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KNOWLEDGE-BASED SHIP TRACKING APPLIED TO HF SURFACE WAVE RADAR DATA

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ABSTRACT

In recent years, low-power high-frequency surface-wave radars have received significant attention thanks to their over-the-horizon coverage capability and the continuous-time operation mode. These radars have become effective long-range early-warning tools for maritime situational awareness applications.

In this paper a knowledge-based multi-target tracking algorithm is described. The advantages in using a prior information on ship traffic are assessed exploiting real data acquired by two high-frequency surface-wave radars. The outcomes confirm the ability of the proposed approach to better follow targets with a time-on-target increment up to 30% with respect to existing methods. A reduction of the track fragmentation up to 20% is also observed.

Index Terms— Knowledge-Based Tracking, Multi-Target Tracking, High-Frequency Surface-Wave Radar, Maritime Surveillance.

1. INTRODUCTION

High-frequency (HF) surface-wave (SW) radar systems are cost-effective tools that have influenced maritime situational awareness applications thanks to their capability of detecting targets over-the-horizon, their continuous-time coverage, and their possibility of estimating ship velocity exploiting the Doppler effect [1]. Low-power HFSW radar systems have been mainly developed for ocean remote sensing applications, e.g. surface currents and sea state mapping [2]. Using HFSW radar systems for target detection - a purpose for which there were not designed - poses additional challenges. Poor range and azimuth resolutions compared to microwave radars, high non-linearity in the state/measurement space, and a significant false alarm rate [3] are all problems to cope with.

In [4], some of the authors addressed these challenges using a signal processing chain consists of three stages: Detection, tracking, and fusion. The detection stage is performed using a 3D ordered statistics (OS) constant false alarm rate (CFAR) algorithm [5] developed at the University of Hamburg. The tracking part is based on the popular joint probabilistic data association (JPDA) rule [6, 7] in combination with the unscented Kalman filter (UKF) [8]. The data fusion strategy adopts the track-to-track association and fusion (T2T-A/F) paradigm [7]. An analysis of the outcomes reveals that track segmentation (i.e. the generation of multiple tracker's tracks starting from an unique source target) remains a challenge. It is mainly due to the intermittent presence of the target contacts. Targets may be missing due to the radar synchronization being turned off, the target aspect angle, or because of sailing into Bragg scattering regions [4].

It is worth noting that the problem of track fragmentation in ship tracking is similar to the phenomenon of the track obscuration in ground target tracking [9]. In that case, the variable structure interactive multiple model (VS-IMM) has been proposed as a solution. Thus, in this paper, a knowledge-based (KB) tracking algorithm based on the VS-IMM estimator and a prior information on ship traffic provided by automatic identification system (AIS) messages is applied to the vessel tracking problem. The improvements on three performance metrics (i.e. time-on-target, false alarm rate, and track fragmentation [4]) are shown using real HFSW radar data.

The reminder of the paper is as follows. The proposed target tracking methodology is presented in Sect. 2. In Sect. 3, the experimental results are described. Finally, conclusions are drawn in Sect. 4.

2. TRACKING METHODOLOGY

This section is devoted to the description of the tracking procedure applied to the HFSW radar for maritime traffic surveillance. This is an enhanced version of the JPDA-UKF approach in [4], which integrates the VS-IMM mechanism able to take advantage of a prior information about historical ship traffic provided by the gathering of AIS messages.

2.1. Dynamic Models

The constant velocity model is adopted to describe the targets' dynamic [7]

$$\mathbf{x}_k = \mathbf{F}_k \mathbf{x}_{k-1} + \mathbf{\Gamma}_k \mathbf{v}_k, \quad (1)$$

where $\mathbf{x}_k = [x_k, \dot{x}_k, y_k, \dot{y}_k]^T$, x_k, y_k are the position components along x, y directions, $\dot{x}_k, \dot{y}_k$ are the corresponding velocity components, $[\cdot]^T$ is the transpose operator,

$$\mathbf{F}_k = \begin{bmatrix} 1 & T_k & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T_k \\ 0 & 0 & 0 & 1 \end{bmatrix}, \boldsymbol{\Gamma}_k = \begin{bmatrix} T_k^2/2 & 0 \\ T_k & 0 \\ 0 & T_k^2/2 \\ 0 & T_k \end{bmatrix},$$

T_k is the sampling time, $\mathbf{v}_k$ takes into account target acceleration and unmodeled dynamics, and is assumed to be Gaussian with zero-mean and covariance matrix $\mathbf{Q}$.

We can define two different matrices $\mathbf{Q}$, depending on whether the target motion is off a sea lane or along sea lane. The former can be described with

$$\mathbf{Q} = \begin{bmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{bmatrix}, \quad (2)$$

where the variances in the two directions σ_x^2 and σ_y^2 are assumed equal.

In the other case (i.e. targets along sea lane), since the state estimation is carried out in the x-y coordinate system, the variances of the process noise components along, σ_a^2, and orthogonal, σ_o^2, to the sea lane need to be converted into the covariance matrix. Thus, we have [9]

$$\mathbf{Q} = \begin{bmatrix} -\cos\psi & \sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \sigma_o^2 & 0 \\ 0 & \sigma_a^2 \end{bmatrix} \begin{bmatrix} -\cos\psi & \sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}, \quad (3)$$

where ψ represents the direction of the sea lane followed by the target.

2.2. Observation Model

Assuming a radar located at the origin in spherical coordinates, the target-originated measurement equation can be expressed as

$$\mathbf{z}_k = \mathbf{h}(\mathbf{x}_k) + \mathbf{n}_k, \quad (4)$$

where, since the radar measures the target range, bearing (azimuth), and range rate, we have

$$\begin{aligned} \mathbf{z}_k &= \left[z_k^r, z_k^b, z_k^{\dot{r}}\right]^T, \\ \mathbf{n}_k &= \left[n_k^r, n_k^b, n_k^{\dot{r}}\right]^T, \\ \mathbf{h}(\mathbf{x}_k) &= \left[h_r(\mathbf{x}_k), h_b(\mathbf{x}_k), h_{\dot{r}}(\mathbf{x}_k)\right], \\ h_r(\mathbf{x}_k) &= \sqrt{x_k^2 + y_k^2}, \\ h_b(\mathbf{x}_k) &= \arctan\left(\frac{y_k}{x_k}\right), \\ h_{\dot{r}}(\mathbf{x}_k) &= \frac{x_k \dot{x}_k + y_k \dot{y}_k}{\sqrt{x_k^2 + y_k^2}}, \end{aligned} \quad (5)$$

with $z_k^r, z_k^b, z_k^{\dot{r}}$ representing the radar measurements of the target range, bearing, and range rate, respectively. The measurement noise vector $\mathbf{n}_k$ is assumed to be Gaussian with zero-mean and covariance matrix

$$\mathbf{R} = \begin{bmatrix} \sigma_r^2 & 0 & \rho\sigma_r\sigma_{\dot{r}} \\ 0 & \sigma_b^2 & 0 \\ \rho\sigma_r\sigma_{\dot{r}} & 0 & \sigma_{\dot{r}}^2 \end{bmatrix}, \quad (6)$$

where σ_r^2, σ_b^2, and $\sigma_{\dot{r}}^2$ are the variances in range, bearing, and range rate, respectively, and ρ is a correlation coefficient defined as in [10].

2.3. VS-IMM JPDA Tracker

When an off-sea lane target enters the vicinity of a sea lane, it could become an on-sea lane target (i.e. a target that follows that sea lane). Similarly, a target on a sea lane may leave it. When an off-sea lane target is in the vicinity of a sea lane, a new mode, representing constrained motion along that sea lane, see Sect. 2.1, is added. Similarly, a decision is made as to whether the considered target leaves the vicinity of a sea lane; in that case, the related mode is removed.

One of the major issues in adding or deleting modes to handle on-sea lane/off-sea lane motion is deciding when to add or delete. Thus, at time k, for each established track, a decision is made about which sea lanes the target can follow. This is carried out by testing whether the predicted location lies within a certain neighborhood ellipsoid of any sea lane (e.g. neighborhood ellipsoids for the cases under test can be seen in Fig. 1). Modes corresponding to sea lanes not validated are removed.

Assume that a target follows a given sea lane and for some reason (e.g. the first order Bragg scattering or radar synchronization), it is not visible (no detections are associated). In that case, the mode corresponding to that sea lane is replaced with a "hidden target" model that modifies the filter estimates and likelihoods using the information that the target detection probability is zero [9, 11]. The "hidden target" model is removed from the mode set if one of the following conditions become true: $i)$ The target becomes visible again or $ii)$ the corresponding sea lane segment is no longer validated.

Starting form the mode set defined by the rules described above, for a given target at time k, the VS-IMM estimator is exploited, see [9, 11] for further details. The multiple model JPDA algorithm [12] is also adopted to cope with the measurement-to-track association problem, see [11] for details.

Finally, the used track management strategy is described. The M-of-N rule is exploited for the track initiation [7, 11]. A confirmed track is an on-sea lane confirmed track if the target that is generating the track follows the same on-sea lane mode for a period time. Otherwise, it is defined off-sea lane confirmed track. An on-sea lane confirmed track is terminated if: $i)$ The likelihood goes down a given threshold, $ii)$ the counter, which takes into account the number of consecutive scans in which the target is not visible, exceeds a given value, $iii)$ the target's track uncertainty has grown beyond a certain threshold, or $iv)$ the target has reached an unrealistic maximum velocity. An off-sea lane confirmed track is terminated if: $i)$ No detection has been validated for the past M^* out of N^* most recent sampling times, $ii)$ the target's track uncertainty has grown beyond a certain threshold, or $iii)$ the

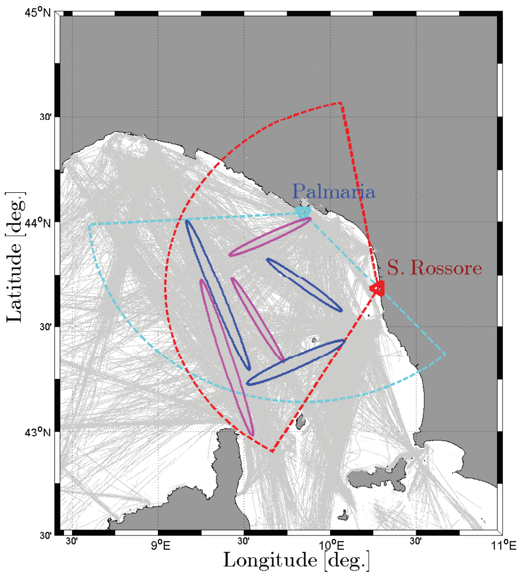

Fig. 1. In red and cyan the S. Rossore and Palmaria radars' fields of view. Magenta ellipsoids indicate the selected areas for the S. Rossore dataset, while in blue the ones for the Palmaria dataset. Gray lines represent the historical AIS tracks.

target has reached an unrealistic maximum velocity.

3. EXPERIMENTAL RESULTS

In this section a comparison between the proposed VS-IMM JPDA and the standard JPDA is provided by using real data acquired by two HFSW radar systems. As already proposed in [4], we use as ground truth for tracking assessment the AIS messages. The association procedure between AIS and tracking outcomes relies upon a nearest neighbor approach. The normalized time-on-target (ToT), the false alarm rate (FAR), and a measurement of the track fragmentation (TF) N^{TF} are used as performance metrics, see [4] for further details.

The proposed KB tracking has been tested on one month of data provided by the NURC BP09 experiment starting from May 7, 2009 to June 4, 2009. Data from the Palmaria and S. Rossore wellen radar (WERA) systems (named Palmaria and S. Rossore datasets) have been processed using the CFAR algorithm developed at the University of Hamburg. The detections are then provided to the KB tracking approach and to the standard JPDA [4] for comparison purposes. Fig. 1 depicts the selected areas to test and compare the two algorithms.

In order to have a fair comparison, we compare the ToT for both the approaches at fixed FAR values. This curve is obtained by varying the parameter N^*. Fig. 2 reports the convex hulls (solid lines) of daily couples (ToT,FAR) (square markers) for the compared approaches varying the N^* (assuming values in the range $[1, 10]$). Mean values are shown in Tab. 1. The performance advantages are clear and more evident in the low false alarm region. Furthermore, the improvements, in the case of S. Rossore, are more straightforward than the ones for Palmaria, because of a worse capability of the radar in S. Rossore to detect vessels.

Table 1. Means for ToT and FAR indexes varying N^* on Palmaria and S. Rossore datasets.

(a) Palmaria

N^*	JPDA		VS-IMM JPDA	
	ToT%	FAR [l/(sm^2)]	ToT%	FAR [l/(sm^2)]
1	36.04	$0.656 \cdot 10^{-11}$	63.03	$1.401 \cdot 10^{-11}$
5	52.84	$1.266 \cdot 10^{-11}$	68.11	$1.769 \cdot 10^{-11}$
10	61.62	$1.681 \cdot 10^{-11}$	69.55	$1.997 \cdot 10^{-11}$

(b) S. Rossore

N^*	JPDA		VS-IMM JPDA	
	ToT%	FAR [l/(sm^2)]	ToT%	FAR [l/(sm^2)]
1	28.24	$0.2262 \cdot 10^{-11}$	55.92	$0.4169 \cdot 10^{-11}$
5	42.65	$0.4735 \cdot 10^{-11}$	58.62	$0.5985 \cdot 10^{-11}$
10	52.79	$0.6563 \cdot 10^{-11}$	60.58	$0.7445 \cdot 10^{-11}$

The last analysis is performed by exploiting the fragmentation index N^{TF}. It is equal to 1.63 for the standard JPDA and 1.32 for the proposed approach in the case of the Palmaria dataset, while it reaches values equal to 1.59 and 1.38, respectively for the S. Rossore dataset. In both the cases, these outcomes confirm the capability of the proposed approach to reduce the track fragmentation.

4. CONCLUSIONS

A KB tracking algorithm based on the VS-IMM estimator, a prior information on ship traffic, and the JPDA approach to cope with the measurement-to-track association problem has been developed. Motion uncertainties due to on-sea lane/off-sea lane motion and sea lane entry/exit conditions have been managed. Furthermore, the phenomenon of the targets' obscuration has been also taken into account.

Experimental results using one month of real data acquired by two HFSW radars have been presented. The advantages, in terms of, time-on-target, false alarm rate, and track fragmentation of the proposed VS-IMM JPDA with respect to the standard JPDA [4] have been shown. AIS messages have been used as ground-truth. An increment up to 30% in the time-of-target index, with comparable values of false alarm rate, is observed. An average reduction in the track fragmentation of 20% for Palmaria and 13% for S. Rossore is also reached.

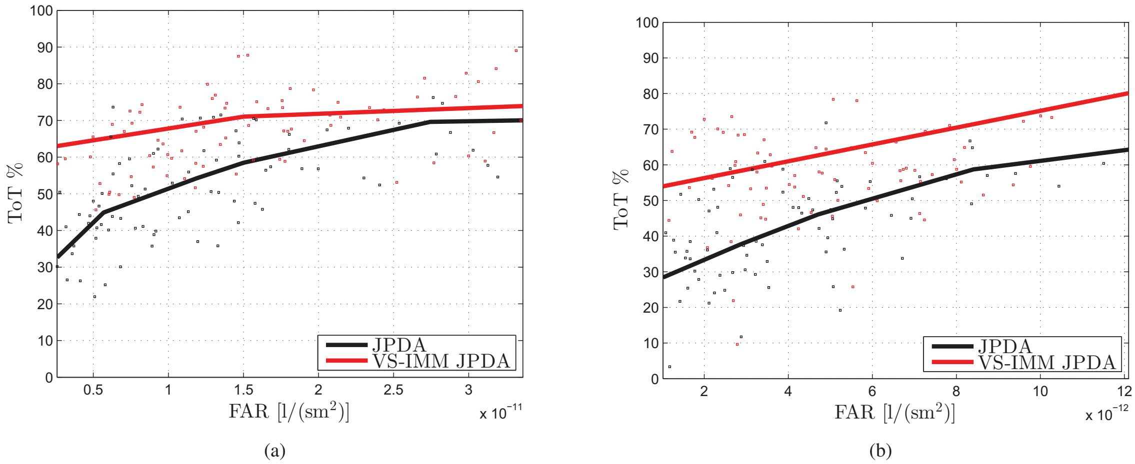

Fig. 2. ToT Vs. FAR varying N^* in the case of (a) Palmaria and (b) S. Rossore. Black and red little squares indicate the daily values for the standard JPDA and the VS-IMM JPDA, respectively.

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Keywords

Knowledge-based tracking, multitarget tracking, high-frequency surface-wave radar, maritime surveillance

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