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Benchmark Analysis of NURC Multistatic Tracking Capability

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Abstract - *This paper provides a brief description and performance results for the multistatic sonar trackers developed at NURC. Our analysis is based on common data distributed as part of the Multistatic Tracking Working Group (MSTWG), as well as sea trial data. We find that the nearest-neighbor tracker provides reasonable performance in benign environments, while the centralized and distributed MHT trackers have complementary strengths in more challenging scenarios.*

Keywords: Multistatic Active Sonar – Sensor Fusion – Multi-Hypothesis Tracking – Distributed Tracking.

1 Introduction

Target tracking significantly improves the detection and localization performance of contact data; as such, it provides significant value added to the undersea surveillance processing chain. Centralized and distributed fusion architectures have complementary strengths: the former is best with high detection redundancy, high false alarm environments; the latter is best with low detection redundancy.

A multistatic sonar tracker benchmarking effort has recently been initiated under the auspices of the Multistatic Tracking Working Group (MSTWG) [1]. Three common datasets have been developed to date for analysis with a variety of approaches to tracking [2-4].

We apply our baseline tracker (NN) to one of these datasets, and illustrate the performance benefits of multi-sensor fusion. In addition, we provide performance results based on sea-trial data to illustrate the performance tradeoffs in using our more advanced multi-hypothesis and distributed multi-hypothesis trackers (MHT, D-MHT).

This paper is organized as follows. In section 2, we briefly describe the NURC multistatic sonar trackers. In section 3, we provide NN tracker results, and in section 4, we provide MHT and D-MHT results. In Section 5, we examine the performance benefits of post-tracker classification. Section 6 provides a brief summary of our findings.

2 Target Tracking at NURC

Over the past several years, the NATO Undersea Research Centre has investigated multi-sensor tracking as part of its research into multistatic active sonar. This research has achieved the following milestones that include the following:

- Development of a baseline nearest-neighbor (NN) multistatic tracking capability [5];
- Development of statistically consistent measurement models for target contact data, to account for a variety of system and measurement errors [6]; application of these models to an analysis of intra-ping simplifying approximations [7] and to sensor placement [8];
- Development of centralized [9] and distributed [10] multi-hypothesis upgrades to the baseline tracker (MHT and D-MHT, respectively);
- Development of centralized and distributed tracker performance models that account for target fading effects [10].

In this section, we provide a brief description of the baseline, MHT, and D-MHT trackers.

Our input to the tracking algorithm is a sequence of time-ordered contact files; each contact file corresponds to a specific source and receiver pair. In the multistatic case, where several sources may ping at the same time, this sequence of files may include a number of files with the same time stamp. Both the baseline tracker and the multi-hypothesis tracker arbitrarily order contact files with the same time stamp, and files are processed sequentially.

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The main goal of an automated tracking algorithm is to drastically reduce the amount of data that an operator must contend with, by removing false contacts and associating target contacts to form tracks. Spurious false contacts often occur randomly in location, and thus will generally not lead to track formation. Contacts due to fixed clutter features and to targets occur with consistency, and generally lead to track formation. In addition to providing a performance improvement in a ROC curve sense, target tracking can significantly increase the localization accuracy that is present in the raw contact data, by smoothing detections over time using target kinematic and measurement models.

2.1 Nearest-Neighbor Tracker (NN)

A detailed description of the baseline tracker is in [5]. Each contact in the first contact file initiates an active track. Subsequently contact files are processed as follows. At each step, all active tracks are ordered based on the number of contacts on which they are based: active tracks are then processed in sequence. For each track, an association criterion is applied to the data whereby only sufficiently close contacts are considered, based on a gating threshold as well as the uncertainty in the predicted track range and bearing from the receiver, and the range and bearing contact uncertainty. If a single contact passes the gating threshold, it is used to update the track. If more than one contact passes the gating threshold, the statistical nearest neighbor is used to update the track. The contact is then discarded, and is unavailable to other tracks. After all active tracks are processed, the remaining contacts initiate new tracks.

There are two mechanisms by which active tracks are terminated. First, if a track fails to associate M contacts out of the first N pings, the track is terminated. Once a track associates M contacts within N pings, it is confirmed. Only confirmed tracks are provided to the tracker output. Once a track is confirmed, it is subsequently terminated when it fails to update for K consecutive pings.

Track location and velocity estimates are updated using an extended Kalman filter (EKF); both the association criterion and EKF use a 2D measurement vector that gives range and bearing from the receiver. The measurement covariance matrix accounts for numerous sources of measurement error including time, bearing, array heading, source and receiver locations, and speed of sound [6].

In addition to kinematic measurement information, sonar contacts include feature information that includes SNR, time extent, beam extent, etc. This feature information is not currently exploited in our tracking algorithms. When processing the contact files, we do apply an SNR threshold to the data to remove low-SNR contacts.

Our filtering is based on a single nearly constant velocity motion model. As a result, the baseline tracker will track both moving targets and fixed features; we do not as yet classify tracks based on velocity characteristics.

2.2 Multi-Hypothesis Tracker (MHT)

A detailed description of the multi-hypothesis tracker is in [9]. The multi-hypothesis tracker uses the same kinematic and measurement models, association gate criterion, nonlinear kinematic filter, and track-length classifier as the baseline tracker. Unlike the baseline tracker, the multi-hypothesis tracker uses a true sliding window *M-of-N* track confirmation scheme. (Rather, the baseline tracker terminates an unconfirmed track that fails to achieve the *M-of-N* criterion). Confirmed tracks are terminated when they fail to update for K consecutive pings. All tracks are terminated when sufficient time has passed since the last track update.

Rather than making an immediate assignment of contacts to tracks, in the multi-hypothesis tracker a set of active tracks and a set of contacts lead to a set of track *hypotheses*. In particular, each contact leads to a new track hypothesis, and each active track leads to a set of track hypotheses, one corresponding to no contact, and one for each of the contacts that satisfies the association gate criterion. More generally, a set of track hypotheses and a set of contacts lead to a new set of track hypotheses, based on the same hypothesis generation methodology. The approach described here is a track-oriented MHT scheme, as opposed to the hypothesis-oriented MHT scheme; the track-oriented approach has significant computational advantages, as it does not require the explicit enumeration of global association hypotheses [5].

A key parameter in multi-hypothesis tracking is *N-scan*, i.e. the number of layers in the set of track hypothesis trees. With a latency specified by *N-scan*, all association hypotheses are *resolved*, i.e. a single global hypothesis is selected. This selection is determined as follows. Each track hypothesis has a log-likelihood track score. The selection of a global hypothesis amounts to the selection of a subset of all track hypotheses, which accounts for all contacts exactly once. This problem can be cast as an integer-programming problem, for which an efficient linear programming relaxation approach leads to a near-optimal selection of a global hypothesis. Having selected a global hypothesis, all track hypotheses that are inconsistent with this global hypothesis are removed.

The track scoring and data association scheme discussed above generally lead to an assignment that minimizes the number of track objects consistent with the data. However, an undesirable aspect of the problem formulation is that no priority is given to the extension of confirmed tracks over the extension of unconfirmed tracks. We correct this with an additional pseudo-track-detection term in the scoring equations. Setting this term close to one amounts to solving the global assignment problem for confirmed tracks only, then fixing the assignment, and solving a second global assignment problem with unconfirmed tracks and remaining contacts.

The multi-hypothesis approach to data association leads to improved tracking performance. In fact, even with *N-scan* set to zero, the near-optimal assignment based on log-likelihood track scoring provides better data association (in a statistical sense) than is obtained in the greedy assignment scheme used in the baseline tracker, where track-to-contact assignments are made sequentially rather than with a global assignment scheme.

2.3 Distributed Multi-Hypothesis Tracker (D-MHT)

A detailed description of the D-MHT is in [10]. Each MHT module takes as input a set of tracks, and generates a set of fused tracks. In particular, in a centralized tracking architecture whereby a single MHT module is employed (as described in the previous section), the input tracks are all point-tracks, i.e. target contacts that are provided by signal and information processing. More generally, inputs may include sequence of associated contacts, i.e. tracks with finite duration in time. The data association logic in each MHT module accommodates associated contacts by only considering fused track updates that are compatible with previous association decisions. Thus, in track fusion, we only break an input track when an anomaly is detected that is incompatible with at least one association hypothesis. In this event, a new track hypothesis is spawned.

The ability to concatenate MHT modules provides a wide variety of possible fusion architectures. A key characteristic of the modules is that data is processed as it becomes available from the previous fusion stage. This is in marked difference with many track-fusion approaches, which operate in batch mode [11], and is critical for real-time surveillance requirements.

3 Baseline Tracking Results

We apply the NN tracker to the NURC-generated dataset [2]. In particular, we apply an SNR threshold to the data so as to have 10 contacts per contact file. This scenario includes four source-receiver combinations, leading to 40 contacts per minute, for 180 minutes.

Key tracker performance metrics of interest include track probability of detection (PD), track false alarm rate (FAR), track localization error (LE), and track fragmentation (FRAG). (In [1], FRAG is defined per unit time). The NN tracker has no latency, and in all cases the execution rate is well below one, i.e. faster than real time.

We are interested to quantify the benefits of target tracking in reducing a large number of contacts into a small set of tracks, with good hold on the target, few false tracks, and improved localization accuracy relative to contact-level data. Also, we wish to quantify the benefits of multi-sensor tracking over single-sensor tracking.

Output performance metrics, for a range of choices for track-initiation parameters and for a number of single-sensor and multi-sensor cases, are given in Tables 1-5. Tracker ROC curves are given in Figure 1.

Table 1. Monostatic (TX1->RX1).

Track Initiation	PD	FAR	LE [m]	FRAG
2/2	0.567	55.67	1034.8	2
3/3	0.478	11.00	146.1	1
4/4	0.433	1.67	2110.5	2
5/5	0.389	0.33	152.7	1

Table 2. Bistatic (TX3->RX1).

Track Initiation	PD	FAR	LE [m]	FRAG
2/2	0.694	66.33	1514.1	2
3/3	0.667	15.67	1451.7	2
4/4	0.633	4.33	1148.0	2
5/5	0.356	1.33	719.4	1

Table 3. Bistatic (TX1->RX2).

Track Initiation	PD	FAR	LE [m]	FRAG
2/2	0.611	65.67	754.0	1
3/3	0.589	21.67	756.6	1
4/4	0.583	5.67	752.1	1
5/5	0.578	1.00	743.4	1

Table 4. Bistatic (TX3->RX2).

Track Initiation	PD	FAR	LE [m]	FRAG
2/2	0.789	60.00	1578.5	3
3/3	0.678	13.00	1278.6	3
4/4	0.667	2.00	1162.0	2
5/5	0.417	0.67	483.9	1

Table 5. Multistatic (4 nodes).

Track Initiation	PD	FAR	LE [m]	FRAG
3/3	0.811	53.67	933.8	4
4/4	0.739	8.33	356.0	3
5/5	0.578	1.33	447.4	2
6/6	0.578	0	439.2	2

Note that, given the increased data rate, a more stringent range of track initiation settings is required in multistatic tracking to achieve comparable numbers of output tracks as in the single-sensor cases. We see that the best ROC-curve performance is achieved in the multistatic case.

The average single-node fragmentation level is 1.63, or 0.54 per hour. The 4-node fragmentation rate is 0.69: this is slightly higher, but tracks are based on four times as much data, so a much greater data reduction is achieved.

The input data exhibits an average localization error of 915.0m for target-originated contacts. Single-node track localization errors vary significantly from node to node; the average values (over all track initiation parameters) are 861m, 1208m, 752m, and 1126m. These values all exceed the average multistatic localization error of 544m.

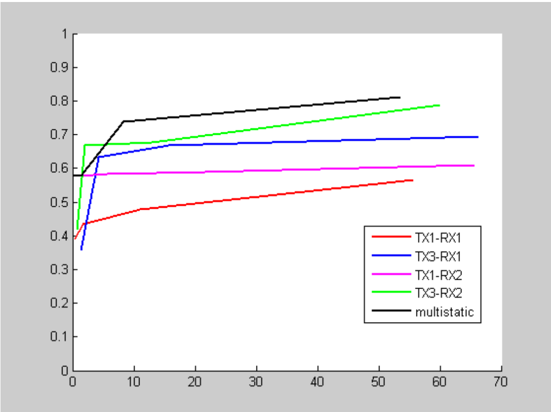

Fig. 1. Tracker ROC curves (PD vs. FAR per hour).

Our performance metrics quantify the benefits of multi-sensor tracking. The visualization of results further confirms performance benefits: single-node false tracks tend to last longer in time, leading to a more cluttered surveillance picture. This follows from the lower data rate and leads to a longer track termination time window.

Figures 2-7 illustrate selected tracking results. Figures 2-5 illustrate cumulative tracking results for one source-receiver pair (TX3->RX2), for all track-initiation settings. Contacts are plotted in blue, tracks are in magenta, and the receiver trajectory is in black. Note the improvement in false track rate and the reduction in target hold with increasingly stringent track-initiation criteria, and the relatively lengthy false tracks. Finally, note that tracking is most effective during the middle portion of the scenario, consistent with the SNR time series of the contact data [2].

Figures 6-7 illustrate multistatic tracking, with the least and most stringent track-initiation settings, respectively. Note increased contact data, greater data reduction, shorter false tracks, and precise track localization.

In future work, we will explore tracking performance with variations on this dataset [2], and additional datasets [3,4]. We will apply NN, MHT, and D-MHT trackers, focusing on the relative merits of MHT and D-MHT trackers.

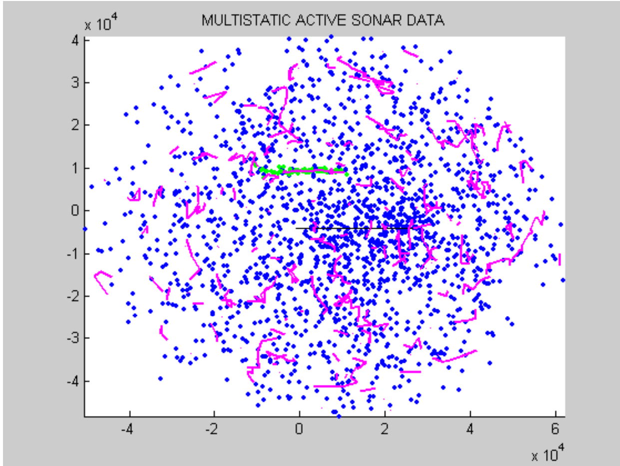

Fig. 2. TX3->RX2 tracks with 2-of-2 initiation logic.

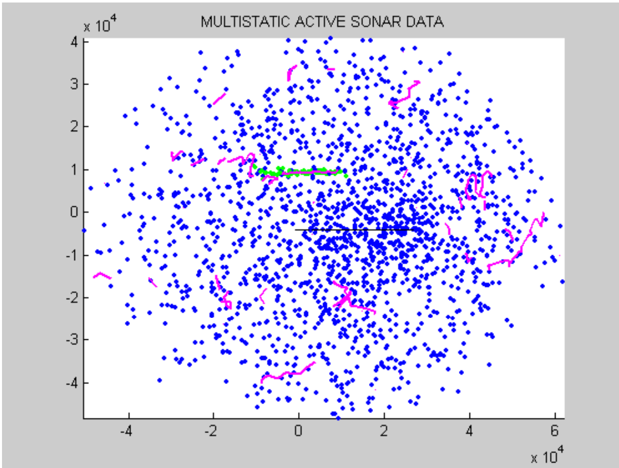

Fig. 3. TX3->RX2 tracks with 3-of-3 initiation logic.

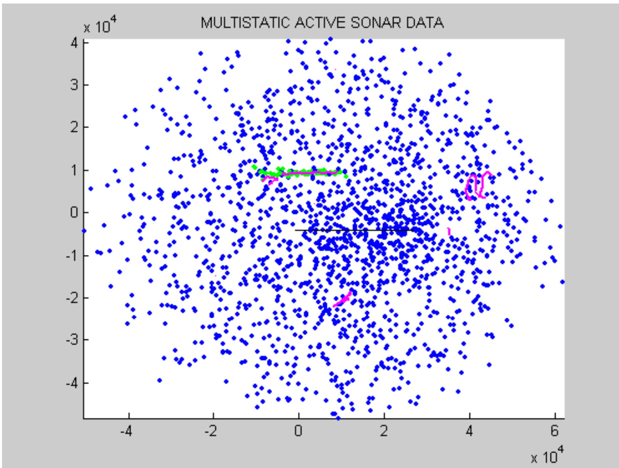

Fig. 4. TX3->RX2 tracks with 4-of-4 initiation logic.

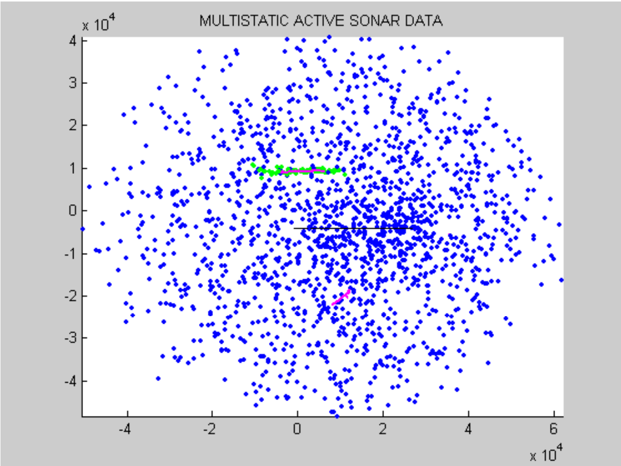

Fig. 5. TX3->RX2 tracks with 5-of-5 initiation logic.

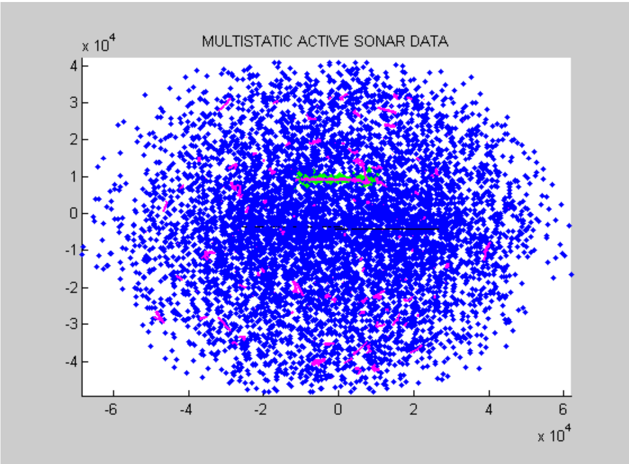

Fig. 6. Multistatic tracks with 6-of-6 initiation logic.

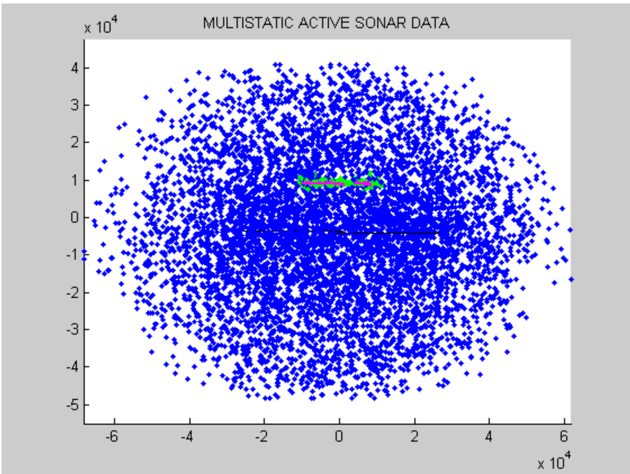

Fig. 7. Multistatic tracks with 3-of-3 initiation logic.

4 Centralized vs. Distributed MHT

In this section, we examine two multistatic scenarios from a recent sea trial with the Netherlands. Both 3hr scenarios include two active sonar equipped vessels with a source and receiver, for a total of four source-receiver combinations. Detailed performance analysis of the MHT and D-MHT trackers for these runs is documented in [12].

Real-time MHT-based results achieved for the two runs are illustrated in Figures 8-9. These results are achieved with real-time contact formation, radio-based contact file exchange, and onboard target tracking. A key pre-processing step in the tracker is to compute statistically consistent contact measurement covariance matrices based on estimates of system and measurement errors [6].

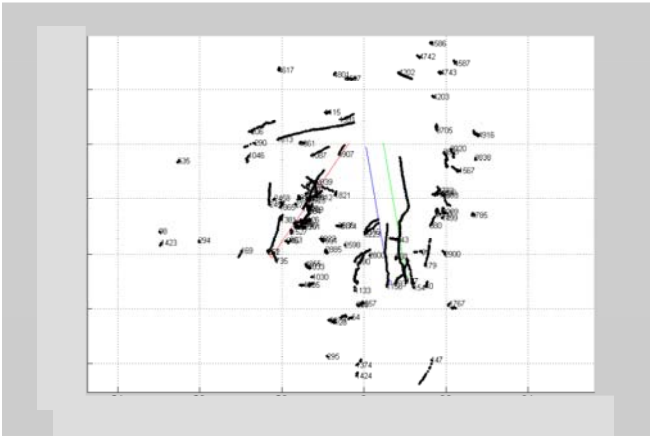
Fig. 8. Real-time MHT-based tracking (run 1).

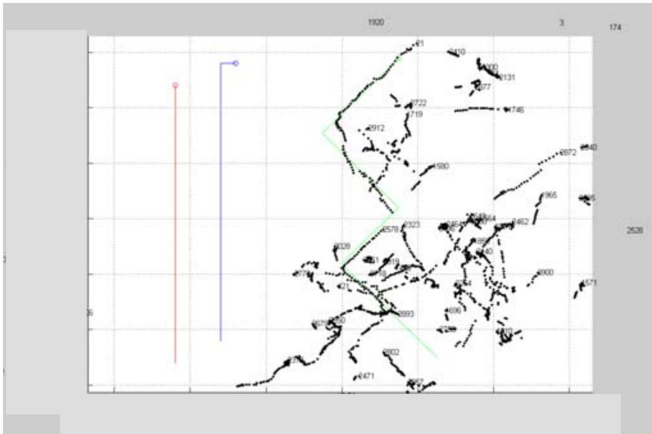
Fig. 9. Real-time MHT-based tracking (run 2).

In both cases, platform trajectories are denoted in red and blue, planned target trajectories are in green, and tracks are in black. In run 1 (Fig. 8), the target track deviates from the planned target trajectory as it moves north as indicated by its track. In run 2 (Fig. 9), 2hrs of data were processed (i.e. the first two-thirds of the run). Note the track fragmentation at the second target turn.

4.1 Tracker Performance Modeling

In [10], centralized and distributed tracker performance models are developed that account for target fading effects (i.e. the scan-to-scan dependence in active sonar detection data). These models are applicable to low-FAR environments only, and suggest the following:

1. With full detection redundancy, centralized tracking marginally outperforms distributed tracking.

2. In the presence of target fading with limited detection redundancy, distributed tracking outperforms centralized tracking.

These modeling results are confirmed with simulated multistatic contact data [10]. Efforts are underway to extend these models to high-FAR environments. We believe these extensions will bear out the following:

3. In high-FAR environments, centralized tracking outperforms distributed tracking.

This result follows from the difficulty in maintaining track in high-FAR environments with low contact data rates; centralized tracking provides a higher data rate to a single MHT module.

4.2 Parametric Study of MHT and D-MHT Performance: Selected Examples

A systematic evaluation of tracking performance for the sea-trial based runs 1-2 illustrated above is documented in [12]. This study includes a wide range of contact data SNR thresholds and track initiation criteria. Tracking performance results are consistent with the modeling predictions (1-3) listed above.

Here we illustrate two examples from this study:

- *Example 1* (Figures 10-11): Run 1, low FAR (5 contacts/file). With the same track initiation settings and a benign environment, we find comparable performance between MHT and D-MHT processing: note that D-MHT generally provides improved target hold, at the cost of a higher false track rate. Further analysis reveals that as target input PD decreases, still with a low input FAR, the D-MHT architecture is more robust and provides better performance.

- *Example 2* (Figures 12-14): Run 2, high FAR (approx. 200 contacts/file). Figures 12-13 provide two (of the four) single-sensor tracking results for the first two legs of the run, and demonstrate the inability to hold track on the target at a low ping repetition data rate and with a high FAR. The D-MHT result, which is based on the fusion of single-sensor tracks, will demonstrate the same inability to track. Figure 14 illustrates successful (centralized) MHT tracking. This success is based on a higher contact file rate that allows for shorter track prediction times and correspondingly smaller data validation gates. This in turn provides robustness against erroneous data association.

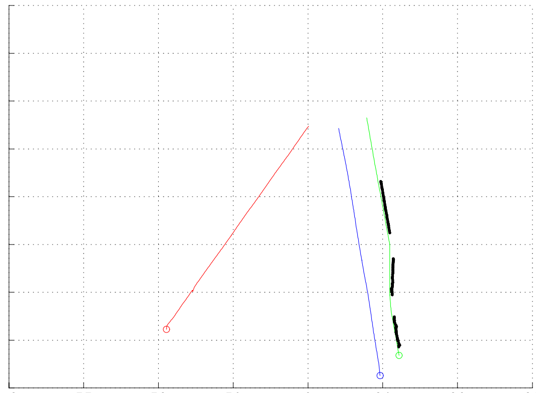

Fig. 10. MHT tracking with low-FAR data for the first sea-trial run: the tracker effectively removes false contacts and provides modest target hold with some fragmentation.

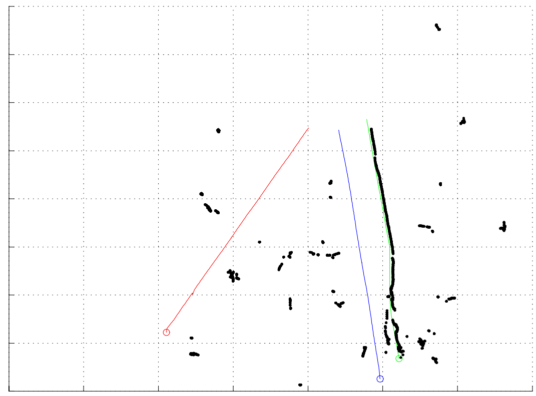

Fig. 11. D-MHT tracking with low-FAR data for the first sea-trial run: the tracker provides excellent target hold with a relatively small number of false tracks.

Further examples of MHT vs. D-MHT tracking are provided in [12], along with quantitative performance evaluation for a wide range of tracker and data-threshold settings. As mentioned in section 3, the same systematic evaluation of MHT and D-MHT architectures is planned for the three MSTWG datasets.

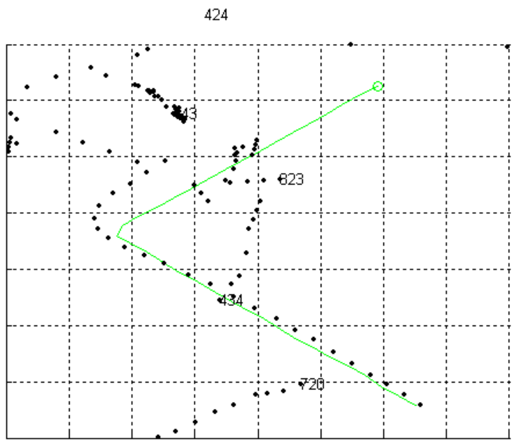

Fig. 12. Monostatic MHT tracks with high-FAR data for the second sea-trial run.

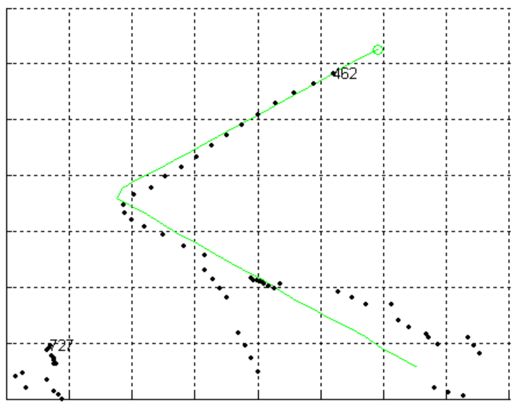

Fig. 13. Bistatic MHT tracks with high-FAR data for the second sea-trial run.

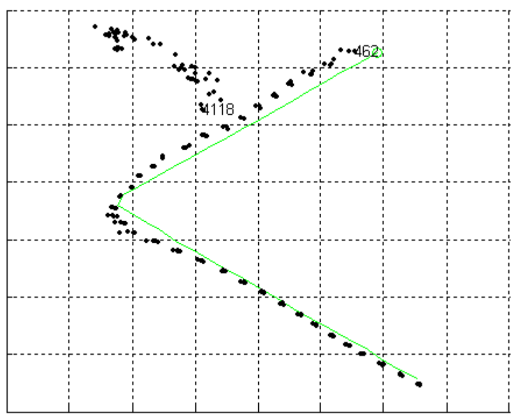

Fig. 14. Full-multistatic MHT tracks with high-FAR data for the second sea-trial run: successful target hold.

5 Track Classification

Classification is an important part of any sonar system's signal and information processing chain. Classification algorithms may be applied as an independent pre-filter prior to the fusion/tracking processing, as an integral part of the fusion/tracking processing itself, and/or as a post-tracking process.

The use of contact feature information can contribute to multistatic tracking performance. One approach is to utilize a single-ping classifier. Alternatively, feature information could be directly utilized within the tracking algorithm, by modifying likelihood computations [13] or by exploiting time-correlations in feature data through state-augmentation techniques.

An additional effort at classification can be made at the tracker output. Output tracks can be evaluated in a track classification process, which can remove (or tag) tracks that are unlikely to be targets. For example, we expect the fusion/tracker algorithms to form tracks on consistent echoes received from fixed bottom clutter features or shipwrecks. These can be identified and removed by evaluating the tracker output using some simple track feature criteria. Likewise, tracks with an excessively large velocity (outside the range of capability for a target submarine) or with less scan-to-scan heading or speed stability may be removed.

Further details on our track classification work may be found in [12].

6 Conclusions and Recommendations

Target tracking significantly improves the detection and localization performance of contact data. These gains can be achieved to a considerable extent, even with a straightforward nearest-neighbor tracker. Further gains are achieved with multi-hypothesis and multi-stage approaches. As described in this paper, centralized and distributed fusion architectures have complementary strengths. In all cases, simple track classification based on track duration, average speed, and heading stability provides additional performance gains.

Our recommendation is that future research in sensor fusion and target tracking for undersea surveillance include the following:

- Continued benchmarking of a number of complementary approaches to target tracking, through collaborative efforts like the MSTWG.
- Implementation of feature-aided and Doppler-aided capabilities in the NURC distributed, multi-hypothesis tracker, and analysis of the value-aided of these enhancements.
- Development of sensor management techniques, to include: sensor placement, modelling of reactive targets, FM/CW

waveform selection, and adaptive SNR-based thresholding of contact data as a function of active track information.

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