Fusion of Over-the-Horizon Radar and Automatic Identification Systems for Overall Maritime Picture

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Abstract—Over-the-Horizon (OTH) radar and Automatic Identification System (AIS) are commonly used in the surveillance of maritime areas. This paper presents a method, which includes tracking and association algorithms, for fusing the information from these two types of systems into an overall maritime picture. Data to be fused consists of asynchronous track estimates from the OTH system and measurements obtained from AIS. The data available at the fusion center, as output of real world systems, contained incomplete information, compared to theoretical tracking and fusion algorithms. A method to estimate the missing information in the input data is described. Results obtained using real data as well as simulated data are presented. This type of fusion provides overall pictures of maritime areas, with benefits for surveillance against military threats, as well as threats to exclusive economic zones.

Keywords: Tracking, sensor fusion, data association, over-the-horizon radar, automatic identification system.

1 Introduction

Over-the-Horizon (OTH) radar systems and Automatic Identification System (AIS) are commonly used as stand-alone tracking systems in maritime surveillance. This paper describes the fusion of the estimates provided by such independent systems, surveying within the same area, into an overall maritime picture. The OTH radar covers a static (fixed) area, while the AIS, mounted on an aircraft, changes continuously its coverage area. A description of the OTH and AIS systems in presented in Section 2. The track estimates obtained from the real systems, OTH, AIS, provide incomplete information (e.g. incomplete covariance matrices), which cannot be used directly in fusion. Preprocessing of these estimates is described in Section 3. For track-to-track association, the M out of N method is used, based on a statistically derived cost, both detailed in Section 4. The fusion filter, based on the Kalman filter, is described in Section 5. Results achieved on real data, obtained courtesy of DRDC (Defense Research and Development Canada) Ottawa, as well as results obtained using simulated data, are presented in Section 6.

2 OTH and AIS systems description

2.1 Over-the-Horizon Radar system data

The OTH radar system commonly measures the range, angle, and range rate of a detected target. Due to multiple-path reflections and clutter, the sensor has a high incertitude in measurements. In addition, the sensor fails to detect a target when the target range rate is below the threshold of the motion target indicator (MTI) system. The multipath problem (several detections obtained for the same target) is already solved at the OTH tracker level, this work focuses on fusing the already estimated tracks. However, the environmental uncertainties, and multimode misidentification [3] reflect in the estimated OTH tracks through higher level of incertitude of the track estimate. Maneuvering targets and slowly moving targets may undergo bursts of missed detections. In analyzing and simulating the OTH data, the probability of detection, denoted as $P_{\text{OTH}}$, the probability of a burst of missed detections, denoted as $P_{\text{M burst}}$, and the length of such burst, denoted as $L_{\text{burst}}$, are considered. The length of a burst of missed detections is equal to the equivalent number of detections that would cover the time interval. The coverage area of the OTH system is fixed; therefore targets entering the OTH surveillance area are consistently detected with the statistics above. The OTH system does not identify the targets through direct communication with them; this information is added through the fusion of the OTH tracks with the AIS data. Thus AIS-OTH fusion converts non-identified OTH tracks into a more informative maritime picture.

2.2 Automatic Identification System data

An AIS commonly integrates a GPS (Geographical Positioning System) receiver with a standardized transceiver system and other navigational equipment on
board ship. The AIS data is usually exchanged between nearby ships and vessel traffic systems, principally for identification of vessels at sea. This data consists of ID, position, course, speed and is used to resolve the problem of identifying ships when not in sight (e.g. at night, in fog, in radar blind arcs or shadows or at distance). The AIS information may become unavailable for certain intervals, e.g. the GPS could lose lock on the required number of satellites by being in the shadow of an obstruction (e.g. mountain, ship superstructure), as detailed in Section 2.3 and shown in Fig. 1. In the real data used, the AIS data was acquired by an AIS receiver on an aircraft that circled the area for a few hours, therefore dynamically changing the coverage region. The precision of such a system is the precision of the GPS, therefore very high and the unique ID provides full target identification. However, ships not equipped with AIS systems, not transmitting AIS data, or out of the coverage area of the AIS receiver are not acquainted for by the AIS receiver. The OTH information adds the tracks not registered by the AIS receiver, as well as track estimates of the AIS registered tracks for periods when the AIS is locked in a blind area. OTH tracks may be considered as skin returns, while the reliability of AIS measurements, with complete target information (unique IDs), may be taken as beacon return (approach close to [4]).

2.3 Dynamics of the coverage areas
Sample of the space-time coverage area dynamics of both AIS and OTH systems, estimated through their detected/tracked targets, over a period of more than nine hours is presented in Fig. 1. During the observed interval the AIS receiver approaches the OTH surveillance area in the first hour, actively overlaps its coverage with the OTH coverage area for one hour, does not receive any information in the following hour, starts receiving again and overlaps its coverage with the OTH coverage area for the next five hours, and finally moves eastward (to the left) out of the OTH coverage region.

3 Preprocessing
3.1 OTH data available for fusion
In a theoretical track-to-track fusion, the track state \( \mathbf{x}_k \) at time \( t_k \) usually includes position \( (x, y) \) for a 2D estimate in maritime surface surveillance) and the respective velocities

\[
\mathbf{x}_k = \begin{bmatrix} x_k & \dot{x}_k & y_k & \dot{y}_k \end{bmatrix}^T
\]

(1)

The corresponding state estimate covariance matrix \( \mathbf{P}(k) \) obtained by the local tracker contains the covariance of each element of the state, as well as all cross-covariances between elements of the state.

![Fig. 1 Dynamics of the coverage areas of AIS (blue tracks) and OTH (magenta tracks) real systems over a period of more than nine hours.](image)

The covariance matrix, as providing information on the certainty of the estimate, is essential in performing further fusion of the estimates. In the real-world OTH system considered herein, even though the estimated state is available with position and velocity components, \( \mathbf{x}_k = [x(k) \quad \dot{x}(k) \quad y(k) \quad \dot{y}(k)]^T \), due to the fact that from the covariance matrix \( \mathbf{P}_k \) only the terms \( P_{11}, P_{33}, P_{13}, P_{31} \) are available, and therefore the uncertainty on the velocity estimates is not known, the velocity information cannot be used. This situation is common for tracking systems that output tracks for displaying purposes and were not designed with the purpose of further fusion, therefore having the covariance matrix partially dropped. A Kalman-type pre-filtering of the OTH estimated tracks with dropped information is performed prior to the fusion with the AIS estimation, described in Section 3.3.

3.2 AIS data available for fusion
While the AIS system does not provide consistent detections over time (due to AIS locks in blind zones, as well as not receiving data from vessels not equipped with the system), the received data is characterized by accurate position information and confirmed identifier (ID). Whereas the covariance matrix is not provided directly, the terms corresponding to the variances of the position estimates are taken from the variance of the AIS
measurement sensor. The cross-covariance between x and y coordinates is considered zero. In order to retrieve the required full state estimate and covariance matrix estimates needed for fusion, a pre-processing of the AIS estimates is performed, similar to the one applied to OTH estimates, and described in Section 3.3.

### 3.3 Processing of OTH tracks and AIS measurements before fusion

The pre-processing involves the stages of track initialization and filtering, only for the purpose of completing the state information and the covariance matrix, up to the first order (velocities). The track re-initialization for pre-filtering is performed using two data points. The partial covariance matrix available from the OTH (or AIS) system,

\[
P_{\text{OTH},k} = \begin{bmatrix} P_{x_x,k} & P_{x_y,k} \\ P_{y_x,k} & P_{y_y,k} \end{bmatrix}
\]

is used to initialize what is the measurement noise in a filtered track:

\[
R_{\text{pre OTH},k} = P_{\text{OTH},k}
\]

The partial state vector available from the OTH system

\[
x_{\text{OTH},k} = [x_k, y_k]^T
\]

and the pre-processed-OTH state and covariance matrix are computed using the information filter approach [1]. The indices 0 and 1 correspond to the times \( t_0 \) and \( t_1 \), being the first two estimates of the track to be initialized.

\[
x_{\text{pre OTH},1} = \left( (H F_0^{-1})^T \left(R_0 + H Q_0 H^T \right)^{-1} H F_0^{-1} + H^T R_1^{-1} H \right)^{-1} \left( (F_0^{-1})^T H^T \left(R_0 + H Q_0 H^T \right)^{-1} z_k + H^T R_1^{-1} z_0 \right)
\]

and

\[
P_{\text{pre OTH},1} = \left( (H F_0^{-1})^T \left(R_0 + H Q_0 H^T \right)^{-1} H F_0^{-1} + H^T R_1^{-1} H \right)^{-1} \left( (H F_0^{-1})^T \left(R_0 + H Q_0 H^T \right)^{-1} H F_0^{-1} + H^T (R_0 + H Q_0 H^T) H \right) \left( (H F_0^{-1})^T \left(R_0 + H Q_0 H^T \right)^{-1} H F_0^{-1} + H^T R_1^{-1} H \right)^{-1}
\]

with \( T_k = t_{k+1} - t_k \). Using the information filter model for track initialization has the advantage of being able to start the pre-filtered track with non-informative prior for the covariance matrix, as the complete matrix is not available [1]. The process noise covariance matrix is chosen modeled as DCWNA (Discrete Continuous White Noise Acceleration) [1]:

\[
Q_k = E \left[ G_k v_k \left(G_k v_k \right)^T \right]
\]

\[
Q_k = \begin{bmatrix} \frac{1}{2} T_k^2 & \frac{1}{2} T_k^4 & 0 & 0 \\ \frac{1}{2} T_k^2 & T_k^4 & 0 & 0 \\ 0 & 0 & \frac{1}{2} T_k^4 & \frac{1}{2} T_k^6 \\ 0 & 0 & \frac{1}{2} T_k^4 & T_k^6 \end{bmatrix} \tilde{q}
\]

The dynamic state and measurement equations, at times \( t_k \) for \( k>1 \) are

\[
x_{k+1} = F_k \cdot x_k + G_k \cdot v_k
\]

\[
z_k = H_k \cdot x_k + w_k
\]

for which the estimation of the complete state \( x_k \) and covariance matrix \( P_k \) uses the common Kalman filter [1]. The noise coefficient \( \tilde{q} \) is chosen such that the already available data in the state estimate and covariance matrix is not changed significantly by pre-filtering.

### 4 Tracks Association

The processing logic for a newly received AIS data is shown in Fig. 2. A similar processing is applied at the receipt of an OTH track estimate. At the time an AIS data sample is received, given that there are already formed OTH and AIS tracks, preprocessed as described in Section 3, as well as possible AIS data from which a track is not initialized yet (in AIS Initial Data Storage in Fig.2). The cost of association of the newly received incomplete AIS estimate with an existing OTH pre-filtered track is computed first as described in Section 4.1. If the association between the AIS and OTH track is not declared, then either the AIS data is filtered into an existing AIS track or the AIS data is used to initialize a new track with an existing single AIS measurement of
same ID. If the association with an OTH track is declared, the AIS data is fused to the OTH track and further AIS data of same ID is filtered into the fused track.

The association is done in two steps. First each best cost found between tracks of different types is recorded for the given pair of tracks. If M past best costs are found recorded for a pair of AIS and OTH tracks within their list of last N associations, then the second step confirms the association and passes them for fusion. This method is recorded in literature as the M out of N association [5].

4.1 Track Association Cost definition

Below the cost computation is detailed for associating a newly received AIS data with an existing pre-filtered OTH track. The same procedure is used for a new sample of OTH data. The association cost of an input data to an already pre-filtered track is computed as the negative logarithm of the likelihood of the measurement conditioned on the predicted state. The association cost is

\[
\text{cost} = -\log\left(p\left(z_{k+1}^{\text{AIS}} | H\hat{x}_{k+1|k}^{\text{OTH}}\right)\right)
\]

Using the normal distribution for the conditional pdf above, (16) translates into

\[
\text{cost} = -\log\left(N\left(z_{k+1}^{\text{AIS}} | H\hat{x}_{k+1|k}^{\text{OTH}}, S_{k+1}^{\text{OTH}}\right)\right)
\]

with

\[
N(z_{k+1}^{\text{AIS}} | H\hat{x}_{k+1|k}^{\text{OTH}}, S_{k+1}^{\text{OTH}}) = \frac{1}{\sqrt{2\pi S_{k+1}^{\text{OTH}}}} \cdot \exp\left(-\frac{1}{2} \left(z_{k+1}^{\text{AIS}} - H\hat{x}_{k+1|k}^{\text{OTH}}\right)^T \left(S_{k+1}^{\text{OTH}}\right)^{-1} \left(z_{k+1}^{\text{AIS}} - H\hat{x}_{k+1|k}^{\text{OTH}}\right)\right)
\]

which is the normal pdf with mean equal to the predicted state and covariance matrix \(S\). The covariance matrix in (16) denotes the covariance matrix of the innovation \(V_{k+1} = z_{k+1}^{\text{AIS}} - H\hat{x}_{k+1|k}^{\text{OTH}}\), estimated by (11)

\[
S_{k+1}^{\text{AIS,OTH}} = H \cdot P_{k+1|k}^{\text{OTH}} \cdot H^T + R_{k+1}^{\text{AIS}}
\]

with the OTH predicted covariance matrix of the state

\[
P_{k+1|k}^{\text{OTH}} = F_k \cdot P_{k|k}^{\text{OTH}} \cdot F_k^T + Q_{k}^{\text{OTH}}
\]

Upper indices were added to indicate the source of the data, when data from both sources are present in the same equation. The position information (available) in the partial covariance matrix of the input data, similar to (2), this time for AIS, is used for \(R_{k+1}^{\text{AIS}}\) in (19):

\[
R_k^{\text{AIS}} = \begin{bmatrix} P_{\text{AIS},u}(k) & P_{\text{AIS},v}(k) \\ P_{\text{AIS},v}(k) & P_{\text{AIS},y}(k) \end{bmatrix}
\]

4.2 M out of N association method

For each input data of ID i, the cost detailed in section 4.1 is computed for the available tracks \(j \in J\) (where \(J\) is the set of tracks of other type), as in (17), this time for AIS, is used for \(R_{k+1}^{\text{AIS}}\) in (19):

\[
c(i,j) = -\log\left(N\left(z_{k+1}^{\text{AIS}} | H\hat{x}_{k+1|k}, S_{k+1}^{\text{AIS}}\right)\right)
\]

The track selected for the recorded association event to this input data \(z_{k+1}^{\text{AIS}}\) is
and the event is recorded to the track combination \((i, j)_{\text{best}}\). Only the last \(N\) such best recorded combinations are stored for each track combination. Once a pair of tracks \((i, j)\) is found having \(M\) combinations together out of the last \(N\) ones, the association is confirmed and the tracks will be fused. A gating, which restricts the number of tracks that enter the association, based on the input data position, currently available pre-filtered tracks positions, input (incomplete) covariance matrices and maximum velocities is applied first, for both \(x\) and \(y\) directions, is detailed below for \(x\):

\[
\left| z_{x,t+1}^i - \hat{x}_{x,t+1|i} \right| < (t_{t+1} - t_{k}) v_{\text{max}} + a \left( \sqrt{R_{11}^i} + \sqrt{P_{11}^i} \right)
\]  

(24)

where \(v_{\text{max}}\) is the maximum velocity allowed for a target and \(a\) is a constant chosen.

5 OTH tracks to AIS information fusion

After the input data passes the \(M\) out of \(N\) association with an existing track, the input data is fused with the track of different type. The estimate of the fused track is computed using the update equation of the Kalman filtering.

5.1 Fused state update using Kalman Filter

Based on the new input data available \(z_{k+1}\), equations of predicted track state in (15), predicted covariance matrix in (20) and innovation covariance matrix in (19), the updated state of the fused track is computed as

\[
\hat{x}_{k+1}^{ij} = \hat{x}_{k+1|i} + W_{k+1}^{ij} (z_{k+1} - Hx_{k+1|i})
\]

(25)

where the combined gain matrix is computed as

\[
W_{k+1}^{ij} = P_{k+1|i} H^T (S_{k+1}^{ij})^{-1}
\]

(26)

The Kalman filter is optimal under the Gaussian-Markov assumption (white, Gaussian noises and initial state, and Markov process). The error of the input AIS and OTH estimates can be assumed as white. The independence of AIS and OTH errors is assumed based on their estimation from different sensors and estimators. The OTH estimator (tracker) uses a dynamic state equation with process noise to approximate the target state, while the AIS uses the (differential) GPS receiver in estimating the highly accurate position. Therefore, their error can be assumed as uncorrelated and, furthermore, an AIS input data and an OTH pre-filtered track can be assumed as having uncorrelated errors. However, as AIS and OTH pre-filtering are based on similar dynamic equations, a correlation of errors is present for an OTH input data and an AIS pre-filtered track. Based on the AIS higher precision, however, the correlation is considered to be insignificant. Therefore, the Kalman filter can be used with good performance for filtering one type of estimate with another.

6 Simulation

6.1 Simulated data

The models of the simulated OTH and AIS tracks were developed such that they closely replicate real OTH and AIS tracks, provided courtesy of DRDC (Defense Research Development Canada) in Ottawa. The statistics of the OTH tracks are modeled through the normal probability of detection, \(P_{\text{DOTH}} = 0.85\), the probability of a burst of missed detections, \(P_{\text{M burst}} = 0.05\), and the Poisson distributed length of such burst, \(L_{\text{burst}}(\lambda)\), with \(\lambda = 8\), described in section 2.1. The length of a burst of missed detections is equal to the equivalent number of detections that would cover the time interval. Initial simulated measurements are considered in ground coordinates (i.e., after mapping the measurements in radar coordinates into ground coordinates). Combination of OTH tracks resulting from multipath propagation is considered already performed at the OTH tracker level, therefore each target is represented by only one track as input for fusion. The simulated track estimates for AIS and OTH systems are generated starting from OTH-type radar measurements in polar coordinates (range, angle and range rate)

\[
z_{\text{polar}} = \begin{bmatrix} r & \theta & \dot{r} \end{bmatrix}^T
\]

(27)

where \(r\) is the target radial measurement, \(\dot{r}\) is the target radial rate measurement and \(\theta\) is the angular target position measurement. For the measurement covariance matrix

\[
R_{\text{polar}} = \begin{bmatrix} \sigma_r^2 & 0 & 0 \\ 0 & \sigma_\theta^2 & 0 \\ 0 & 0 & \sigma_\dot{r}^2 \end{bmatrix}
\]

(28)

the standard deviations \(\sigma_r\), \(\sigma_\theta\), and \(\sigma_\dot{r}\) were set to 1000 m, 0.8 m/s, respectively 0.01 rad. The standard polar-to-Cartesian translation with approximate terms based on linearization [1], [2] is used,

\[
x_k = r_k \cos(\theta_k)
\]

(29)

\[
y_k = r_k \sin(\theta_k)
\]

(30)
which results in the terms of (27) at each sampling interval of the form [1]:

\[
R_{xx,k} = r^2 \sigma_{x}^4 \sin^2(\theta_k) + \sigma_{x}^2 \cos^2(\theta_k) \\
R_{yy,k} = r^2 \sigma_{y}^4 \cos^2(\theta_k) + \sigma_{y}^2 \sin^2(\theta_k) \\
R_{xy,k} = (\sigma_{x}^2 - r^2 \sigma_{x}^2 \sigma_{y}^2) \sin(\theta_k) \cos(\theta_k)
\] (31)

For the simulated sensors precision, the above standard conversion does not generate large bias errors [4]. The dynamic model used to simulate the OTH tracks is based on the Kalman filter, with plant equation and measurement equations given by [1]:

\[
x_{k+1} = F_k \cdot x_k + G_k \cdot v_k \\
z_k = H \cdot x_k + w_k
\] (34)

where \(x_k, x_{k+1}\) are the states (at discrete sampling times \(t_k, t_{k+1}\)) of the track in Cartesian coordinates, \(F_k\) is the transition matrix, \(G_k, v_k\) represent the process noise, \(H\) is the measurement matrix and \(w_k\) is the measurement noise. The resulting state vector is modeled as in (1) and the state transition matrix \(F_k\) has the form in (10). The process noise is modeled using the DCWNA model in (11) and (12) with \(q\) being the power spectral density of the process noise [1]. The measurement vector \(z_k\), with components transformed in Cartesian coordinates (29)-(33), the matrix \(H\), and process noise vector \(w_k\) are used in the forms [2]

\[
z(k) = \begin{bmatrix} x(k) \\ y(k) \\ \hat{r}(k) \end{bmatrix}^T
\] (36)

\[
H(k) = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & \cos(\theta(k)) & 0 & \sin(\theta(k))
\end{bmatrix}
\] (37)

and

\[
w(k) = \begin{bmatrix} w_x(k) \\ w_y(k) \\ w_\theta(k) \end{bmatrix}^T
\] (38)

respectively. Based on (36) and (38) the measurement noise covariance matrix has the form

\[
R(k) = \begin{bmatrix}
R_{xx}(k) & R_{xy}(k) & 0 \\
R_{yx}(k) & R_{yy}(k) & 0 \\
0 & 0 & \sigma^2
\end{bmatrix}
\] (39)

Each generated track is tagged with identifier (ID), which for the AIS completely identifies a target, while for OTH it does not (e.g. a single target for which track is lost and restarted might have different OTH IDs at different times). For the M out of N association method, the values \(M = 3\) and \(N = 4\) were used. Results obtained on simulated data, containing 10, respectively 50 targets, are presented in the next figures. In Fig. 4 the tracks of 10 targets are shown during the processing, over a given window interval. While in Fig. 4 the final results, with full tracks, over the whole simulated interval (around 20 hours) are displayed. The end of each track is marked with a circle, while the first fusion time of a pair of two tracks is marked with a star.

![Fig. 3 Simulated AIS (cyan), OTH (red) and fused (violet) tracks, during processing, over a time window interval.](image1)

![Fig. 4 Final fusion results for 10 simulated targets within the simulated OTH surveillance region. All tracks are fused. Circles mark end of the tracks, stars mark first fusion times for each pair of fused tracks.](image2)
Fig. 5 Simulated AIS (light blue), OTH (red) and fused (violet) tracks, during processing, over a time window interval.

Fig. 6 Final fusion results for 50 simulated targets within the surveillance region. Fused tracks are violet and non-fused AIS measurements are light blue.

6.2 Real data

Sample of the results obtained on real data with M = 3 and N = 4 in the association method, are presented next. In Fig. 7 a snapshot of time is displayed, while in Fig. 8 the whole history of tracks, fused or not, is presented. All the overlapping AIS-OTH tracks are properly fused. For the OTH-AIS pair in Fig. 8 not fused, and which seem to be from same target, the AIS receiver does not receive data while the target is tracked within the OTH surveillance region.

Fig. 7 Real data AIS (blue), OTH (red) and fused (violet) tracks, during processing, over a time window interval.

Fig. 8 Results obtained with simulated data. OTH tracks not fused are marked with red, AIS tracks with light blue and fused tracks with violet. First fusion moment is marked with star.

7 Conclusions

A method of fusing AIS data with incomplete OTH tracking data is presented. The fusion of AIS with OTH data results in a more informative surveillance picture. It facilitates tracking targets with complete AIS ID information, over periods the AIS is not transmitting, based only on OTH data. The probability of loosing (and reinitializing) an OTH track decreases very much, once associated to an AIS ID. The non-cooperative targets tracked by OTH are quickly identified as the ones not being fused with any AIS data. Future work is intended for association logic at boundaries between coverage areas of different sensors, as well as making further use of the highly precise AIS data position information.
References


