Selected System Aspects for the Design of SONAR Nodes in a Multistatic Surveillance Network

Marco Driesen[1], Frederik Kühne[1], Karoline Gussow[1], Bastian Kaulen[1],
Christian Kanarski[1], Finn Röhrdanz[1], Konstantinos Karatziotis[1], Lukas Schirmer[1], Ralf Burgardt[1],
Viktoriia Boichenko[1], Erik Mackensen[2], Dirk Meyners[2], Eckhard Quandt[2], Gerhard Schmidt[1]
[1] *Chair of Digital Signal Processing and System Theory, 24143 Kiel, Germany,*
Email: {madr, frk, kars, bk, chk, finr, koka, lusc, rabu, vib, gus}@tf.uni-kiel.de
[2] *Inorganic Functional Materials, 24143 Kiel, Germany, Email: {erm, dm, eq}@tf.uni-kiel.de*

Abstract

Monitoring maritime infrastructures has become increasingly important due to recent events. SONAR systems are primarily used for this purpose in the underwater sector, especially multistatic SONAR networks. The design of such networks, particularly developing a single system within this network, is highly complex and multi-layered. Therefore, this study provides a comprehensive overview of all relevant aspects of such a single system. For a structured analysis, the concept is divided into the three central domains of hardware, signal processing, and network integration and discussed based on these.

Multistatic MIMO-SONAR Systems

The protection of maritime infrastructure has become increasingly important in recent years. Existing surveillance technology, particularly in the underwater area, is still underdeveloped, emphasizing the need for new, innovative systems. Underwater surveillance is predominantly carried out using SONAR systems, with traditional approaches usually operating monostatically according to the SIMO principle. In this case, the transmitter and receiver are located at the same position, and spatial signal processing is only possible with multiple receiving elements. A promising alternative are multistatic SONAR networks (MSN) combined with MIMO technology [1]. These are based on networks of separate transmitter and receiver nodes that improve the resolution and detection rate in the surveillance area. They also enable more cost-effective surveillance, as a single transmitter can serve multiple receivers. Another advantage of MSNs is that the receiver positions remain unknown to intruders, making it significantly more difficult for them to enter the area undetected [2].

Despite these advantages, an MSN entails considerably greater complexity. While monostatic systems process all relevant data directly at a central location, separating transmitter and receiver nodes in MSNs requires precise synchronization for a correct fusion of measurement data from different sensor pairs. MSN complexity can be viewed from two perspectives: the overall system and the individual nodes. The overall system encompasses all participating components as well as the deployment environment, while a single node can be, for example, a monostatic sensor with a transmit and receive aperture or a single hydrophone. This paper focuses on the conception of a single system, while the overall system is only considered marginally.

Overall System

Numerous adjustable parameters are involved in designing the overall system, including the type and number of nodes, their placement or movement patterns, and their coordination with each other. These parameters can be optimized for various target criteria, such as maximum spatial coverage or high-resolution monitoring of a specific area. Since a detailed analysis of these aspects falls more into the realm of operations research, they will not be discussed further in this paper.

Single System

The architecture of a single system is complex and comprises numerous aspects, which can essentially be divided into three categories: hardware, signal processing, and network integration. Figure 1 shows an overview that combines the three central domains.

Hardware Considerations

To operate a multistatic SONAR network, various devices capable of transmitting and receiving the corresponding signals are required. In the field of maritime infrastructure, devices such as sonar buoys, fixed arrays, and autonomous underwater vehicles (AUVs) are particularly suitable for continuous monitoring.

Body

The maritime environment is highly complex, as numerous influencing factors determine it. Waves and currents, which in turn depend on the weather, influence the positioning of the systems. Accordingly, static systems must be fixed or kept in a stable position, while dynamic systems such as AUVs require suitable propulsion concepts. Systems such as sonobuoys, whose main body floats on the water surface and is therefore directly exposed to the waves, should also be designed so that their transducers are decoupled from these movements as far as possible. Furthermore, all water-sensitive components, especially the electronics, must be ensured to be reliably protected from water ingress. The greater the operating depth, the more demanding the sealing needs to be. The choice of material also plays a decisive role, as operation occurs predominantly in salt water – an extremely corrosive environment for many materials. In addition, the positioning of the communication hardware should be chosen

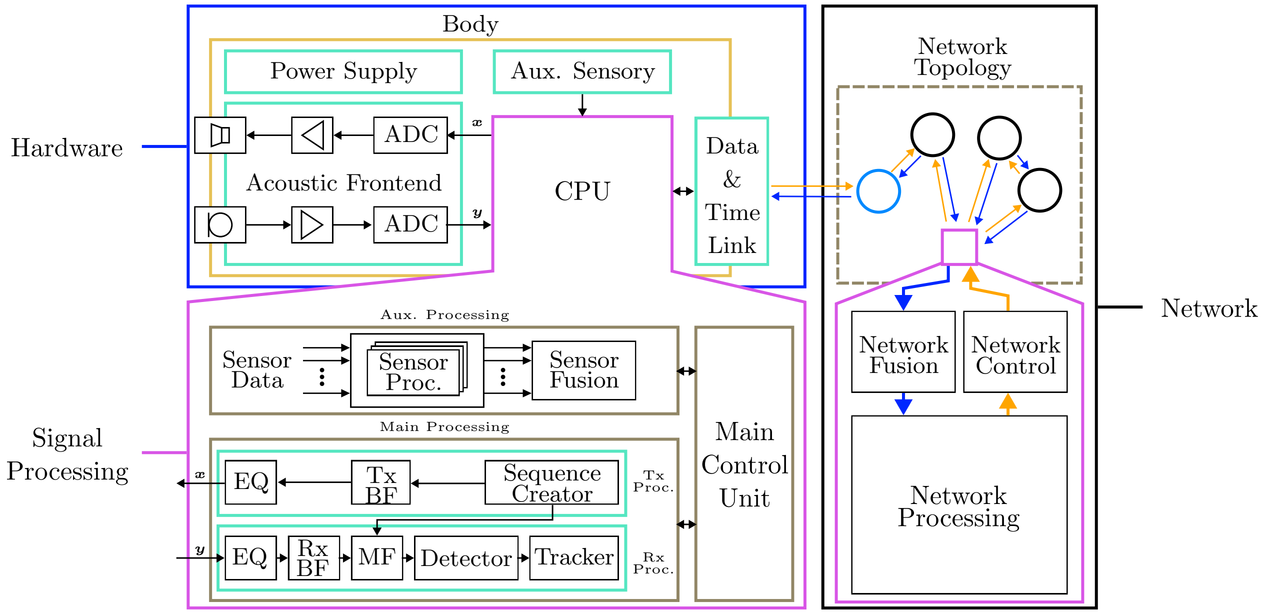

Figure 1: Overview of all domains of a single system in an MSN.

carefully. For wireless radio communication, it is advisable to position the antennas above the water's surface as far as possible for emerged systems and to adjust their alignment to the directional characteristics to ensure a stable connection.

Localization

In order to integrate the individual subsystems into the overall system, precise position information is required, depending on the configuration. GPS receivers can be used for systems with at least partial or temporary access to the water surface to determine the global position. However, depending on the environment, GPS cannot be available at all, is subject to considerable inaccuracies, or can be manipulated by third parties. Therefore, data fusion with additional sensors, such as inertial measurement units (IMUs) and Doppler velocity logs (DVLs), utilizing estimation methods is useful to increase positioning accuracy. While IMUs provide relative motion data, DVLs offer velocity measurements relative to the seafloor, significantly improving dead reckoning navigation, especially in GPS-denied environments.
Particular attention must be paid to the fact that the positions of the transducer apparatus are crucial for integration, which is why the corresponding sensors should also be accommodated there. Orientation is not critical for omnidirectional transducers or arrays without spatial signal processing. However, if the transducers have spatial dependencies in terms of sensitivity or if arrays are used for beamforming or similar methods, the orientation in the azimuth angle is critical.

Signal Path

A central component of a SONAR system is the transmit and receive path, which must guarantee high signal integrity. A digital-to-analogue converter, a suitable power amplifier, and corresponding projectors are required for transmission. In contrast, hydrophones adapted preamplification, and an analog-to-digital converter is required on the receiving end. It is important that the noise and the maximum signal level of the preliminary stage are lower or higher in the signal path direction than the downstream components. Furthermore, all stages must cover the desired frequency range and may only distort to an extent that can be compensated. When selecting cables and connectors, care should be taken to ensure they are not exposed to additional external noise sources. Transmission is susceptible to interference at low signal levels. Only careful consideration of all these aspects ensures that the system achieves an optimal signal-to-noise ratio and thus guarantees reliable and precise data transmission.

Control and processing unit

A control unit that manages, processes, and forwards the recorded data is also essential. Depending on the requirements in terms of computing power, energy consumption, and latency, various hardware platforms can be considered, including microcontrollers, FPGAs, or mini PCs. The decisive factor is that the computing capacity is sufficient to carry out the required processing steps directly on board in real-time without placing an excessive load on the available energy source in the event of a self-sufficient supply. The choice of a suitable platform, therefore, depends on the complexity of the signal processing, the real-time requirements, and the available energy.

Communication interface

Suitable communications hardware is required to transmit data. For this, it must be determined in advance which transmission channel and data rates will be used and what range the communications interface must be able to cover. Possible options include wireless transmission using radio technology or acoustic underwater communication. The antenna or acoustic front end, as well as their directional characteristics, determine the range and radiation direction of the transmission. Depending on the application, omnidirectional antennas are useful for uniform coverage, and directional antennas are better for focused signal transmission with a longer range. Furthermore, for energy-autonomous systems, particular attention must be paid to the efficiency of the hardware used.

Power supply system

The electronic components installed require different power supplies, whereby the sensors, in particular, should be supplied via high-quality power supply units in order to avoid interference from mains noise or voltage converters. If the system is not connected to the mains voltage, it also requires a self-sufficient power supply. Space restrictions, weight limits, and the planned duration of use are key criteria when selecting the energy source. Lithium-ion batteries are particularly suitable due to their high energy density and low mass. Marine-grade solar panels can also be integrated to extend the runtime, provided the system has regular access to the water surface. Efficient power management, in combination with intelligent load management, is essential to minimize energy consumption. Components that are not required should be switched to energy-saving states. For example, computationally intensive signal processing can be optimized using time-out mechanisms by automatically deactivating the main processing chain if no relevant signal is detected for a defined period of time.

Signal Processing Architecture

The processing of the data to be sent or received can be divided into the main processing, in which the actual SONAR processing takes place, and an auxiliary processing, which determines the required additional information.

Main Processing

Equalization

On both the transmit and receive sides, the characteristics of all components in the signal path must first be equalized. This includes all the steps previously described in the hardware section. If only a specific frequency range is used, the incoming signals can be passed through a bandpass filter, so that equalization ideally only needs to be performed in the desired band.

Beamforming

After equalizing the hardware stages, beamforming (BF) follows, and the type and resolution depend primarily on the acoustic front end. In monostatic systems, high angular resolution depends primarily on a large number of transducer elements. While this also applies to individual multistatic sensor pairs, it is less critical here, as a small number of transducer elements can be compensated for by merging the various individual systems. Particularly with classic delay-and-sum beamforming, a small number of elements results in a broad main lobe and low side lobe levels. However, with appropriate parameterization and coordination of all systems, more suitable beam patterns can be achieved using other methods, such as adaptive beamformers. For example, depending on the surveillance area, zones could be defined in advance or intelligently detected in real-time in which grating lobes are tolerable or in which louder sources of interference should be spatially blocked. Approaches in which an MSN identifies a potential intruder and automatically increases the angular resolution in the relevant area are also conceivable. These considerations are mainly valid on both the transmitting and receiving sides.

Matched filtering

The output of the beamformer is fed to the matched filter, which correlates the received signal with the original transmitted signal. This allows the detection of reflecting sources along the distance over each previously processed beam angle. This results in the plan position indicator (PPI), a target matrix with beam angles as rows and distances as columns. The exact procedure for matched filtering depends on the SONAR operating mode. In classic SIMO SONAR, one transmission sequence is used for correlation. In certain MIMO configurations, however, orthogonal transmission sequences are used to calculate which signal components are associated with which transmission angle. This allows transmit beamforming to be implemented on the receive side via matched filtering, thus resulting in a higher angular resolution [3].

In the context of multistatic systems, the matched filter can also be parameterized. Range, ping rate, and source level are often interrelated. These parameters could be adaptively adjusted to the environment or the respective situation as needed, similar to BF. For example, the individual systems could coordinate such that, in the event of a potential intruder, the MSN allows the closer nodes to increase the ping rate – thus shortening the time until the next ping. At the same time, the calculated range per ping could be reduced to reduce the computational load, and the source level lowered to minimize reverberation and disruptive reflections.

Furthermore, higher sampling rates generally achieve very high spatial resolution in terms of distance, which, however, is not necessarily required in subsequent processing steps. To reduce computational effort and resolution, neighboring cells can be combined in a pooling process. In this case, it makes sense to initially use a high aggregation factor when no contacts are detected and only increase the distance resolution if the situation requires it.

Detector

The detector extracts so-called contacts from the PPI obtained in the previous step. These are identified when a certain threshold is exceeded for a cell. This threshold is primarily determined by the desired probability of false alarm and can be either a fixed value or adaptively adjusted. The latter is beneficial in environments such as ports, where background noise can fluctuate greatly. With regard to a distributed node system, the thresholds can also indicate the weighting of a node's information when centralizing this data.

The detector also significantly reduces the required transmission rate, as only the positions of the detected contacts need to be forwarded. However, depending on the system configuration, it may be advantageous to combine the target matrices after the matched filter. As already explained, systems whose beamformer performance is not optimal on their own can also be used in the MSN. If detection is based on the PPIs of the individual nodes, this may lead to more false positives than if the PPIs are combined beforehand.

Tracker

The tracker links consecutive detected contacts into trajectories, thus enabling the tracking of individual targets' movements over time. Key design decisions include the choice of model to describe target movement, the association strategy for adding new detections to existing trajectories, and the appropriate fusion of data from multiple systems.

Auxiliary Processing

In addition to pure SONAR signal processing, other parameters such as position, orientation, and speed of the node are of interest. This information serves both to improve signal processing and to integrate an individual system into the overall system.

In MSNs, the Euclidean distances between sending and receiving nodes are required for PPI generation. These can also be determined using matched filtering instead of GPS estimates. For example, all transmitting nodes in a frequency band outside the SONAR usable band could transmit a localization signal. This can also be used to determine the orientation of the node using algorithms that estimate the angle of arrival. Furthermore, these estimators and data from sensors such as IMUs, GPS, or DVLs can then be merged using proven methods such as Kalman filtering.

As not all targets in a surveillance area also represent threats, mechanisms for classifying contacts are also required to enable the MSN to react autonomously to the situation. The features required for this can be extracted, distributed from the signal reflected by the target or emitted by the target itself, and classified centrally so that it can react accordingly.

Network Integration

In a multistatic SONAR system, the information from individual nodes must be consolidated at a central location. This requires key design decisions regarding network topology, data processing, and communication infrastructure. First, it must be clarified which information will be centralized at which instance and to what level of abstraction signal processing should already be completed at these locations. The former influences the choice of network topology and is primarily determined by the positioning of all systems within the overall system and the resulting distances to be bridged. Possible topologies range from classic star or ring topologies to hybrid structures. For example, a very powerful node at the center of a star topology could serve as a gateway to a central network for all other participants. Depending on the interface and topology, surface and underwater gateways may also be required for the communication infrastructure. The degree of abstraction can be interpreted as data compression and, thus, also as information loss. It depends on the fusion strategy – that is, the level of abstraction at which the data is fused – in the processing network and is limited by the required data rate and the computing capacity of the central processing instance. The fusion strategy should be designed to achieve the best possible localization accuracy with a minimum data rate and take the individual system configurations into account.

The greatest challenges are, therefore, the range, susceptibility to interference, and available data rate, which in turn depend on the selected communication interface(s). LoRaWAN, for example, offers long ranges with minimal energy consumption but with a data rate in the kbit/s range, while Wi-Fi enables high data rates of several Gbit/s but only functions reliably over short distances. Submerged systems also rely on acoustic underwater communication or resurfacing mechanisms. MSN communication, regardless of the selected interface, is characterized by high heterogeneity as well as frequent interruptions and failures. Since temporal synchronization, in particular, is essential for the operation of an MSN, appropriate error compensation measures must be taken. Delayed information must either be subsequently integrated into the processing or discarded.

Other factors include energy consumption and security: Powerful antennas for long distances consume much energy, and communication must be secured against eavesdropping and tampering.

Summary and Outlook

This publication examines various perspectives on a multistatic SONAR system. First, the overall system was briefly described from a higher-level perspective, before shifting to a detailed examination of a single system within the network. In this context, the key aspects and challenges of the hardware, signal processing, and network integration domains were identified. This publication serves as a guideline and overview for the design of such systems, allowing future work to build on this concept and further develop specific aspects.

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