to the gateway buoys. Subsequently, the NaviPAS module scheduled the propagation time estimation messages to create the propagation time matrix $\mathbf{T}$. During the experiments, the NaviPAS module required a GUWAL message to initiate each distance estimation. Since only the gateway buoys had a LTE link, all propagation time estimates, except for the estimate between the Bottom node and the AUV, could be gathered this way. This single propagation time estimate was simulated using the previously calculated propagation time estimation statistics. Applying the introduced MDS algorithm to the estimated propagation time matrix $\mathbf{T}$, the relative positions of the nodes were calculated. The calculated relative positions are shown in Figure 3 as blue dots. The mean absolute error in distance resulting from the calculated relative positions $\mathbf{P}$, compared to the GNSS positions, is $\mu_{\mathbf{P}} = 7.83\,\mathrm{m}$, with a standard deviation of $\sigma_{\mathbf{P}} = 6.12\,\mathrm{m}$. The relative error $\epsilon_{\mathbf{P}}$ is calculated as $\epsilon_{\mathbf{P}} = \frac{\|\mathbf{T}-\mathbf{T}_{\text{true}}\|_F}{\|\mathbf{T}_{\text{true}}\|_F}$, where $\|\cdot\|_F$ denotes the Frobenius norm. Normalized to the propagation time matrix calculated from the GNSS coordinates, the relative error $\epsilon_{\mathbf{P}} = 8.77\,‰$. The resulting topology is subject to translation, rotation, and reflection ambiguities compared to the GNSS positions in Figure 2. Without extrinsic information, the NaviPAS module cannot resolve these ambiguities.

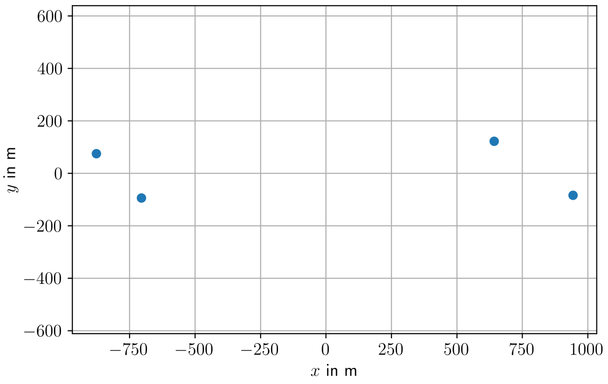

Figure 3: Estimated relative positions of the nodes. The resulting topology is subject to translation, rotation and reflection ambiguities compared to the GNSS positions.

Regarding navigation, the calculated relative position errors must be considered alongside the nodes' movement velocity and the interval in which new position estimates are generated. Gathering the complete propagation time matrix $\mathbf{T}$ took approximately 2 minutes, triggered by manual GUWAL commands to the NaviPAS module. Allowing the NaviPAS module to schedule the propagation time estimation messages automatically in a round-robin fashion enables the propagation time matrix $\mathbf{T}$ to be gathered slightly faster in simulations — though prior knowledge of the communication nodes within range is required. Much more time can be saved if the initial TWR messages are interpreted as a broadcast to all nodes, with each node scheduling its response in a Time Division Multiple Access (TDMA) scheme [12]. With this approach, the number of acoustic messages is reduced from $3 \cdot \frac{M^2-M}{2}$ to $2 \cdot \frac{M^2-M}{2} + 1$ messages. This approach was implemented in the NaviPAS module and verified through simulations.

Conclusion

The experiments during REPMUS 2024 have shown that the GUWMANET® protocol can be extended to provide relative positioning information using acoustic communication and two-way ranging. Multidimensional Scaling (MDS) was extended to incorporate extrinsic information, such as the known depths of the nodes. The estimated propagation times and distances were compared to the actual distances between the nodes, allowing for the derivation of the propagation time estimation distribution.

Future work will focus on resolving the ambiguities in the relative positions and the topology estimation without requiring a complete propagation time matrix. The experiments have shown that, due to the multiple access schemes of the physical layer standards, the propagation time measurement take a significant amount of time. Thus, extending one of the physical layer standards to support a Frequency Division Multiple Access (FDMA) scheme or Code Division Multiple Access (CDMA) scheme could be beneficial and should be further investigated [13].

Furthermore, the resolution of the modem times reported to the NaviPAS module should be improved to enhance the accuracy of propagation time estimates and consequently, the relative position determination.

References

[1] (2014), 1-4 M. Goetz, I. Nissen: GUWMANET - Multicast routing in Underwater Acoustic Networks. Military Communications and Information Systems Conference (MCC), 2012.

[2] ISO/IEC: Information Technology - Open Systems Interconnection - Basic Reference Model: The Basic Model. ISO/IEC 7498-1:1994, 1994.

[3] Nissen, Ivor and Goetz, Michael: Generic Underwater Application Language (GUWAL). Final Demonstration, La Spezia.

[4] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen and K. McCoy: The JANUS Underwater Communications Standard. Underwater Communications and Networking (UComms), 2014, 1-4.

[5] P. van Walree, H. Buen and R. Otnes: A performance comparison between DSSS, M-FSK, and frequency-division multiplexing in underwater acoustic channels. Underwater Communications and Networking (UComms), 2014, 1-5.

[6] H. S. Dol, P. Casari, T. van der Zwan and R. Otnes: Software-Defined Underwater Acoustic Modems: Historical Review and the NILUS Approach. IEEE Journal of Oceanic Engineering, vol. 42, 2017, 722-737.

[7] NATO Standardization Office (NSO): Digital Underwater Signalling Standard for Network Node Discovery & Interoperability. ANEP-87 Ed: A Ver. 2, 2024.

[8] J. Alves et al.: Underwater communications research and development at CMRE. OCEANS, 2015, 1-7

[9] Wang, Anyi and Song, Yang: Improved SDS-TWR Ranging Technology in UWB Positioning. International Conference on Sensor Networks and Signal Processing 2018, 222-225.

[10] I. Dokmanic, R. Parhizkar, J. Ranieri and M. Vetterli: Euclidean Distance Matrices: Essential theory, algorithms, and applications. IEEE Signal Processing Magazine, 2015, 12-30.

[11] Y. Hsieh, Z. Qi and D. Pompili: Full-duplex underwater acoustic communications via self-interference cancellation in space. Journal of Communications and Networks (JCN), vol. 25, 2023, 167-181.

[12] F. Despaux, A. van den Bossche, K. Jaffrss-Runser, T. Val: N-TWR: An accurate time-of-flight-based N-ary ranging protocol for Ultra-Wide band. Ad Hoc Networks, vol. 79, 2018, 1-19.

[13] Yang, T. C.: Spatially multiplexed CDMA multiuser underwater acoustic communications. IEEE Journal of Oceanic Engineering, vol 41, 2015, 217-231.