'SIMULTANEOUS LOCALISATION AND TRACKING'
ONBOARD AUVS WITH MULTISTATIC SONAR DATA

Martina Daun a, Lars Broetje a, Frank Ehlers b

a Fraunhofer Institute for Communication, Information Processing & Ergonomics (FKIE)
b NATO Undersea Research Centre (NURC)

Contact author: Frank Ehlers, NATO Undersea Research Centre (NURC), Viale S. Bartolomeo 400, 19126 La Spezia, Italy; Tel.: 00390187527416, Fax: 00390187527330; frankehlers@ieee.org

Abstract: Multistatic Sonar Systems (MSS) based on manned or stationary systems provides necessary performance for Anti Submarine Warfare (ASW) surveillance operations. Sufficiently accurate sensor models are implemented in data fusion algorithms in order to exploit the added-value of the multiple aspects on the target. The logical follow-on is to use them to control the sensors, leading to an MSS based on AUVs [1,8]. This autonomous MSS has to cope with severe communication constraints, either as a direct result of the environment or for tactical reasons. For example, covertness can assist in detecting smart targets when being obliged to evade a multistatic network of unknown topology. We focus on an important step towards a persistent and covert autonomous multistatic system which is to maintain navigation & timing accuracy onboard the receiving AUVs by using the active acoustic transmissions of the multistatic sources plus their echoes from the ensonified environment. Therefore, we combine navigation and tracking strategies in a two-step algorithm, called ‘Simultaneous Localisation and Tracking’ (SLAT): First, we identify stationary contacts using available bistatic tracking & data fusion algorithms as well as ‘standard’ navigational data from AUVs. The latter is gained from an inertial navigation system, Doppler velocity log (DVL) and depth sensor. Then, we extent the Multihypothesis Tracking (MHT) to generate target tracks and state estimation of the sensors and the environment. We evaluate SLAT with data from the sea trial GLINT’10 executed with NURC’s AUVs and sensor arrays. The performance is measured by comparing localisation accuracy for an EchoRepeater (E/R) track. SLAT even works if the DVL data are not used! This means that SLAT can be used to realize a covert (non-emitting) receiving AUV which is able to maintain a sufficient self-localisation by utilising the acoustic transmissions and their echoes quasi as an “underwater-GPS”.

Keywords: Multistatic Sonar, Multihypothesis Tracking, AUV Navigation
1. MOTIVATION AND SETUP DESCRIPTION

The main task of an AUV in the ASW application considered here is the localisation and tracking of objects of interest (targets) using multiple bistatic sonar data. To be able to perform this task, a precise knowledge of the position of the acoustic sources as well as of its own sonar sensor position and heading is mandatory. A suitable sonar sensor consists of several hydrophones oriented in a line building a linear array. Due to the length of the array, for example 10-20 m, it is usually towed by the AUV, resulting in a (potentially significant) difference between array and AUV position and heading. While the AUV state can be determined relatively well, there is no or only poor knowledge on the array position and, especially important for multistatic track fusion, on the array heading because it lacks of position sensors at all or of sensors of sufficient accuracy. Taking the AUV state instead of the array state in the tracking filter or using the poor array sensors leads to a decrease in target tracking accuracy. A first step towards an improved tracking accuracy is therefore building a motion model for the towed array depending on the motion of the AUV (see Sec. 1B). Nevertheless, except for highly sophisticated models (probably strongly dependent on the actual type of array antenna), there is still room for improvement, e.g. for the heading angle of the array when the AUV manoeuvres. Inaccuracies in the target localization may also result from potential inaccuracies in the knowledge of the sources positions and an insufficient estimation of the errors due to an imprecise time synchronization between transmitting and receiving units, as described in [5].

A) Bistatic setup
The bistatic measurement setup (Fig. 1) consists of the following parameters:

1) target position \( q = (x, y)^T \) and source position \( s = (s_x, s_y)^T \)
2) receiver position \( o = (o_x, o_y)^T \) and orientation (heading) \( \Theta \)
3) time synchronization errors between the clock of the receiver and the source \( \Delta t \)
4) the propagation speed of sound in water \( c_S \)

We can express the measurement equations for the azimuth \( \varphi \) and time of arrival \( \tau \) by

\[
\varphi = \arctan \left( \frac{x-o_x}{y-o_y} \right) - \Theta, \quad \tau = (|q-s|+|q-o|) / c_S - \Delta t
\]

where \( | \cdot | \) denotes the Euclidian norm. Generally, only estimates of the parameters of the bistatic setup are available. The precision of these estimates is affected by the variability of the underwater sound channel (probabilistic features) and the modelling precisions.

B) Modelling the relationship between AUV and receiving array
The array antenna is towed in short distance to the AUV. Thus, we model the antenna to follow the course of the AUV. The receiver position is thereby placed in the centre of the array as this is the reference position used in the beamforming algorithm. To calculate the receiver state (position and heading) we, first, determine the time that the AUV has needed to travel the distance between array centre and AUV, and, second, we use the
position and the heading of the AUV at the previous time. The assumed error in the receiver state is the error of the AUV state (provided by the navigation filter) plus some noise to capture model imprecision.

Fig. 1 a) Bistatic Setup; sound from source at \( s \) is reflected by the target at \( q \) and received at \( o \). \( \phi \) is the heading of the receiver relative to North. b) SLAT setup:

Discover and utilize knowledge about the underwater environment.

2. TECHNIQUES FOR AUV NAVIGATION AND TARGET TRACKING

The implementation of an advanced navigation and tracking filter is based on well-established methods for navigation and tracking. We shortly outline the principles in this section, for more details we refer to the documented literature.

A) AUV navigation

NURC’s AUV navigation is based on an Inertial Measurement Unit (IMU), measuring 3D accelerations and 3D rotation rates. Since every positioning and attitude determination based on an IMU only suffers from error propagation [2], aiding by additional navigation sensors has to be done. GPS positioning data, being a common choice for aiding IMUs in land or air vehicles, is not available for underwater applications. Here, integrating a Doppler velocity log (DVL) giving vehicle speed over ground is useful. Furthermore, by evaluation of pressure measurements the vehicle depth can be calculated. In our example (NURC’s Ocean Explorer OEx), additional measurements for aiding the IMU are position (GPS, only on the surface), velocity (gained from DVL) and depth. Onboard the AUV a navigation filter is implemented to process the available measurement data and calculate an state estimate of the AUV [4]. To process the data offline and to incorporate the programming code in the tracking filter, we decided to implement our own navigation filter in Matlab. This navigation filter consists of an Error state space Kalman Filter in a closed-loop implementation [2], estimating the errors in the AUV state (position, velocity and attitude) as well as in the sensor biases, i.e. accelerometer, gyroscope, DVL and depth biases. To reduce computational effort, high rate IMU data (100 Hz) is processed in the prediction step only [3], not in the measurement update. No motion model is needed.

B) Target Tracking

The key task of tracking in multi-bistatic sonar systems is ensuring the multi-sensor fusion gain. The challenge lies thereby in handling a large number of false alarms and the measurement ambiguity due to poor localisation accuracy of a single bistatic measurement. Both issues make the task of data association difficult and accentuate the need for appropriate association tools, which was discussed in detail in [5]. We did show that it is possible to incorporate precise sonar sensor modelling into a Multihypothesis tracking framework and therefore improve the performance of the tracking approach. The multistatic concept discussed in [5] was based on stationary sources and receivers. In the current paper we want to discuss the potentials of using autonomous receivers.
3. COMBINING NAVIGATION AND TRACKING

Our overall goal is to introduce a self-correcting multistatic system, motivated by the need for high localisation performance and robustness. Therefore, we intend to improve the target localisation and tracking by improving the estimation of the aforementioned inaccuracies (see section 1). This is realised by incorporating acoustic sonar measurements of fixed clutter objects. Eq. (1) shows the multistatic measurement equations. Obviously, they do not only contain information about the target but also about the source (position \( s = (s_x, s_y)^T \)) and the receiver (position \( o = (o_x, o_y)^T \), bearing angle \( \theta \), and time offset \( \Delta t \)).

A) OPEN Loop SLAT

Obviously, we can use the measurement of the direct blast (direct path between source and receiver). This gives high estimation accuracy in timing, at least in cases the source positions are not too far off. The accuracy for bearing estimation is limited, and worst if the acoustic source is positioned in end-fire or in front of the receiving array. Therefore, additional source for information are necessary. Let us assume that the positions of some targets are known. These targets can be echoes of non-moving objects like wrecks or small islands. Knowing their positions (according to some given uncertainty) allows to correct the heading and position of the receiver, the positions of the acoustic sources and estimate the time offsets between transmitting and receiving units. However, in the multistatic sonar environment the key challenge is to handle imprecision of measurements and multiple false alarms. We need to know which measurements belong to the clutter targets, which is often not determinable from measurements of a single time scan. Choosing here a MHT-based approach gives us the possibility to try out different associations and decide later which association might has been the right one.

After correcting the unknown parameters, the target tracking, also based on a MHT, follows. We call this concept simultaneous localisation and tracking (SLAT). Our Open loop SLAT-MHT algorithm therefore consists of a setup estimation and a tracking block (see Fig. 2 left).
**B) Closed Loop SLAT**

Extending the Open Loop SLAT concept explained in 3.A by allowing the updated AUV state to be fed back into the navigation filter leads to 'Closed Loop SLAT', depicted in Fig. 2 right. Here, the corrected array positions estimated by the SLAT-MHT are transformed into an AUV position by an appropriate motion model between AUV and towed array (see 1 B). These position estimates can be fed back into the AUV navigation filter where they are aiding the IMU by treating them as position measurements. Since we use a multihypothesis target tracking, each hypothesis generates a different AUV position estimate, which must be processed separately. This results in multiple parallel navigation filters, with the number of filters depending on the actual number of hypothesis in the MHT.

**C) Extraction of clutter points**

Using knowledge about landmarks (here: known clutter points) to improve tracking or localisation performance is well established in robotics (see for example [6]) and often called 'simultaneous localisation and mapping' (SLAM) in that context. While in SLAM localisation of the robot and exploration of the environment is done all together, we process a two step algorithm assuming that there is a first phase to explore the region of interest and to extract 'landmarks'. We call this phase 'preparation'. In the second phase, the localisation of the robot (here: AUV) and tracking of targets of interests is done simultaneously by exploiting given landmarks. This gives us a substantial difference to SLAM techniques. An important step towards robust localisation and tracking is to handle the association problem [7] for sonar measurements, which is done here by MHT. Adding an automatic classification hint for contacts [8] could further improve the performance of the MHT achieved so far.

## 4. RESULTS

First, we describe the data set from the sea trial GLINT’10. In the second subsection, results of applying the concepts developed in the previous sections are shown and discussed.

**A) Description of the Experiment:**

GLINT’10 experiment was executed in the Mediterranean Sea, South of Elba in August 2010. 2 AUVs (called Groucho and Harpo) as well as 2 acoustic sources took part. The data set analyzed in this paper consists of two sub-experiments: “2nd August” and “3rd August”, respectively. Figure 3 shows the geometry of these two runs.

The moored acoustic source DEMUS transmitted every 24 seconds a HFM signal with a bandwidth of 400 Hz at a centre frequency of 2800 Hz. Additionally, an Atlas MF source was operating in alternating ping timing, resulting in 12 seconds as overall ping repetition rate.

The clutter objects selected in the first SLAT step are shown in Figure 4. A passive acoustic BBN reflector (a filled air hose) deployed during experiment was an "artificial" clutter object.

**B) Multi-bistatic experiment results**

**B.1 Preparation (Extraction of clutter points)**

For application of the MHT we use the best of our knowledge about the system parameters. AUV localisation is done with the help of navigational data generated from GPS (when surfaced), IMU, Doppler velocity log (DVL) and depth sensor.
Fig. 3. Geometry of the GLINT’10 runs on Multistatic Sonar. Legend: Black lines: Navigational data from 2 AUVs travelling clockwise on the triangle shape pre-planned tracks. Blue triangles: Acoustic sources. Red lines: EchoRepeater (E/R) target. Blue crosses: 3 stationary bottom targets and stationary BBN target (nearby the E/R course)

Furthermore, we exploit GPS data of the DEMUS source and of the research vessel Alliance deploying the ATLAS source. Since data recording and pulse trigger were not GPS synchronized, inter-ping timing were estimated from the difference of measured and expected arrival time corresponding to the direct blast (Figure 4, right, green line). By application of the MHT we identified three strong clutter targets as displayed in Fig. 4 (left). These tracks were used to calculate expectation and covariance of the clutter points. The BBN target could not be extracted from an own track with this settings of the MHT (we only note some deviation of the E/R track in direction to the BBN, indicating multi-target interference). This shows that the BBN clutter target is much weaker than the other clutter targets, however we use the known position of the BBN target in SLAT.

B.2 Setup Estimation
The automatic estimation of the time offsets is displayed in Fig. 4 (right, blue line). It is compared to the calculation when using only direct blast measurements. We note a smoothing effect and correction for jumps during the AUV maneuvers.

Fig. 4. Extraction of clutter points (red crosses) by MHT (left), Estimation of time offsets (right)

B.3 Multi-bistatic tracking with Open Loop SLAT
In GLINT’10 data an EchoRepeater (E/R) target was included in the experiments. Since its position is not used by SLAT, we can compare the E/R tracking performance of different approaches to evaluate performance of SLAT. We use the following criteria: the length of the track in pings and the position error averaged over the length of the track.

Tab. 1 summarizes the results for the four data sets (2 runs, 2 AUVs). Comparing the standard results with the (Open Loop) SLAT approach, we achieve significant improvements of approx. 20 m in RMS position error for the Groucho Run and approx. 10 m for Harpo. Worse performance for Harpo could be attributed to a missing clutter target, since the northern clutter target was not found in Harpo data sets. The full multistatic contact and track fusion has not been performed here, since the focus of this paper is on the validation of the covert (non-communicating) operation of AUVs.

Tab. 1. Perf. eval. for GLINT’10 data sets

<table>
<thead>
<tr>
<th></th>
<th>Track existence [pings]</th>
<th>RMS horz. position error [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd Aug. Groucho</td>
<td>max. 1160</td>
<td>1006</td>
</tr>
<tr>
<td>SLAT</td>
<td>967</td>
<td>35.8</td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Aug. Harpo</td>
<td>max. 500</td>
<td>480</td>
</tr>
<tr>
<td>SLAT</td>
<td>480</td>
<td>39.1</td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Aug. Groucho</td>
<td>max. 1160</td>
<td>1109</td>
</tr>
<tr>
<td>SLAT</td>
<td>1117</td>
<td>58.8</td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Aug. Harpo</td>
<td>max. 1160</td>
<td>1035</td>
</tr>
<tr>
<td>SLAT</td>
<td>1036</td>
<td>55.3</td>
</tr>
</tbody>
</table>

### B.4 Aiding navigation of the AUV with Closed Loop SLAT

As already mentioned, our goal is to realize a robust self-correcting multistatic system with high localisation performance. For evaluation of the robustness of the SLAT approach, we tested the behaviour when main AUV navigation sensors failed, that is we turned the DVL & depth measurement data off. Fig. 5 (left) shows, that the navigation filter based on an unaided IMU soon leads to high localisation errors due to error propagation. In contrast, using for IMU aiding the array positions estimated by the SLAT-MHT results still in a sufficient AUV localisation when DVL data is dropped. (see Fig. 5 right). The availability and the capability to exploit echoes from bottom targets is essential to achieve a sufficient AUV localisation without DVL.

### 5. SUMMARY, CONCLUSION, AND RECOMMENDATION

We use data from the sea trial GLINT’10 executed with NURC’s AUVs and sensor arrays to test the SLAT approach. Performance measure is the localisation accuracy achieved for the moving Echo Repeater. We found that SLAT is robust against synchronisation errors. It even works if the DVL data inside the AUV are not used.

SLAT can be used to realize a covert (non-emitting) receiving AUV, which utilises the acoustic transmissions and their echoes quasi as an “underwater-GPS”.

Sensor & timing calibration have to be part of the preparation for autonomous operations. Biased heading sensors or asynchronous or non-stationary triggering of acoustic sources and registration processes are causing huge errors in tracking and data fusion steps, leading to wrong automatic decisions. The run geometries shown in figure 3 could become part of a built-in test function for an autonomously operating AUV team. If bottom targets for the application of SLAT are available, the team could automatically calibrate its sensors and actuators, resulting in an accurate a-priori state information as a basis for afterwards started autonomous behaviours.
Fig. 5. Without DVL and depth data long time AUV navigation is not possible (left). In spite of missing DVL and depth data Closed Loop SLAT enables sufficient AUV localisation during the whole run (right). DVL is turned off in the 1st circle when echoes of the clutter points are found in the acoustic data (black cross).

ACKNOWLEDGEMENTS
This work was made possible through collaboration between NURC, a NATO Research Centre and Fraunhofer FKIE (DEU). Many thanks to all members of NURC's CASW project and especially to all participants of the GLINT’10 sea trial.

REFERENCES