Underwater acoustic source localization using a multi-robot system: the DAMPS project

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***Abstract*—This paper presents the funded project DAMPS, that addresses the development of a multi-robot system for the position tracking of noise sources in underwater environment. The robots composing the team collaborate in order to fuse the local information coming from the analysis of a Passive Acoustic Monitoring sensor, with the final aim of estimating the position of a the acoustic source. The team is thus a distributed, modular and reconfigurable sonar system that can be controlled remotely from a Control&Command center. In this paper we highlight the functional architecture that will be implemented within the project, the possible algorithmic approaches to be employed within the submodules and possible application scenarios.**

***Index Terms*—underwater acoustic source localization, acoustic communication, multi-robot control**

I. INTRODUCTION

Underwater acoustic source localization is used in many underwater applications such as tracking marine mammals [1], search&rescue operations [2], off-shore exploration tactical surveillance [3], oceanographic data collection and pollution monitoring [4]. Underwater localization of a noise source is a challenging task due to technological and environmental constraints. Acoustic sensors inevitably face unpredictable and frequency-dependent attenuation, time-varying multipath effects, large Doppler and delay spreads, and limited bandwidth. Existing underwater acoustic systems for source localization rely on PAM (Passive Acoustic Monitoring) sensors which can provide the source bearing, but not the range. Combining bearing estimations coming from multiple sensors placed in different locations it is possible to estimate the position of the acoustic source.

Multi-robot systems are usually employed in this kind of tasks and, as the technological maturity level is getting more and more mature in the last years, also in many other ones that benefit from the coordination among multiple robots. Two recent examples are the EU-funded projects WiMUST [5], that aims at developing a system of cooperative autonomous underwater vehicles (AUVs) for geotechnical surveying, and BugWright2 [6], that aims at developing an adaptable autonomous robotic solution for servicing ship outer hulls. However, deploying multiple robots presents challenges in several aspects, such as communication [7], localization [8], perception [9] and coordination [10], that need to be properly addressed adopting specific methodological approaches.

DAMPS (Distributed Autonomous Mobile Passive Sonar system) is a research project co-funded by the italian SEGREDIFESA (Segretariato Generale della Difesa) in the scope of the PNRM (Piano Nazionale della Ricerca Militare). It addresses the development of a multi-robot system for the position tracking of noise source in underwater environment. It has been proposed as a passive, distributed and reconfigurable sonar system, composed by a team of AUV (Autonomous Underwater Vehicles) and distributed detection systems based on local processing of the data coming from PAM sensors and data fusion among the vehicles through a safe underwater communication infrastructure. The team, that navigates in formation, globally constitutes a volumetric sonar with variable geometry, selected depending on the tactic environmental situation by an operator connected from a remote control station. DAMPS is conceived as a system-of-systems: it is a mobile and modular macro-sensor, its reconfigurability optimizes its performances, its modularity makes robust with respect to faults, its mobility makes it compatible with different environments and operational modes. Figure 1 shows a graphical representation of the DAMPS system.

The consortium consists of 3 italian organizations, both industrial and academic. The industrial partners are WSense and GRAAL TECH, while the academic partners are gathered in the interuniversary center ISME, that includes the universities of Genova, Salento, Cassino, Pisa, Roma "La Sapienza" and Firenze. In this paper we describe the functional architecture, the main features that the consortium will implement for the development of the DAMPS system and the envisioned application scenarios.

The paper is organized as follows: Section II describes the functional architecture of the system, analyzing possible methodological approaches that will be investigated during the project; in Sec. III we give an overview of the possible application scenarios in which the DAMPS system can be employed; Section IV presents the conclusions and future works.

II. CONCEPT AND FUNCTIONAL ARCHITECTURE

The DAMPS system is composed of a team of AUVs that collaborate in order to localize a target in underwater environment. The system works in the following way: each AUV composing the team locally processes the signal coming from its PAM sensor, detects a potential target and shares the locally-processed information through the communication system with the other members of the team, initializing an algorithm that allows to fuse the data. This combination of local decision-making and autonomous cooperation in the data fusion terminates with the transmission of the estimated target position to a remote station, where a human operator can integrate such information and reconfigure the system or other potential assets.

In this section we give a top-down description of the system architecture, shown in Fig. 2, considering the following components:

- AUVs architecture;
- communication system;
- Command & Control system (C&C in the following);
- navigation, guidance and mission management system;
- sonar system;

In particular, the Control&Command system, provided with a GUI (Graphical User Interface), makes use of the communication system to control and operate the sonar system, which is composed of a set of AUVs. The communication system offers transmission technologies developed for terrestrial communications, such as WiFi, UHF, 3G/4G and satellite, or through acoustic communication used in underwater domain, using adaptive and dynamic network protocols.

Each one of the AUVs exhibits a functional architecture as in Fig. 3.

The networking framework, being part of the communication system, allows the AUVs to share data and telemetry and, at the same time, to send them to a remote operator. The navigation and mission management system is in charge of the AUV control depending on the environmental feedback and on the data coming from the other AUVs or the operator. Within each vehicle a local sonar system is installed, that is able to detect the target position, thanks to the analysis of the data coming from the PAM sensors and the algorithm that allows the data fusion among multiple vehicles. Each sub-component installed within the AUVs is connected thought ROS (Robotics Operating System) that allows the communication among the modules.

A. Vehicles

From the hardware architecture point of view the generic vehicle composing the DAMPS system has the following requirements:

- reduced weight and size in order to ease the deployment;
- high modularity in terms of payload, allowing to easily change the sensor depending on the specific mission to be accomplished;
- possibility to navigate both as glider and AUV, in order to reduce consumption and noise;
- hovering capability, allowing to keep the team stationary;

B. Communication system

Currently, the only reliable technology for underwater communication that allows to communicate at long distances is acoustics. The usage of different acoustic communication channels, such as commercial acoustic modems, SDMs (Software Defined Modems), allows to offer better performances and to satisfy the network requirements in different application scenarios. The communication system has to be able to interface with modems that work with different bandwidth and frequencies, in order to allow the communication in different application scenarios. The communication system foresees the usage of a networking framework that allows both the terrestrial and underwater communications. The operator will be able to control the system remotely in a *transparent* manner, sending commands, receiving telemetry and alarms via the C&C platform. Additionally, the communication system needs to support data compression, due to the limits imposed by the reduced dimension of the data which is possible to send by the acoustic modems.

C. C&C system

The C&C system provides a single access point to manage and visualize all the data gathered by the DAMPS system. It will be capable of planning and send commands to the AUV network, providing a user-friendly interface controllable by a remote operator. It provides a single interface for all the main features of the DAMPS system and it will be capable of managing all the operation related to the control and the

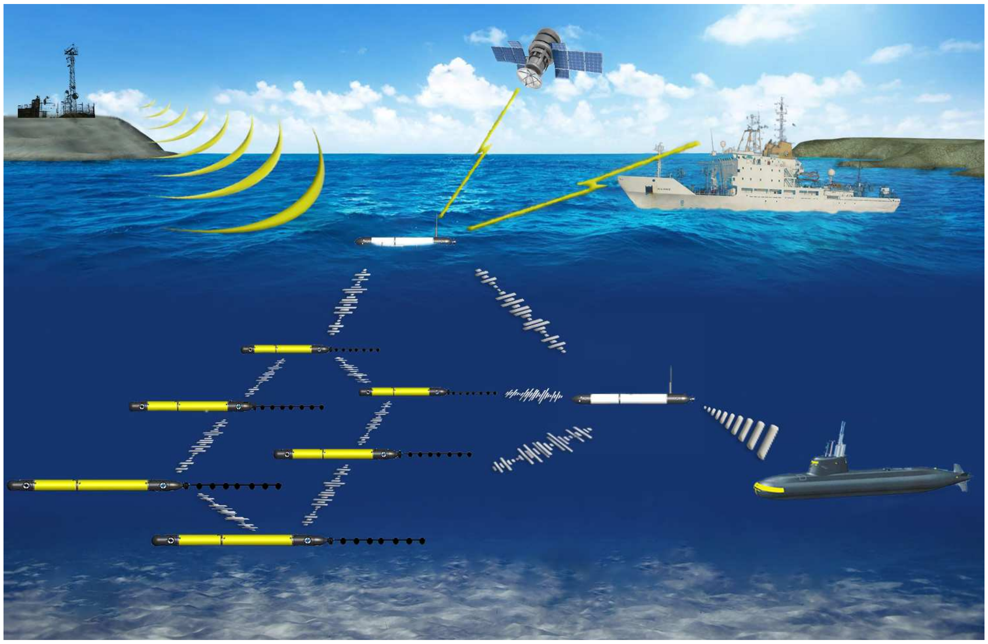

Fig. 1. Graphical representation of the DAMPS system

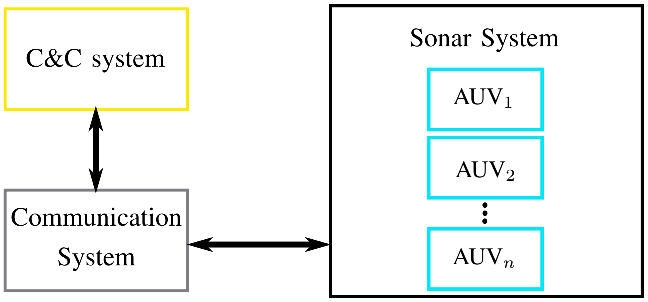

Fig. 2. DAMPS overall functional architecture

planning of the AUVs used in the mission. It is composed by two main components: the back-end and the front-end. The front-end is a web-based graphical interface that allows the interaction between the operator and the system, while the back-end part is in charge of analyzing data and of providing it to the front-end.

D. Navigation system

In order to enable an AUV to navigate in a safe manner it needs to estimate its own pose with respect to a known fixed reference frame. Many techniques can be found in literature for addressing this problem, and they can be grouped into three categories:

- Dead Reckoning: it uses proprioceptive sensors such as accelerometers, gyroscopes and DVL (Doppler Velocity Log) in order to obtain the position and the velocity of the AUV. The position is estimated relying on data-fusion techniques and Bayesian estimators such as KF (Kalman Filter), EKF (Extended Kalman Filter), UKF (Unscented Kalman Filter) [11], PF (Particle Filter) [12];
- Acoustic positioning systems: the techniques lying on this category rely on acoustic devices capable of obtaining ToF (Time of Flight) measurements from beacons or modems. Usually these devices exhibit a low rate of communication and a high communication latency and they do not allow to obtain high-frequency measurements. Common examples of this category are USBL (Ultra-Short Baseline), SBL (Short Baseline), LBL (Long Baseline);
- Geophysics: in this category lie all the techniques that use the external environment to obtain information useful for navigation. Common sensors are cameras, SONARs, echosounders, magnetometers, etc.

E. Guidance

The formation control for the team can be implemented in several ways, varying the level of coordination among the vehicles that compose it. The underwater environment imposes a strict limit in the quantity of data that the AUVs can share, and the distances among the vehicles introduce significant communication delays.

In a first approach, one of the AUVs is chosen as leader of the formation, and it sends periodically its position to the other ones. All the AUVs know their desired position relative to the leader, and the convergence of each vehicle toward its relative position in the formation makes the team move in formation. In this kind of approach the vehicles do not necessarily know the path that the leader will perform, but they will eventually follow it. The approach is simple and scalable, but the presence of a single leader represents a single-point-of-failure. In case

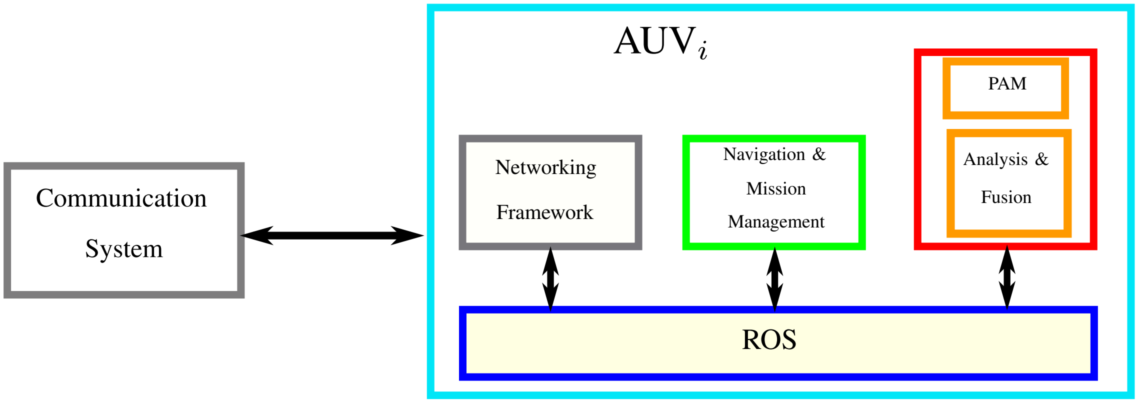

Fig. 3. General AUV functional architecture

of fault of the leader, the team would not know how to proceed within the formation.

In a second approach, all the AUVs know the path to follow and their relative position within the formation. Using a proper temporal parametrization, each vehicle can compute, in a distributed manner, a virtual reference [13]. Also in this case, the convergence of each vehicle toward its relative position in the formation makes the team move in formation.

F. Mission Management

The Mission Management system represents the higher level of decision-making within each AUV. Its goal is to supervise the execution of the mission, coordinating the other subsystems, taking decisions in an autonomous and distributed manner for the execution of particular sub-tasks within the assigned mission. In particular, it will be composed by a software system in which templates of typical missions will be present. These templates can be potentially defined with some user-defined parameters. For instance, in order to perform the maintenance of the requested formation, the guidance and control system needs the output of the navigation system, and the AUV absolute position estimation is characterized by an increasing uncertainty over time if all the AUVs stay underwater. One of the possible missions to be handled by the mission management system is to decide when to request the resurfacing of one of the support AUVs in order to acquire GNSS (Global Navigation Satellite System) localization data and reduce the uncertainty of the position estimation. Another sub-task that is constantly monitored by the mission management system is the communication and the reception of commands from the C&C center. The system decides which AUV has to resurface in order to communicate with the control center and to receive new commands about the mission. For instance, in case the operator decides to change formation, the mission management system spreads the information among the team, making the guidance and control systems bring the team toward the new requested configuration.

G. PAM sensor

The PAM module represents the acoustic sensor installed on each AUV. In the following we present different classes of sensors and we report the main features:

- Vector sensors [14]: 2D vector sensors are able to compute three signals corresponding to the level of an omnidirectional hydrophone and to a pair of orthogonal dipoles. The orientation with respect to the magnetic North is compensated through an integrated compass. The signal on dipoles can be considered as proportional to the particle velocity along the corresponding axis. The processing of 2D AVS signals provides the Direction of Arrival (DoA) of the acoustic source in terms of bearing. 3D AVS can be used to compute also the elevation angle.
- Towed arrays [15]: they are the most used system for the detection of the DoA of an acoustic source. The number of hydrophones and the spacing among them are variable. The performances of the sensor in terms of angular resolution increase together with the number of elements;
- Volumetric arrays: 3D multi-hydrophones configurations that can be installed on AUVs or gliders [16]. They have apertures in all three spatial dimensions since they can form beams in any direction in bearing and elevation.

H. Local analysis and data fusion

The local analysis module receives in input the raw data from the PAM sensor. It performs the data computation in order to compute the DoA of potential signals, performs a comparison of the intensity of the signal corresponding to such DoA with a predefined threshold value and, if the intensity is higher than the threshold, it gives in output a signal reporting the estimated DoA. The analysis of the raw data depends on the specific PAM sensor taken into account. Regarding towed arrays it is estimated via a beamforming procedure. In literature it is possible to find three algorithms:

- Sum and Delay Beamformer [17];
- Subband Phase Shift Beamformer;
- Frost Beamformer [18].

The goal of the sonar system is to estimate the state of a target, intended as the position with respect to an inertial frame, using the angular measurements in output from the local analysis module. This kind of problems is known in literature as Bearing-Only-Tracking (BOT). Given the lack of information about the distance between the AUV and the target, its state is not fully observable from a single AUV. For this reason it is necessary to implement distributed estimation algorithms in which multiple AUVs share the respective local information.

It is possible to differentiate between two different kind of approaches depending on the type information that the AUVs communicate among them:

- Estimate and Share [19];
- Share and Estimate [20].

In the *Estimate and Share* approach, each AUV estimates the state of the target using its local estimation of the DoA and the estimation of its position. The estimation of each vehicle, which is related to the observable component of the state of the target using only local information, is sent through the communication system and it is used by the other AUVs for optimizing their estimations. In the literature there are many techniques to be used for the fusion of estimations coming from different nodes in a network.

In the *Share and Estimate* approach, each AUV estimates the state of the target using its local estimation of the DoA and of its position, but also the estimation of the DoA and the positions of the other AUVs. In this case each AUV estimates the state of the target and sends through the communication system the information relative to the readings of its PAM sensor and its position.

In both the approaches the estimation of the state of the target is obtained with algorithms such as pseudo linear regression, Extended Kalman Filters or Particle Filters.

III. APPLICATION SCENARIOS

Possible application scenarios in which the DAMPS system will be validated include ASW (Anti-Submarine Warfare) operations and passive monitoring of marine mammals.

Given that the characteristics of the generic scenarios in terms of ranges and frequencies are wide, all the technical choices will be better specified depending on the PAM sensors, the communication and the localization systems and on the relative influence among each other in terms of performances. Regarding the specific application scenarios, it is possible to identify [21]:

- Hold at risk;
- Sea shield;
- Mammals monitoring.

A graphical representation of the scenarios is provided in Fig 4.

In the *Hold at risk* scenario the system patrols an access zone and the C&C station is placed onshore in a fixed position. The requested patrolling velocity is low, with the possibility to have a static system.

In the *Sea shield* scenario the DAMPS the C&C center is placed onboard a HVU (High-Value Unit) and the patrolling velocity of the system is arbitrary.

In the *Mammals monitoring* scenario the system can be stationary, and C&C station can potentially be anywhere.

IV. CONCLUSIONS

In this paper we have presented the main features of the DAMPS project, that addresses the development of a multi-robot system for position tracking of a noise source in the underwater environment. The overall concept and the functional architecture that will be implemented within the project has been outlined. All the submodules and the relations among them have been described, highlighting the required features and possible algorithmic approaches that can be adopted to design the system.

Future works will concern the implementation of all the submodules and the validation of the entire system through numerical simulations in order to evaluate the impact of the chosen algorithms on its performances. The following phase foresees the experimental validation in a realistic scenario at sea.

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REFERENCES

[1] V. Schmidt, T. C. Weber, D. N. Wiley, and M. P. Johnson, “Underwater tracking of humpback whales (megaptera novaeangliae) with high-frequency pingers and acoustic recording tags,” *IEEE Journal of Oceanic Engineering*, vol. 35, no. 4, pp. 821–836, 2010.

[2] L. D. Stone, C. M. Keller, T. M. Kratzke, and J. P. Strumpfer, “Search analysis for the underwater wreckage of air france flight 447,” in *14th International Conference on Information Fusion*. IEEE, 2011, pp. 1–8.

[3] E. Cayirci, H. Tezcan, Y. Dogan, and V. Coskun, “Wireless sensor networks for underwater survelliance systems,” *Ad hoc networks*, vol. 4, no. 4, pp. 431–446, 2006.

[4] D. Shin, S. Y. Na, J. Y. Kim, and S.-J. Baek, “Fish robots for water pollution monitoring using ubiquitous sensor networks with sonar localization,” in *2007 International Conference on Convergence Information Technology (ICCIT 2007)*. IEEE, 2007, pp. 1298–1303.

[5] P. Abreu, G. Antonelli, F. Arrichiello, A. Caffaz, A. Caiti, G. Casalino, N. C. Volpi, I. B. De Jong, D. De Palma, H. Duarte *et al.*, “Widely scalable mobile underwater sonar technology: An overview of the H2020 WiMUST project,” *Marine Technology Society Journal*, vol. 50, no. 4, pp. 42–53, 2016.

[6] “BugWright2 website,” https://www.bugwright2.eu/, accessed: 2021-09-01.

[7] R. Manjula and S. S. Manvi, “Issues in underwater acoustic sensor networks,” *International Journal of Computer and Electrical Engineering*, vol. 3, no. 1, p. 101, 2011.

[8] T. Halsted and M. Schwager, “Distributed multi-robot localization from acoustic pulses using euclidean distance geometry,” in *2017 International Symposium on Multi-Robot and Multi-Agent Systems (MRS)*. IEEE, 2017, pp. 104–111.

[9] M. Pfingsthorn, A. Birk, and H. Bülow, “An efficient strategy for data exchange in multi-robot mapping under underwater communication constraints,” in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010, pp. 4886–4893.

[10] J. P. Queralta, J. Taipalmaa, B. C. Pullinen, V. K. Sarker, T. N. Gia, H. Tenhunen, M. Gabbouj, J. Raitoharju, and T. Westerlund, “Collaborative multi-robot search and rescue: Planning, coordination, perception, and active vision,” *IEEE Access*, vol. 8, pp. 191 617–191 643, 2020.

[11] B. Allotta, A. Caiti, R. Costanzi, F. Fanelli, D. Fenucci, E. Meli, and A. Ridolfi, “A new AUV navigation system exploiting unscented kalman filter,” *Ocean Engineering*, vol. 113, pp. 121–132, 2016.

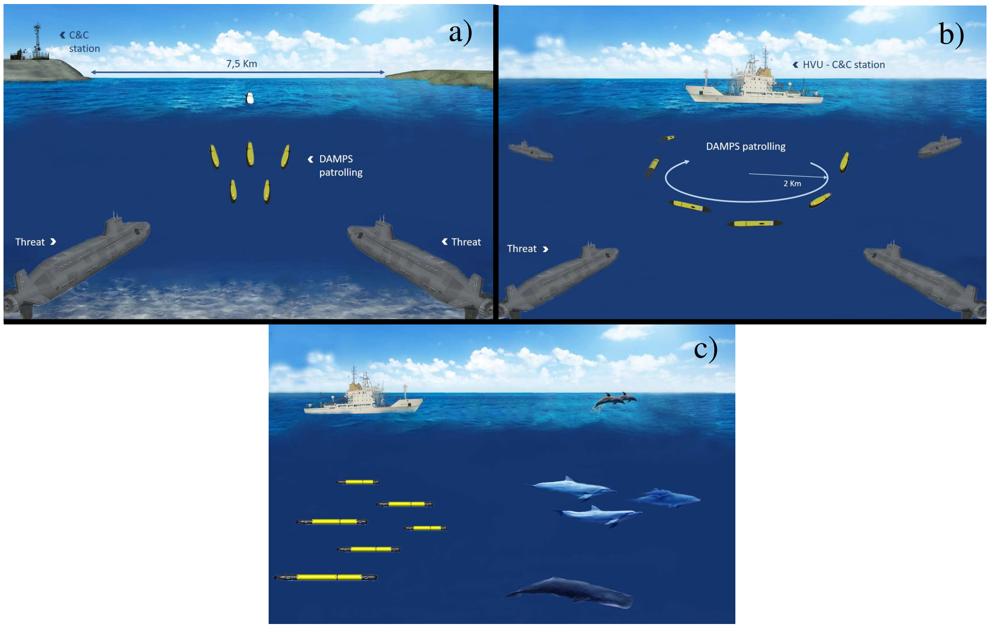

Fig. 4. Graphical representations of: a) Hold at risk, b) Sea shield, c) Mammals monitoring

[12] F. Maurelli, S. Krupinski, Y. Petillot, and J. Salvi, “A particle filter approach for AUV localization,” in *OCEANS 2008*. IEEE, 2008, pp. 1–7.

[13] F. Vanni, A. P. Aguiar, and A. M. Pascoal, “Cooperative path-following of underactuated autonomous marine vehicles with logic-based communication,” *IFAC Proceedings Volumes*, vol. 41, no. 1, pp. 107–112, 2008.

[14] A. Nehorai and E. Paldi, “Acoustic vector-sensor array processing,” *IEEE Transactions on signal processing*, vol. 42, no. 9, pp. 2481–2491, 1994.

[15] G. Edelson and D. Tufts, “On the ability to estimate narrow-band signal parameters using towed arrays,” *IEEE Journal of Oceanic Engineering*, vol. 17, no. 1, pp. 48–61, 1992.

[16] J. Gebbie, M. Siderius, P. L. Nielsen, and J. Miller, “Passive localization of noise-producing targets using a compact volumetric array,” *The Journal of the Acoustical Society of America*, vol. 136, no. 1, pp. 80–89, 2014.

[17] T. Yardibi, C. Bahr, N. Zawodny, F. Liu, L. Cattafesta III, and J. Li, “Uncertainty analysis of the standard delay-and-sum beamformer and array calibration,” *Journal of Sound and Vibration*, vol. 329, no. 13, pp. 2654–2682, 2010.

[18] B. Deepa, V. J. Joseph, D. S. Bhai, and A. A. Varghese, “Time domain adaptive beamformer for sonar signal processing,” in *2013 Third International Conference on Advances in Computing and Communications*. IEEE, 2013, pp. 145–148.

[19] K. Ho and Y.-T. Chan, “An asymptotically unbiased estimator for bearings-only and Doppler-bearing target motion analysis,” *IEEE Transactions on Signal Processing*, vol. 54, no. 3, pp. 809–822, 2006.

[20] S. Radtke, K. Li, B. Noack, and U. D. Hanebeck, “Comparative study of track-to-track fusion methods for cooperative tracking with bearings-only measurements,” in *2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS)*. IEEE, 2019, pp. 236–241.

[21] E. McCutcheon, M. T. Haggett, and A. E. UK, “Counting the ASW calories: Maximising sonar performance under weight and size constraints,” 2019.