Contact Fusion and Multi-Hypotheses Tracking for Low Frequency Active Sonar Data

Kathrin Seget[1,2], Holger Schmaljohann[1] and Arne Schulz[1]

[1]Bundeswehr Technical Centre for Ships and Naval Weapons,
Naval Technology and Research (WTD 71)
Research Department for Underwater Acoustics and Marine Geophysics (FWG),
Klausdorfer Weg 2-24, 24148 Kiel

[2]Institute for Circuit and System Theory,
Faculty of Engineering, University of Kiel,
Kaiserstrasse 2, 24143 Kiel

Abstract: Towed low frequency active sonar systems (LFAS) are used in Anti-Submarine Warfare (ASW) to detect submarines. LFAS systems are hampered by reverberation in shallow water environments because the interaction of sound with the sea bottom can lead to a large number of point-like sonar contacts resulting in a high false alarm rate. Reducing the false alarm rate under a non-decreasing probability of detection is preferable for further signal processing of the data, especially for target tracking.

In a sea experiment with an LFAS system two different sonar signals have been transmitted within each ping. Fusion of the contacts obtained by processing these independent signals yields a reduction of the false alarm rate since only fused contacts are passed to the tracking stage. Contacts that have not been fused are assumed to being caused by noise. In addition to a reduced false alarm rate contact fusion provides a Doppler information of the considered contact.

A different approach of fusing the sonar contacts and extracting its Doppler information is to use the data association scheme of a multi-hypotheses tracking (MHT) algorithm where different hypotheses for the association of contacts from the independent signals are stated. Thus, false alarms are distinguished from target contacts.

This paper compares both mentioned fusion approaches by means of several tracking-performance metrics. A good tracking performance for a one-sensor-tracking scenario as it is analyzed here is a precondition for a high quality track fusion in a multistatic scenario which is subject to current research.

1 Introduction

In Anti-Submarine Warfare (ASW) modern submarines are to be detected even at long distances. This leads to a huge surveillance area where the usage of active sonar is required. When active sonar is used, scattering of acoustic energy results from objects in the water column (e.g. shoals of fish or submarines) as well as from the sea bottom and the sea surface. Thus, processing of the received acoustic data, especially in shallow waters, often
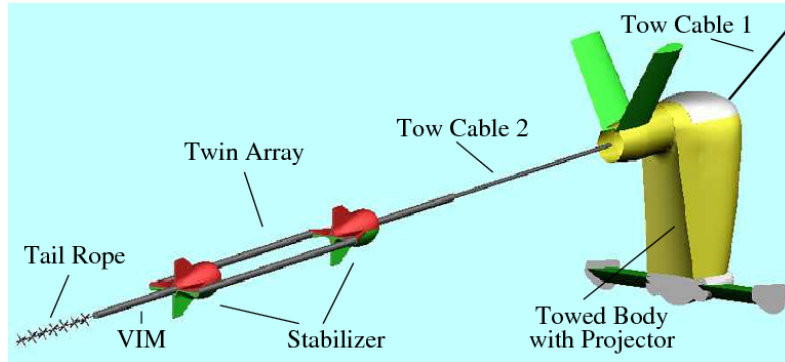
Figure 1: Sketch of an LFAS system. Acoustic energy is emitted by the towed body connected to the vessel by Tow Cable 1. Two single line hydrophone arrays are towed in parallel behind the projector (so called twin array configuration). Behind the twin array a vibration isolation module (VIM) and a tail rope are installed.

leads to numerous sonar contacts resulting in a high false alarm rate. Signal processing before multi-hypotheses tracking (MHT) aims at reducing the false alarm rate and keeping or improving the probability of detection.

Figure 1 shows the sketch of the towed low frequency active sonar system (LFAS) used to collect the presented data. The antenna consists of two single line arrays towed in parallel. This so called twin array configuration resolves the left-right ambiguity and the long aperture of the line array results in a good angular resolution. Thus, localization precision in LFAS data is high.

Utilizing the high spatial resolution, the false alarm rate can be reduced by classifying contacts as echoes resulting from moving or stationary objects. Since targets to be tracked usually navigate and are not fixed in space, only contacts from moving objects are subject to further processing. Moreover, the classified contacts can be used in scenarios where it is of interest to track stationary targets as well. By applying two tracking algorithms to track stationary and moving targets separately, the computational costs of the algorithm can be reduced, since computation time grows exponentially with the number of processed contacts. Thus, two trackers, each processing N contacts is more effective than one tracker processing $2N$ contacts.

Data presented here has been collected in a sea trial using an LFAS system towed behind the German research vessel FS PLANET. During the trial two different sonar signals were transmitted within each ping. Fusion of the contacts obtained by processing these independent signals yields a further reduction of the false alarm rate since contacts that cannot be fused are assumed to being caused by noise. Besides a reduced false alarm rate, contact fusion provides additional Doppler information for the fused contact.

A decreased false alarm rate is desirable. But only under the condition that the probability of detection does not decrease at the same time, i.e. that target contacts are not affected by the contact fusion. The possibility of incorrect contact fusion, and thus, a wrong discrimination of target contacts is existent. Therefore, a second approach of fusing sonar contacts and extracting its Doppler information has been applied to the data. To avoid wrong fusion

decisions different association hypotheses are stated using the data association scheme of a MHT algorithm. Due to multiple fusion hypotheses the possibility of correct fusion increases. Both contact fusion approaches are compared using tracking-output metrics describing the quality of the fusion procedures.

The comparison results are of interest for implementation of track fusion since a higher quality of a track extracted from contacts of a single sensor leads to better input data for track fusion in a multistatic scenario and is expected to improve the multistatic tracking performance.

2 Contact Classification

For contact classification the fact is used that contacts caused by bottom features are fixed in space. The high spatial resolution of LFAS signals is a prerequisite for achieving sufficiently good results in contact classification.

To decide whether a contact belongs to a moving object or not, an algorithm tracking stationary objects is applied. In a first step the geographical position of each contact is determined. Sequentially, for each contact it is checked if it can be associated to an existing track. The decision, whether or not a contact is associated depends on the spatial distance between the contact and the considered track as well as on the actual measurement error. The assignment criteria is chosen in a way that only contacts belonging to stationary objects are likely to fulfil this condition. Two types of contacts are discriminated by the algorithm: contacts caused by moving objects and those caused by stationary objects or noise.

3 Contact Fusion

To reduce the influence of noise and that of frequency dependent scattering, the advantage of having transmitted two different sonar signals within each ping is used. One of the signals is a hyperbolic-frequency-modulated (HFM) signal with a positive frequency gradient (HFM up) and the other one is a HFM with a negative frequency gradient (HFM down). Each signal provides the same range resolution which is assumed to give a sufficiently high probability of fusing the contacts resulting from the same object.

After fusing the HFM up and the HFM down contacts the radial velocity of the fused contact can be estimated by using the distance between the contacts and the knowledge of different signal parameters as center frequency and bandwidth [TE06]. Contacts that have not been fused are discriminated as false alarms and thus, are not passed to the tracking stage. Figure 2 shows the impact of the fusing and classifying procedures for reducing the false alarm rate as a receiver-operating-characteristics (ROC) curve where the probability of detection for a moving object is plotted over the number of false alarms. Target contacts remain unchanged and, obviously, the initial slope of the curve increases. This indicates an improved system performance.
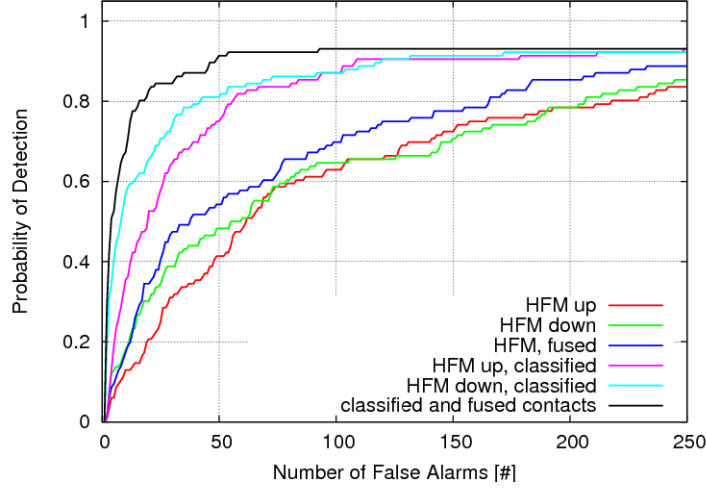
Figure 2: ROC-like curves before and after applying the different processing steps. The combination of contact classification and contact fusion outperforms the other processing steps without a significant (none in this case) loss of target contacts.

4 Description of the MHT Algorithm

Tracking using the MHT scheme as described in [KKU06] is done in the Cartesian plane. Thus, state vectors are defined as Cartesian vectors with information on position and velocity:

$$\mathbf{x} = (x, y, \dot{x}, \dot{y})^T. \tag{1}$$

Assuming a Nearly Constant Velocity model, the underlying system is linear in its system description:

$$\mathbf{x}_{k+1} = \mathbf{A} \cdot \mathbf{x}_k + \mathbf{w}_{k+1} \tag{2}$$

with the system matrix $\mathbf{A}$ and $\mathbf{w}$ as a Gaussian distributed random variable modeling the process noise.

The measurement vector $\mathbf{z}$ contains information on range r and angle φ between contact and receiver.

If HFM up and HFM down contacts are fused before passed to the tracking stage, the fused contact $\mathbf{z}_k^F$ contains Doppler information that is proportional to the range rate $\dot{r}$.

$$\mathbf{z} = (r, \varphi)^T, \qquad \mathbf{z}^F = (r, \varphi, \dot{r})^T. \tag{3}$$

The vectors $\mathbf{z}$ are nonlinearly dependent on the state vectors $\mathbf{x}$ according to the measurement function h and distorted by additive White Gaussian measurement noise $\mathbf{v}$.

$$\mathbf{z}_k = h(\mathbf{x}_k) + \mathbf{v}_k. \tag{4}$$

For track initialization the measurement vectors are transformed into the Cartesian plane applying an Unscented Transform [JU04]. To process the nonlinear measurements for updating existing hypotheses the Unscented Kalman Filter (UKF) is used applying an Unscented Transform in the filtering step where hypotheses states are transformed to $\mathbf{x}_{trans}$ to allow for an appropriate update of the hypotheses states with the measurements.

Data association is realized by applying the MHT scheme as described in [KKU06] where the target state is represented by several different hypotheses. New hypotheses are built by associating the contacts $\mathbf{z}^j$ to already existing hypotheses states $\mathbf{x}^i$.

For every new composed hypothesis a corresponding weight is calculated according to

$$\hat{\mathbf{w}}_{k+1}^{ij} = \begin{cases} \mathbf{w}_k^i \frac{P_d}{f_c} \mathcal{N}(\mathbf{z}^j; \mathbf{x}_{trans}^i, \mathbf{S}^{ij}) & j > 0 \\ \mathbf{w}_k^i (1 - P_d) & j = 0 \end{cases} \tag{5}$$

The consideration of the case $j = 0$ accounts for the fact that all contacts are false alarms. For $j > 0$ the considered contacts include false alarms as well as a target contact. P_d is the probability of detection and f_c denotes the clutter density. $\mathbf{S}$ is the innovation covariance and results from the Kalman filter update step. To assure that the calculated weights represent probabilities, the weights $\hat{\mathbf{w}}^{ij}$ have to be normalized to $\mathbf{w}^{ij}$ such that

$$\sum \mathbf{w}^{ij} = 1 \tag{6}$$

holds true.

To limit the number of hypotheses gating, pruning and merging [BP99] are applied to the MHT algorithm. Moreover a max-depth-width-pruning is used where after n pings only those hypotheses with the strongest m weights remain in the hypotheses-tree. Furthermore sequential track extraction [VK98] is included in the track management of the algorithm to confirm and delete tracks.

5   Contact Fusion within the MHT Scheme

In case contacts from HFM up and HFM down sonar signals are passed to the tracking stage separately, the update step of the UKF is applied consecutively for each type of contacts. This procedure is similar to the processing of contacts from different waveforms as presented in [DE08].

Thus, different hypotheses for the fusion of HFM up and HFM down contacts are stated. For the hypotheses where both contacts are assigned, Doppler information can be extracted and used additionally in the filtering step. Within each filtering step the case that the target is not detected, i.e. that all contacts are false alarms, is considered by establishing the hypotheses where no contact is assigned. Weighting of the hypotheses is done according to (5) and (6). The methods of hypotheses management as well as track management are applied as described in section 4.

6 Tracking Results

The following section presents preliminary contact fusion results of one chosen data set. Centralized as well as distributed track fusion which requires high-quality tracking outputs of contacts from one sensor is still under investigation.

The verification of the developed contact classification algorithm has been done in [SSS09] where with ROC curves and tracking-output metrics the value of the algorithm has been shown. Therefore, only contacts classified as moving objects are considered for following signal processing.

Further, it has been shown in [SSS09], that the processing of classified and fused HFM up and HFM down contacts provides a better tracking performance compared to the performance that is achieved by processing classified HFM up or HFM down contacts separately. There is a possibility that association errors in the fusion stage occur, i.e. that contacts not originated from the same object are fused and thus, a wrong Doppler information is extracted. Furthermore, target contacts could be handled as false alarms if they only appear in one class of contact types. To overcome this potential reduction in tracking performance, classified HFM up and HFM down contacts are passed to the MHT where contact fusion is realized as described in section 3.

Contacts not having been fused in the fusion stage are assumed to being false alarms and are not passed to the tracker. With the same fixed amount of contacts processed by the tracker, the probability of detection increases after fusion as shown in figure 2. Therefore, the tracker has been modified. For both tracking scenarios, in a first association step the tracker checks the strongest n contacts regarding the signal-to-noise ratio for a suitable association. In addition, the modified MHT includes a second step, which is activated if no contact can be assigned to an already extracted track. Then the strongest $n+m$ contacts are checked for association to the hypotheses.

Fusion approach	Latency	TPD	TFAR
Contact fusion before tracking	9	0.92	0.22
Contact fusion within MHT data association	9	0.79	1.42

Table 1: Tracking-output metrics for different input data fused according to the presented fusion approaches.

Table 1 shows the tracking results of the presented MHT. They are expressed by different typical metrics [GCLC+08]. The latency corresponds to the number of pings, until the target is tracked. The track probability of detection (TPD) is the ratio of the number of pings with the target being tracked to the total number of pings the target is present. The track false alarm rate (TFAR) gives the mean number of false tracks per ping. The listed metrics in table 1 assess the quality of the presented contact fusion approaches. According to the presented metrics, contact fusion before the tracking stage is preferable to contact fusion within the MHT data association scheme since for this certain data set contact fusion within the MHT leads to a decreased TPD and an increased TFAR.

Although, it is not unusual that HFM up or HFM down contacts are not formed coexis-

tently, for this dataset missing target contacts happen much likely simultaneously for the single types of contacts. As the fusion of contacts leads to results with insignificant fusion errors, considering the same amount of false alarms, the probability of detection increases notedly. In such a scenario fusing the contacts before the tracking stage leads to a higher tracking performance.

7 Conclusions and Outlook

Two approaches of fusing contacts of independently transmitted sonar signals by one sensor have been presented. Comparing the output of a multi-hypotheses tracking algorithm applied to one single data set, the results show a better tracking performance for contacts fused before passed to the tracking stage. For this specific data set target contacts are formed coexistently and fused correctly and, thus, remain in the data whereas false alarms are discriminated correctly and are not processed any further. This leads to a significant increase of the probability of detection.

In contrast to the presented results, in a scenario where different sensors are used to collect data and where it is more likely that target contacts are formed asynchronously, the presented approach of fusing contacts in the data association scheme of a tracking algorithm would yield an improved tracking performance. Such a scenario is a distributed multistatic tracking scenario with different sensors collecting data that have different aspect angles to the target. The aspect angle significantly influences the target strength. Thus, the probability of detection within one ping differs from sensor to sensor, and the contact fusion within the data association of the MHT would be the better choice.

The presented results are preliminary. In a first step a method to extract high quality tracks from contacts of a single sensor is under investigation. These results will be used for realizing track fusion in a multistatic scenario.

Furthermore, the results of the contact classification algorithm which groups contacts into echoes from moving or stationary objects will be used for further fusion and tracking related work. An interaction of trackers' output such that tracks from moving and stationary objects will, if necessary, automatically be merged is of interest, e.g. if a target stops moving for some time.

References

[BP99]   S. Blackman and R. Popoli. *Design and Analysis of Modern Tracking Systems*. Artech House Radar Library, 1999.

[DE08]   M. Daun and F. Ehlers. Multistatic Multihypothesis Tracking: Environmentally Adaptive and High-precision State Estimates. In *Proceedings of the International Conference on Information Fusion*, Cologne, 2008.

[GCLC⁺08] D. Grimmett, S. Coraluppi, B.R. La Cour, T. Lang, C.G. Hempel, P.A.M. de Theije, and P. Willett. MSTWG Multistatic Tracker Evaluation Using Simulated Scenario Data Sets. In *Proceedings of the International Conference on Information Fusion*, Cologne, 2008.

[JU04] S.J. Julier and J.K. Uhlmann. Unscented Filtering and Nonlinear Estimation. *Proceedings of the IEEE*, 92(3), 2004.

[KKU06] W. Koch, J. Koller, and M. Ulmke. Ground Target Tracking and Road Map Extraction. *SPRS Journal of Photogrammetry & Remote Sensing*, 61, 2006.

[SSS09] H. Schmaljohann, K. Seget, and A. Schulz. Detection and Tracking Techniques for Shallow Water LFAS Data. In *Proceedings of UDT Europe*, Cannes, 2009.

[TE06] D. Tielbürger and F. Ehlers. Method for determining target data using an active sonar, 2006. Patent: DE 10 332886, AT326706E, EP 1500953.

[VK98] G. Van Keuk. Sequential Track Extraction. *IEEE Transactions on Aerospace and Electronic Systems*, 34, 1998.