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Tracking crossing targets in passive sonars using NNJPDA

SonuVarghese[a*], Sinchu P[b], Subhadra Bhai D[b]

[a]*Model Engineering College, Thrikkakara, Kerala*
[b]*Naval Physical Oceanographic Laboratory, Thrikkakara, Kerala*

Abstract

This paper presents an effective solution to the problems of multi-target tracking in passive sonar. Since bearing information alone is used, target crossing problems arises in passive sonar. Nearest Neighbor Joint Probabilistic Data Association (NNJPDA) is employed for the information processing. Further a prediction mechanism is used, where the track bearing depends only on the predicted value not on the measurements. This leads to the correct assignment of measurements with the track in the clutter and thereby avoids the track loss. The state estimation is then refined by Kalman filtering based on the corrected measurements from the NNJPDA technique. Thus accurate and continuous track is maintained.

Keywords: Tracking; Passive sonar; Kalman filter; NNJPDA.

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1. Introduction

Target detection and tracking are two important functions of sonar systems. Once the direction of arrival of target is obtained, continuous tracking is necessary to classify the target. The tracking of multiple targets in passive sonar is a highly challenging task and is rarely discussed in the literature. The difficulty is due to the low information content and non-linearity of the received measurements. The common scenarios such as high clutter density, closely spaced targets and crossing targets add the difficulty of maintaining continuous and accurate tracks in passive sonar. Since passive sonar has only bearing information, it is likely that bearing trajectories of two targets or more targets cross each other. This can result in track loss. In this paper, crossing target problem in passive sonar is resolved using Nearest Neighbor Joint Probabilistic Data Association (NNJPDA) and a prediction mechanism. The measured value which is considered as the detection data is given to NNJPDA algorithm. Thus, the measurement values are assigned to the correct track. Here, the technique of uncertain information[1] processing is employed to solve the multi-target tracking problems. Thereby, the accurate track is maintained even after the targets cross. After the NNJPDA data association, track estimate is refined by Kalman filtering.

*Corresponding author:sonuvarghesemoly@gmail.com, ph: +918086416238

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Many algorithms are proposed for multi-target tracking in clutter environment; however, the application in passive sonar is less. The Joint Probabilistic Data Association (JPDA)[1] is a well-known approach for uncertain information processing, however, its computational complexity increases with number of targets and measurements. A Dempster Shafer (DS)[2] theory approach has an excellent ability to track multiple targets and has less computational complexity than JPDA. Joint Integrated Probabilistic Data Association (JIPDA)[3], and Multiple Hypothesis Tracking (MHT)[3] are two common algorithms for solving the multi-target passive tracking problems in clutter. MHT gives good performance for closely spaced target under small non-linear measurement conditions. Markov Chain Monte Carlo JIPDA (MCMCJIPDA)[3] approximation to JIPDA provide similar tracking results with less computational complexity. An another method suitable for the scenario with high bearing rate and multiple crossing targets is Cell Probability Density Function (CPDF)[4]. It decreases the implementation complexity and allowing the development of independent detection and tracking.

MHT approach used in narrow band passive sonar[5] provides better tracking in crossing situations. The system track all detectable frequency lines of multiple targets and frequency line information can be used to separate targets closely spaced in bearing. In selective signal tracking[6] coarse spectral features are used to facilitate tracking of contacts, especially weak ones, in cluttered scenarios with crossings and this method has less computational load and more robustness. NNJPDA[1], a modified version of JPDA, also abandons the weighted average updating of tracks in favor of one to one assignments of measurements to tracks. Thus, the computational complexity is reduced. If weighted averaging is used for closely spaced targets, the target track will be attracted to each other causing track bias and track coalescence. Hence, in this work NNJPDA is used for association. The association probability is computed for each measurement track pair. The measurement track pair with maximum probability is selected as the correct measurement track pair. These measurements are used to obtain the track estimate and are refined through Kalman filtering. Thus it is suitable for tracking in target crossing environment.

The rest of the paper is organized as follows. Section 2 represents the system model. The proposed scheme is explained in section 3. In Section 4, the simulation and results showing target crossing situation is presented. Some concluding remarks are offered in Section 5.

2. System model

The detection and estimation of a target in passive sonar is carried out with the acoustic signals like mechanical vibrations or sound signals generated from the target. The signal from the sensor array is processed to get the detection output. Tracking is performed on the detection output, which is corrupted by noise. Hence before tracking, noise is to be minimized. Kalman filter is a set of mathematical equations implementing a Predictor-corrector estimator. When some presumed conditions are satisfied, it minimizes the estimated error covariance[7]. As the new measurement arrives, it is processed in a recursive nature. From the noisy measurements it produces a best estimate. In estimation, the system is modeled with two equations called state equation and measurement equation. When the target is moving with constant bearing rate, state equation contains two states namely bearing and bearing rate. For a motion with constant bearing acceleration, there are three states –bearing, bearing rate and bearing acceleration. Measurement equation gives the measured bearing in both type of motion. When one bearing measurement is obtained, Kalman filter passes through three stages called gain update, filter update and prediction update[1]. Kalman gain determines whether the filter gives more weightage to predicted value or measured value. If the gain is low, it follows predictions otherwise, follows measurements. In this paper, multi-target scenario is considered and NNJPDA data association technique is used prior to Kalman filtering to obtain the track output.

2.1. Constant bearing rate model

The state equation containing the bearing and bearing rate of the target moving with constant bearing rate is modeled as,

$$\begin{pmatrix} P_{n+1} \\ V_{n+1} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} P_n \\ V_n \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} A_n \tag{1}$$

where P_n and V_n represents the bearing and bearing rate of the target on the nth scan and A_n is the random input at that time. Measured bearing of target is given by,

$$Y_n = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} P_n \\ V_n \end{pmatrix} + \varepsilon_n \tag{2}$$

where ε_n is the error in the measurement. The gain of Kalman filter in this motion is given by,

$$K_n = \frac{\Sigma_{n/n-1} \begin{pmatrix} 1 & 0 \end{pmatrix}}{\begin{pmatrix} 1 & 0 \end{pmatrix}^2 \Sigma_{n/n-1} + r} \cdot \tag{3}$$

where $\Sigma_{n/n-1}$ represents the predicted error co-variance matrix and r is the variance of measurement noise. Based on the gain and predicted estimate of bearing and bearing rate, actual estimate of target is computed using equation 4.

$$\begin{pmatrix} P_{n/n} \\ V_{n/n} \end{pmatrix} = \begin{pmatrix} P_{n/n-1} \\ V_{n/n-1} \end{pmatrix} + K_n \left(Y_n - P_{n/n-1} \right) \tag{4}$$

where K_n is the Kalman gain. The predicted estimate is calculated as,

$$\begin{pmatrix} P_{n+1/n} \\ V_{n+1/n} \end{pmatrix} = \begin{pmatrix} P_{n/n} + V_{n/n} \\ V_{n/n} \end{pmatrix} \tag{5}$$

If conventional tracking, a peak picking method, is applied for multi-target tracking scenario, the track of weak target will be lost during the crossing of target. In this model, a target with constant bearing rate and a fixed target are considered. NNJPDA is used to process uncertain information and thereby assign the measurement track pair correctly based on the association probability[1] of each measurement track pair. The corrected measurements are given to Kalman filter providing a refined track output. Since the correct measurement to track pair is obtained, the track is maintained even after the crossing of target.

2.2. Constant bearing acceleration model

The state equation containing the bearing, bearing rate and bearing acceleration of the targets moving with constant bearing acceleration is modeled as,

$$\begin{pmatrix} P_{n+1} \\ V_{n+1} \\ A_{n+1} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P_n \\ V_n \\ A_n \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} W_n \tag{6}$$

where W_n is the random input. Measured bearing of target is given by,

$$Y_n = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} P_n \\ V_n \\ A_n \end{pmatrix} + \varepsilon_n \tag{7}$$

where ε_n is the error in the measurement. The Kalman gain, actual estimate and predicted estimate are calculated using the equations similar to the constant bearing rate model with some changes in the parameter size. A target with constant bearing acceleration and a fixed target are considered in this model.

3. Proposed scheme

NNJPDA is used to obtain the correct measurement track pair and decide clutter as false measurements. The resulting measurements from NNJPDA are refined using a Kalman filter in two states or three states model. Thus, for Constant bearing rate model, NNJPDA and two states Kalman filtering together provides the correct tracking even in the target crossing situations. For Constant bearing acceleration model, NNJPDA and three states Kalman filtering together provides the correct tracking even in the target crossing situations.

In data association, first step is to decide a validation region about a predicted measurement so that the target originated measurements are valid. Those measurements outside this region are not considered for association and which are inside the region are candidates for association. Then the probability of each validated measurement assigned to each track is obtained. The measurement with maximum probability gets assigned as correct measurement of each track. Once the correct measurement track pair is obtained, the state estimate is updated using Kalman filter

The association probability is calculated for each measurement-track pair. Each validated measurement is considered with each of the tracks and all tracks are thus considered with all measurements. Then the association probability of all these pairs is computed. The probability of assigning a measurement to none of the track is also computed. For each measurement the track having maximum probability is selected as the correct pair corresponding to that measurement. Doing this for all obtained validated measurements the correct measurement to track association is obtained. Once a measurement is associated to a track, that measurement track pair is deleted from further calculations. If the probability is greater for the measurement associated to none of the track, then it can be considered as clutter detection. Then the associated measurement track pair is used for state estimation using Kalman filter. Thereby the measurements obtained during the crossing of weak and strong target situation will not lead to blindly following the strong track and eliminating the weak track.

When the targets are crossing, the unavoidable problem of merged measurements will occur. This happens when the sensor cannot resolve the individual detections for the targets. Under such situation NNJPDA cannot find solution to the problem. Hence a prediction mechanism is used, where the track bearing depends only on the predicted value not on the measurements. Thus, when crossing of the two targets are detected, prediction mode is used to obtain the track estimates and therefore, the track can be maintained even when the merged measurements problem arises.

4. Simulation

4.1. Set up

In this paper, two cases in passive sonar are considered. In the first case, a weak target moving with constant bearing rate and a strong fixed target is taken. The initial bearing and the bearing rate of weak target is taken in such a way that crossing of two targets occurs. Then another scenario is selected in such a way that the first weak target moves with constant bearing acceleration and the second target, a fixed one. Here, the two targets are separated initially. As the time goes the first target move closer to the stronger one and crossing occur.

First, the detection output for both situations are simulated and tracking is done based on this output. A threshold value is selected in such a way that the bearing values with signal greater than threshold in the detection output is obtained as measurements. NNJPDA is implemented to associate the obtained measurements with the correct target. A prediction mechanism is also implemented to resolve the merged measurement condition during crossing. Then a Kalman filtering is done for state estimation.

4.2. Results

4.2.1. Single target scenario

A single target moving at constant bearing rate and moving at constant bearing acceleration can be efficiently tracked using Kalman filter. The Mean Square Error (MSE) of the estimates in the above cases was computed and is compared with the MSE of the estimate obtained without using Kalman filter. In Fig. 1, the MSE of measurement error and the MSE of estimate error in two states is plotted against the number of sensor scans. Fig. 2 illustrates the comparison of MSE of measurement and estimate error in the three states model plotted against the number of sensor scans. In both figure, the estimate error is less than the measurement error. Here, the measurement error is the MSE of estimate without using Kalman filter and estimate error is the MSE of estimate using Kalman filter.

There are separate set of sensors for capturing signal in different frequency bands. Detection and tracking of a target is performed parallel in all these bands. Using Kalman filter, tracking is done in different frequency bands and these individual band outputs are combined using another Kalman filter. Then the MSE of each band estimate and combined band estimate is computed and plotted against the number of sensor scans in the Fig. 3. Here the combined estimate is better than each band estimate in terms of MSE.

4.2.2. Multi-target scenario

In multi-target scenario conventional tracking scheme was observed to fail in case of target crossing environment. The track of the weak target is lost after the crossing point. This drawback of conventional tracking is overcome by associating the data prior to tracking. NNJPDA data association is used in this work. The normalized energy density plot of the detection data at a particular sensor scan, waterfall of the detection system and waterfall of track output of a fixed bearing target and a target moving with constant bearing rate is illustrated in Fig. 4. Fig. 5 represents the normalized energy density plot, waterfall of detection system and waterfall of track output of a fixed bearing target and a target moving with constant bearing acceleration.

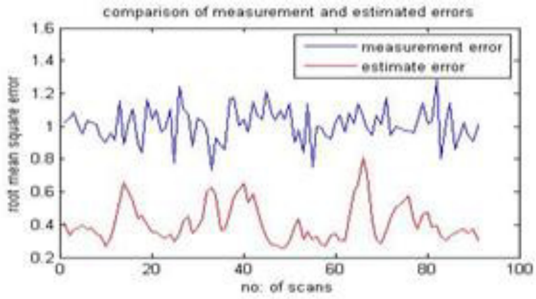

Fig. 1. Comparison of MSE between measured bearing and estimated bearing in two states.

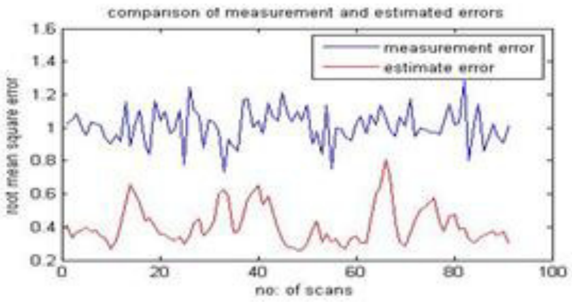

Fig. 2. Comparison of MSE between measured bearing and estimated bearing in three states.

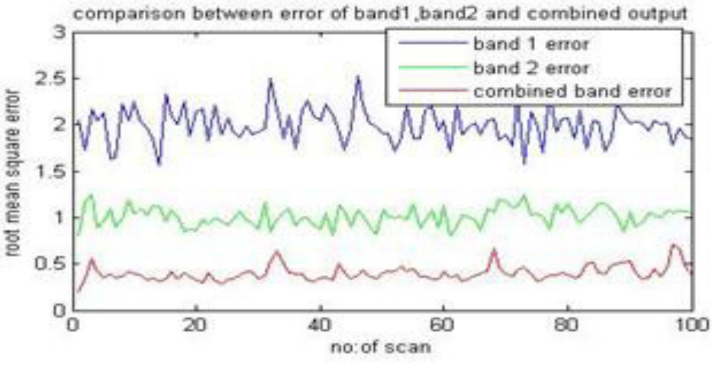

Fig. 3. Comparison of error between two band outputs and combined outputs.

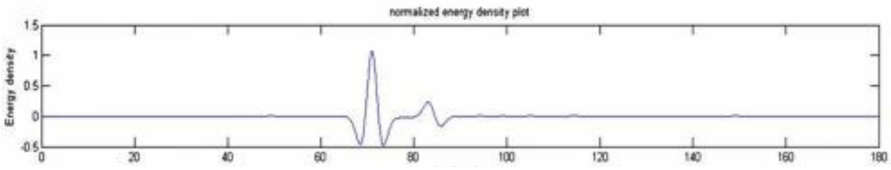

Fig. 4. Tracking output of Constant bearing rate model using NNJPDA for a two crossing target case.

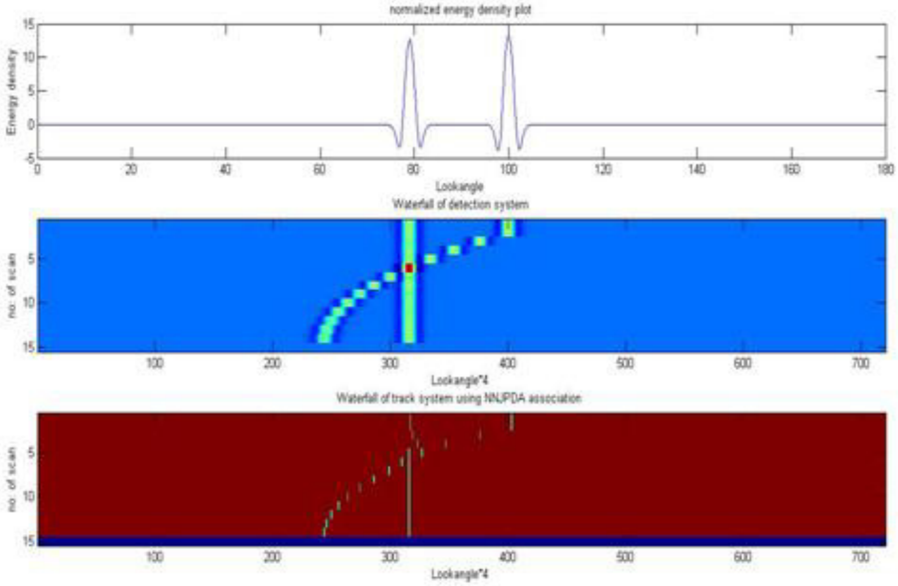

Fig. 5. Tracking output of Constant bearing acceleration model using NNJPDA for a two crossing target case.

5. Conclusion

Tracking of a single target using Kalman filter helps in the noise reduction. Better tracking happens in the full band tracking than individual band tracking in terms of noise reduction. However, when multi-target scenario is considered, tracking of closely spaced targets faces track loss during their crossing. By suitably employing NNJPDA data association prior to Kalman filtering, the track loss is avoided in such situations. Even when the two targets cross, the track of both weak target and strong target is maintained. The target moving with constant bearing rate is tracked using a two state Kalman filter and the target moving with constant bearing acceleration is by a three state Kalman filter. In the two motion model, the target track is maintained in the crossing situation.

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