The GM-CPHD Applied to the Corrected TNO-Blind, Adjusted SEABAR07 and Metron Multi-Static Sonar Datasets

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ABSTRACT

The Gaussian Mixture Cardinalized PHD (GM-CPHD) Tracker was applied to the corrected TNO-Blind dataset, the SNR adjusted datasets in SEABAR07 and to the Metron dataset generated for the MSTWG (Multistatic Tracking Working Group). The increasing difficulty of the datasets is handled by improvements on the tracker. The tracking results (plots and metrics of performance) are included.

Keywords: CPHD, Multistatic Active Sonar, Sensor Fusion, Target Tracking

1. INTRODUCTION

The TNO-Blind dataset was created by Dr. Pascal de Theije for the MSTWG, and presented the challenge of discovering the number of targets present in the interest region and their tracks. An incorrect value in the RMS registration error for the time measurement has been identified \cite{1}. Its correction considerably improves the tracking results we previously reported on the TNO-Blind dataset \cite{2}.

The SEABAR07 datasets, also the subject of study by many members of the MSTWG, present the challenge of real sonar data obtained in a sea trial that took place in October 2007 on the Malta Plateau. At the time we reported results of the application of the GM-CPHD Tracker to the SEABAR07 datasets, the SNR adjusted version of the datasets \cite{3} was not available to us. In this work we compare our results obtained on the SEABAR07 datasets \cite{2} to the new results obtained on the adjusted SEABAR07 datasets.

The Metron dataset was generated by Kirill Orlov of Metron, Inc. to continue the evaluation of the tracking algorithms of the MSTWG participants. It was intended to be the follow-up to the SEABAR and TNO-Blind datasets in terms of providing a difficult realistic scenario. In this paper we present the winnowing and contact sifting needed to be carried out before tracking could be performed, along with the results obtained by the application of the GM-CPHD tracker to scenario 1 (out of 5) in the Metron dataset.

2. GM-CPHD TRACKER

The Cardinalized Probability Hypothesis filter is a recursive filter that propagates both the posterior likelihood of (an unlabeled) target state and the posterior cardinality density, i.e. the probability mass function of the number of targets \cite{4}.

Under linear Gaussian dynamics and the assumption of state independence for the probability of detection and the probability of survival, closed form filter equations are given in \cite{5}. In that work, the posterior PHD surface is approximated by a Gaussian Mixture and is shown to remain a Gaussian Mixture after the update step. Hence, the propagation of the whole surface can be replaced by the propagation of the weight, mean and covariance of each mode in the mixture. Mode means and covariances are propagates by an Extended Kalman Filter while mode weights are calculated using the PHD equations. In common with other similar trackers such as the MHT, the number of Gaussian modes could increase exponentially with the number of scans, and as such track-management (pruning, merging, etc.) is necessary to make the approach practical.

In our analysis \cite{6}, we divide the state space into infinitesimal bins and for each bin, we ask the question: “Is there a target at this location?” The filter contains equations for the prediction and the Bayesian update of the probability of each bin containing a target. Integration of the PHD surface over a volume gives the expected
number of targets therein. In the limiting case in which bins’ volumes go to zero, the filter’s equations converge to the PHD/CPHD filter of Mahler [4] and to the Intensity Filter of Roy [7].

We employ the GM-CPHD filter with a linear motion model and a nonlinear measurement model in which range, bearing and range rate (when available) form the measurement. Our implementation is thus capable of processing both Doppler sensitive (i.e., a constant frequency pulse - CW) and Doppler insensitive waveforms (i.e., a linear frequency modulated pulse - LFM). For LFM waveforms, the range rate measurement \( \dot{r} \) is not significant and hence ignored. In its original form the GM-CPHD filter is not able to provide scoreable tracks, so a track management scheme was devised [8] [9]. This is a set of policies dealing with events such as track initiation, update, merging, spawning and deletion.

3. CORRECTED TNO-BLIND DATASET

3.1 TNO Description

The TNO Blind dataset features three sensors in 2D Cartesian space (Figure 1) with the following characteristics:

- Sensor 1 is bistatic and an FM sensor, giving 180 pings at a pulse repetition time of 60s.
- Sensor 2 is monostatic and a CW sensor, giving 210 pings at a pulse repetition time of 50s.
- Sensor 3 is bistatic and both an FM and a CW sensor, giving 113 pings at a pulse repetition time of 90s. The odd pings are FM contacts, the even pings are CW contacts.

The ground truth for one target with sinusoidal trajectory was revealed in order to ease tuning the tracker. RMS registration errors were given in the dataset description as:

- Sound speed: 2m/s
- Time measurement: 0.001sec FM and 0.1sec CW
- Bearing measurement: 1°
- Doppler measurement: 0.5m/sec.
3.2 Correction

Tharmarasa et al [1] compared the target originated measurements and the target trajectories and found anomalies in the time measurements’ standard deviation. Their results were much improved by using a larger standard deviation ($\sigma_r = 1000m$) for the bistatic range measurements in terms of decreased track breakage and increased track probability of detection.

Such a value for the bistatic range RMS error translates as:

$$\sigma_t = \frac{\sigma_r}{c} = \frac{1000m}{1500m/sec} = 0.67 sec$$

as the RMS error for the time measurement. We used this updated value in our most recent runs.

3.3 TNO Results

The parameters of the GM-CPHD tracker were set as in the following:

- Probability of detection of target, $P_d = 0.6$.
- Probability of death of target, $P_{death} = 0.05$.
- Birth probability = 0.001.
- Process noise variance = $2.5 \times 10^{-7} m^2/s^2$.
- Two-dimensional position/velocity kinematic model.
- Track initiation weight threshold = 0.8.
- Track deletion weight threshold = 0.15.
- Tracks merging weight threshold = 1.7.
- Maximum number of targets = 30.
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<th>FAR</th>
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Table 1. TNO MOPs.

The top 40 contacts (sorted by SNR in decreasing order) were fed to the tracker. Only contacts with SNR higher than 13.5dB were used. Adjustments for the parameters above were made when deemed necessary. For a detailed explanation of the above parameters, please refer to the work of Erdinc et al [6].

The updated $\sigma_t$ value had a great impact on the quality of the tracks as can be seen in Figure 2. A concern we had identified in our previous work on the TNO-Blind dataset was track fragmentation. It now appears that the fragmentation was due to employing the incorrect $\sigma_t$ value, as updating it to its correct value dramatically reduced the fragmentation. Also, sensor-ID information was incorporated into the track management resulting in robust mode-linking, initiation and termination of tracks.

The decrease in track fragmentation (FRAG) is evident when comparing the MOPs obtained before and after the correction was applied in the case of Target 1, the given target. Also, a considerable increase in the tracks’ probability of detection (PD), a lower number of false tracks, FTs (and thus a lower false alarm rate FAR) along with an increase in the RMS error can be noted. The ground truth for the other targets present in the surveillance area was revealed and therefore metrics of performance (MOPs) were calculated for the other targets as well, with the resulting MOPs values similar to the ones for Target 1 after the correction was applied.

4. ADJUSTED SEABAR07 DATASET

4.1 SEABAR07 Description

The SEABAR07 scientific sea trial featured the deployable multistatic system (DEMUS) consisting of one source (BTX) and 3 receiver sonobuoys (RX1, RX2, RX3). We present results obtained using datasets A01 and A56 (A05 and A06 combined). The scenarios include maneuvers (A01) and target births (A56).

The receivers were able to provide both Doppler-sensitive (CW) and Doppler-insensitive (LFM) contacts with a ping period of 60sec. The target was towed by a NURC research vessel and consisted of an echo repeater (ER) giving out strong aspect-independent echoes. The experiment was performed in shallow water and therefore high levels of reverberation, clutter and noise are present in the data that make it a challenging situation for the tracker.

4.2 Adjustments

The tagged contacts’ SNR were adjusted by replacing the ER amplification levels with values of aspect-dependent target strength (TS). The modeled TS values were based on source-target-receiver geometry and two bistatic TS models, i.e. the Basis and Cylindrical models. This processing was performed in order to lower the artificially high ER levels to more realistic ones while also providing an aspect dependent target. ROC curves ($PD$ vs $P_{FA}$) and a more complete description of the above mentioned processing can be found in the work of Grimmett [3]. Also, the fluctuating ER delay previously noticed in the A56 dataset was corrected.

Only contacts with SNR higher than 12dB were used in order to be able to compare the results with our previous work. On the A01 Basis dataset, this threshold gives an input PD of 0.5 and an input $P_{FA}$ per scan of about 40 while on the A56 Basis dataset, the threshold gives an input PD of 0.2 and an input $P_{FA}$ per scan of about 50 [3]. In the Cylinder datasets, the PD is lower and the $P_{FA}$ per scan is higher, thus creating a more challenging scenario for the tracker.
Figure 3. SEABAR07 Contacts

Figure 4. Basis Contacts

Figure 5. Cylinder Contacts
Plots of contacts (differentiated by SNR levels) for the original and the adjusted datasets can be seen in Figures 3, 4 and 5. It can be noticed that, with respect to the original datasets, there are fewer contacts in the vicinity of the target when using the Basis model and even fewer when using the Cylinder model. Also, it can be noticed that in the adjusted SEABAR07 data, A56 provides a more difficult scenario than A01 because in A56 there are portions of the target trajectory not covered by any contacts.

In our previous attempt at tracking the SEABAR07 datasets, we fed into the tracker only the top 10 (highest amplitude) contacts per waveform per receiver at each scan. This is a problem when dealing with a realistic dataset as the number of sonar contacts per scan can be in the hundreds, and in principle each deserves to be explored with its own mode but for a manageable number of modes we required relatively few contacts per scan. The issue has been fixed and currently the GM-CPHD can accept any number of contacts per scan. Runs with 10 up to 750 contacts per scan were made and in the end it was decided that inputing the top 40 contacts per scan achieves a good balance between the number of target detections and the number of false tracks.

4.3 SEABAR Results

The parameters of the GM-CPHD tracker were set as in the following:

- Probability of detection of target, \( P_d = 0.3 \).
- Probability of death of target, \( P_{death} = 0.05 \).
- Birth probability = 0.00001.
- Process noise variance = 0.00001 \( m^2/s^2 \).
- Two-dimensional position/velocity kinematic model.
- Track initiation weight threshold = 0.7.
- Track deletion weight threshold = 0.3.
- Tracks merging weight threshold = 1.7.
- Maximum number of targets = 30.

In our previous work with the A56 dataset, we observed some accidental targets not part of the sea trial such as an oil platform, surface ships and sea bottom features that are responsible for the high number of false tracks of this dataset (not visible in the zoomed in plots of Figures 7 and 8).

The fusion of Doppler-sensitive CW contacts with the highly resolving (but perhaps overly sensitive to fixed clutter) FM contacts and the use of multiple sensors are beneficial because they both increase PD. On the adjusted SEABAR07 datasets, fusing FM and CW contacts proved critical, as results based on FM only contacts were unsatisfactory. Once again, an important FAR reduction associated with the addition of CW contacts to the FM contacts was observed.

The MOPs in Table 2 confirm that the use of the Basis model takes the original A01 dataset to a higher level of difficulty and similarly, the use of the Cylinder model makes the scenario even more difficult than the use of the Basis model; this is evident in the decrease in PD, increase in track fragmentation, number of false tracks and RMS error.

A second GM-CPHD concern we had identified in our previous work with the SEABAR07 datasets was the GM mode-placement for initialization. Mode placement is a concern for a GM-CPHD in sonar data: when false alarms are few it is an easy task to assign a mode to each contact in a scan, but in the sonar situation, with hundreds of contacts per scan, this is not an option. Thus, we decided to cluster the contacts in a scan using the kmeans algorithm into a certain number of clusters (to be adjusted for each scenario) and assign a mode with a large covariance to the centroid of each cluster.
Figure 6. SEABAR07 Results

Figure 7. Adjusted SEABAR07 Results (Basis Model)

Figure 8. Adjusted SEABAR07 Results (Cylinder Model)
5. METRON DATASET

5.1 Metron Description

The surveillance area is a $72000 \times 72000 \text{ m}^2$. The 25 stationary sensors are laid out as two concentric square grids as seen in Figure 9. All the sensors are receivers with the exception of the 4 marked sensors which are colocated source/receiver units.

Two waveform types are simulated: CW and FM. CW yields position and Doppler information for contacts, whereas FM only yields position information. The ping schedule is the following: S1 CW, S2 FM, S3 CW, S4 FM, S1 FM, S2 CW, S3 FM, S4 CW with a ping occurring every 180 sec. The pattern is repeated up to 200 pings.

There are 4 targets. Each target completes four cycles of motion about the perimeter of a square region. Target motion specifications can be found in Table 3. The contacts generated by targets 2 and 3 have been labeled [10].

Measurements were generated with the following parameters:

- Sound speed is 1500 m/s
- Bearing error is normally distributed with mean 0.0° and std 8.0°
- Time difference of arrival (TDOA) error is normally distributed with mean 0.0sec and std 0.4sec
- Bistatic Doppler error is normally distributed with mean 0.0 m/sec and std 0.5 m/sec (CW only)

5.2 Winnowing

The Metron dataset contains too many contacts at each scan for the GM-CPHD to handle successfully and therefore, a winnowing step was devised. For a CW contact, we winnow by a simple detection test on SNR and Doppler (see Eq. 2). For a FM contact, we winnow by SNR only. The Doppler and SNR distributions for the tagged contacts $f_1$ and the clutter $f_0$ are given in the description of the dataset. The details of their calculation are to be given in a future publication. Selecting a suitable threshold requires tuning. The contacts that survive the winnowing are fed to the predetection fusion stage.

$$\frac{f_1 \text{(snr)}}{f_0} \times \frac{f_1 \text{(doppler)}}{f_0} \geq \text{threshold} \quad (2)$$

5.3 Predetection Fusion

We believe that the multi-sensor PHD needs further investigation. There are good but contending ideas from Dr. Roy Streit and Dr. Ron Mahler. The fusion concern stems from the PHD need to make the bins independent after every update, and if the updates are simultaneous this is a problem. Hence we chose to do predetection fusion/contact sifting [11].

Usual predetection fusion is simply a likelihood ratio test. But in this (practical) case the alternative hypothesis is composite: the location of the target is not known so a more sophisticated fusion scheme must be used. We have observed that the measurement errors of the Metron dataset result in the measurements’ Cartesian covariance ellipses being very eccentric. Some uncertainties are as much as 10-20km (major axis of ellipse). Therefore, for each contact, we generate 100 samples via Monte Carlo according to the contact’s measurement error covariance matrix. Without this step a large covariance measurement would still only be “seen” in the grid cell at the measurement’s nominal value.
We then “sift” these according to a grid (we use $25 \times 25$): if a contact yields a sample that is quantized to a grid cell, then that contact is added to the cell’s list. We test each grid cell’s number of hits against a threshold calculated according to binomial distribution and desired fused $P_{fa}$. For cells that pass the test, a PMHT measurement model and the EM algorithm are used on that cell’s listed contacts to refine the estimated measurement location and to estimate the posterior covariance. Afterwards, we merge detections that gate with each other, since often neighboring cells have used the same detections from the initial Monte Carlo step.

### 5.4 Metron Results

It should be mentioned that running the GM-CPHD without winnowing and without contact sifting resulted in unsatisfactory performance. Our results on scenario 1 of the Metron dataset are made possible by the addition of winnowing and predetection fusion steps before the tracker is run. Plots of the generated tracks are displayed in Figure 10. The ellipses reveal the location and covariance of the Gaussian modes, the magenta dots represent the measurements at the current scan.

These results are obtained with perfect initialization, i.e. a mode of weight 1 has been placed at the initial scan at the exact location of each target. Our tracker doesn’t include an IMM at the current time. This is an improvement we would like to make in the future as it would increase the performance on datasets such as Metron in which there are sharp turns along the target trajectory.

The tracking performance is good as little fragmentation is present, the track detection probability is high, the number of false tracks is very low and therefore the false alarm rate is very low, while the RMS error is acceptable.

### 6. CONCLUSIONS

Most treatments of the SEABAR07 and TNO-Blind multi-static datasets have used a traditional MHT target tracker, although we have seen others as well. A fielded system would probably use the MHT; we do have an MHT, but we would prefer to offer an alternative and exploratory perspective, and accordingly have proffered the GM-CPHD and in related work, the MLPDA [2].

Our results on the TNO-Blind dataset have been much improved by the corrected time measurement registration error. They are in line with the results of Tharmarasa et al [1] which similarly have better track probability of detection and less track fragmentation after the correction was applied.

The SNR adjusted version of the SEABAR07 datasets gave us the opportunity to improve the GM-CPHD by changing the GM mode-placement for initialization scheme to the one described in Subsection 4.3.
The adjusted SEABAR07 datasets present more of a challenge to our tracker than the original scenarios, noticeable in Figures 6, 7, 8 and the MOPs comparison of Table 2, but the GM-CPHD is able to successfully follow the target trajectory when a sufficient number of contacts is available.

When the GM-CPHD tracker was applied to the Metron simulated multi-static sonar data, it encountered an extremely challenging dataset. The data is very noisy and obeys strong statistical models (doppler, clutter, signal-excess, aspect-dependent SNR), perhaps more than would practically be found.

Feeding the tracker all the measurements in a scan, i.e. the combined measurements from 25 pings (from 25 receivers) obtained at the same time stamp, results in considerably long run time and poor performance as such a large number of measurements at each scan is a problem for the GM-CPHD, especially in the track management.

In order to be able to track on the Metron multisensor data, winnowing by amplitude and doppler along with a predetection fusion scheme had to be applied before the GM-CPHD tracker. This new approach has been
proven to work well as demonstrated by the plots of the tracks obtained on scenario 1 of the Metron dataset.

The work on the Metron dataset also underlined the need to incorporate a multi-model capability in the GM-CPHD tracker in order to improve performance when dealing with abrupt 90° corners.

REFERENCES