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EXTENDED TARGET TRACKING USING JOINT PROBABILISTIC DATA ASSOCIATION FILTER ON X-BAND RADAR DATA

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ABSTRACT

X-band Marine radar systems are low-cost tools for monitoring multiple targets in a surveillance area. Although they may suffer from several sources of interference, high resolution measurements in both space and time can be provided. Such features offer the opportunity to get accurate information not only about the targets' kinematics, as other conventional sensors, but also about the targets' extent.

In this paper, a signal processing chain composed by a detector and a joint probabilistic data association tracker is proposed to address the problem of tracking using X-band Marine radar data. Estimations of both the targets' kinematics, i.e. positions and velocities, and length and width, are provided. The performance assessment, conducted on real data acquired by an X-band Marine radar located in the Gulf of La Spezia, Italy, demonstrates the ability of the processing chain to obtain high tracking performance with a limited computational burden.

***Index Terms*—** Maritime Surveillance, Multi-Target Tracking, Extended Target Tracking, X-band Marine Radar.

1. INTRODUCTION

Radars are widely exploited technologies for maritime surveillance. Inside this category, new X-band marine radar systems represent low-cost tools for tracking multiple targets (e.g. cargo ships, rubber boats, etc.). Features such as high resolution in both space and time make these kinds of systems very appealing. Indeed, by comparing them with conventional radars, they are also able to provide indications about the targets' extent. On one hand, this further information can aid some subsequent processing steps, such as the target classification; on the other hand, one of the main assumptions of tracking algorithms, i.e. the target can generate at most one detection per frame, is no longer valid. Thus, the development of new techniques is strongly recommended to properly track these targets usually named extended targets (i.e. targets that occupy more than one radar cell per frame). This research field is often called extended target tracking (ETT).

The literature is vast and several approaches can be found. Some examples are in [1, 2], where sequential Monte Carlo methods together with the track-before-detect theory are exploited to track extended targets. Whereas in [3], the authors propose an approach for ETT under the assumption of Poisson distributed measurements. The random hypersurface model is introduced in [4]. Furthermore, an approximate Bayesian solution to the ETT problem under the hypothesis of elliptical spread of targets is pioneered by Koch in [5].

It is worthwhile pointing out that many of these approaches address the ETT problem only in the single target case. Furthermore, the tractability of the problem from a computational point of view is often neglected. Indeed, due to the high spatial resolution of these kinds of radars, the computational burden should be taken into consideration to guarantee good tracking performance in near real time.

To this aim, in this paper we propose a signal processing chain using a pixel-wise detector, a post-processing using Morphological operators, a clustering and feature extraction phase, and a standard joint probabilistic data association (JPDA) tracker [6]. This processing chain enables the estimation of both the targets' kinematics and sizes with a limited computational burden, which is a desirable feature when a huge amount of data has to be processed in a short time. The validation is conducted on real data acquired by an X-band Marine radar located in the Gulf of La Spezia, Italy. Automatic identification system (AIS) messages are used as ground-truth. A set of performance metrics (i.e. time-on-target, track fragmentation and accuracy, and false alarm rate) are used to assess the performance.

The rest of the paper is outlined as follows. Sect. 2 is devoted to the description of the signal processing chain, while the performance assessment is provided in Sect. 3. Conclusions are drawn in Sect. 4.

2. SIGNAL PROCESSING CHAIN

This section is devoted to the description of the chain exploited to process data provided by the radar system. A maximum likelihood pixel-wise detector, under the hypothesis of exponential distribution of the amplitude of the acquired data, is applied first. The rate parameters, which characterize the whole exponential distributions under the *target* (i.e. λ_t) and *non-target* (i.e. λ_{nt}) hypotheses, are estimated using the *k-means* clustering algorithm [7]. Afterwards, a post-processing based on Morphological operators [8] is exploited to enforce the spatial coherence on the detector's outcomes. A closing operator [8] is applied first. A line following the range direction is used as structuring element in order to compact the target's detection cloud along this direction. Then, an opening operator along the azimuth dimension is also applied to remove some artifacts on the boundaries of the detected targets.

Starting from the output of the post-processing phase, a clustering is carried out to group the detections that are likely to be generated by the same targets. The clustering procedure exploits the group connectivity of detections, i.e. the spatial relation of a detection with its neighbors. A detection is said "8-connected" if at least another detection belongs to its 8-neighborhood (i.e. the adjacent pixels in vertical, horizontal, and diagonal directions). If a detection is said "8-connected" then it can be considered part of the cluster. As a general and simple model for the target extents, we exploit the common ellipsoidal representation, e.g. see [5]. In many real-life target tracking scenarios, the targets are neither sufficiently far from the sensors to generate only a single measurement, nor are they sufficiently close to the sensors such that their features are clearly articulated [9]. This consideration mainly justifies the model hypothesis for the targets' extents. Then, starting from the clusters, the parameters that fully characterize the elliptical model are estimated. The estimation is carried out using the normalized second central moments [10]. Finally, we can exploit standard multi-target tracking techniques to solve the ETT problem. In this paper, the JPDA tracker [6,11] is used.

Let us define the target state vector $\boldsymbol{x}_k$ at time k in Cartesian coordinates as

$$\boldsymbol{x}_k \triangleq [x_k, \dot{x}_k, y_k, \dot{y}_k, l_k, w_k]^{\mathrm{T}}, \tag{1}$$

where x_k, y_k and $\dot{x}_k$, $\dot{y}_k$ are the position and velocity components along the x, y directions, respectively and l_k and w_k represent the length and the width, respectively.

The targets' motion can be described with the nearly constant velocity model [6]. The target dynamic model is given by

$$\boldsymbol{x}_k = \mathbf{F}\,\boldsymbol{x}_{k-1} + \boldsymbol{\Gamma}\boldsymbol{w}_k, \tag{2}$$

where

$$\mathbf{F} = \begin{bmatrix} \mathbf{I}_2 \otimes \tilde{\mathbf{F}} & \mathbf{0}_{4\times 2} \\ \mathbf{0}_{2\times 4} & \mathbf{I}_2 \end{bmatrix}, \tag{3}$$

$$\boldsymbol{\Gamma} = \begin{bmatrix} \mathbf{I}_2 \otimes \tilde{\boldsymbol{\Gamma}} & \mathbf{0}_{4\times 2} \\ \mathbf{0}_{2\times 2} & \mathbf{I}_2 \end{bmatrix}, \tag{4}$$

$$\tilde{\mathbf{F}} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix}, \tag{5}$$

$\tilde{\boldsymbol{\Gamma}} = [T_s^2/2,\ T_s]^{\mathrm{T}}$, $\mathbf{I}_d$ is the identity matrix with size d, $\mathbf{0}_{r\times c}$ represents the null matrix with r rows and c columns, T_s is the sampling time, $\otimes$ denotes the *Kronecker product*, and $\boldsymbol{w}_k$ takes into account the target acceleration and the unmodeled dynamics and it is assumed to be Gaussian with zero-mean and covariance matrix

$$\mathbf{Q} = \mathrm{diag}\left(\sigma_v^2, \sigma_v^2, \sigma_l^2, \sigma_w^2\right), \tag{6}$$

where diag$(\cdot)$ denotes the diagonal matrix, and σ_v^2, σ_l^2, and σ_w^2 are the variances of the additive acceleration, length, and width, respectively.

The measurement vector $\mathbf{z}_k$ at time k is defined as follows

$$\boldsymbol{z}_k \triangleq \left[z_k^r, z_k^\phi, z_k^l, z_k^w, z_k^\theta\right]^{\mathrm{T}} \tag{7}$$

where z_k^r and z_k^ϕ are the range and azimuth measurements of the center of the ellipse that fits the target, z_k^l and z_k^w are its lengths of the major and minor axes (i.e. the length and width of the target), while z_k^θ is a measure of the ellipse orientation.

The target-originated measurement equation is thus

$$\boldsymbol{z}_k = \boldsymbol{h}(\boldsymbol{x}_k) + \boldsymbol{\omega}_k, \tag{8}$$

where

$$\boldsymbol{h}(\boldsymbol{x}_k) \triangleq \left[\zeta_k^r,\ \zeta_k^\phi,\ \zeta_k^l,\ \zeta_k^w,\ \zeta_k^\theta\right]^{\mathrm{T}} \tag{9}$$

is the measurement function with

$$\zeta_k^r \triangleq \sqrt{x_k^2 + y_k^2},\ \zeta_k^\phi \triangleq \arctan\left(y_k/x_k\right), \tag{10}$$

$$\zeta_k^l \triangleq l_k,\ \zeta_k^w \triangleq w_k,\ \zeta_k^\theta \triangleq \arctan\left(\dot{y}_k/\dot{x}_k\right), \tag{11}$$

and $\boldsymbol{\omega}_k$ is the instrument noise vector assumed to be Gaussian with zero-mean and covariance matrix

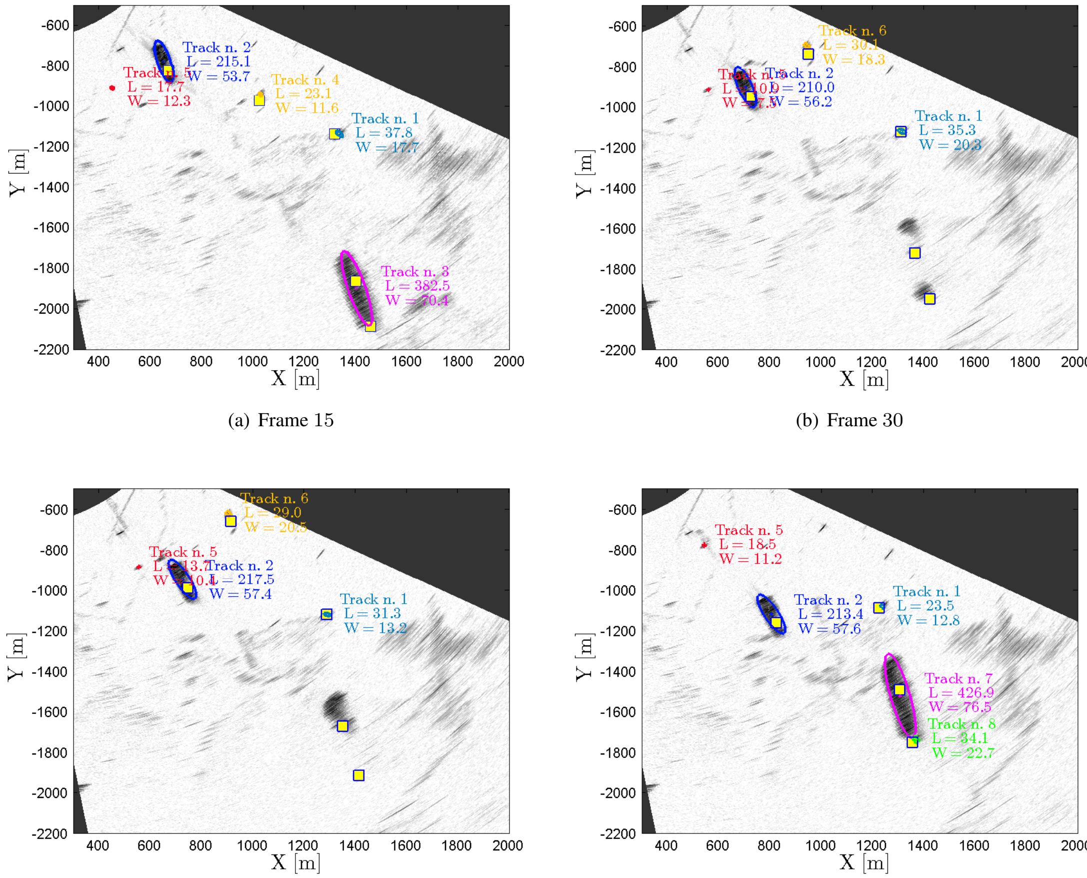
$$\mathbf{R} = \mathrm{diag}\left(\sigma_{rr}^2, \sigma_{r\phi}^2, \sigma_{rl}^2, \sigma_{rw}^2, \sigma_{r\theta}^2\right), \tag{12}$$

where σ_{rr}^2, $\sigma_{r\phi}^2$ represent the variances in range and azimuth, σ_{rl}^2, σ_{rw}^2 are the variances for the two sizes, and $\sigma_{r\theta}^2$ represents the variance for the ellipse's orientation. Note that the model assumes that the target orientation, θ_k, is equal to the motion orientation, i.e. $\theta_k = \arctan(\dot{y}_k/\dot{x}_k)$.

The measurement-to-track association procedure relies upon the JPDA paradigm [6, 11]. The track management is based on the popular M/N logic [6]. The filtering stage, which exploits the motion and observation models described in Eqs. (2) and (8), respectively, is performed using the unscented Kalman filter (UKF) [12].

3. EXPERIMENTAL RESULTS

The experimental activity is conducted on a dataset that consists of 300 frames acquired by the X-band Marine radar in the Gulf of La Spezia, Italy. The automatic identification



(a) Frame 15

(b) Frame 30

(c) Frame 35

(d) Frame 55

Fig. 1. Outcomes of the proposed processing chain on X-band Marine radar data: (a) Frame 15, (b) Frame 30, (c) Frame 35, and (d) Frame 55. Red tracks refer to unassociated AIS-JPDA contacts. The obscuration phenomenon of the pink target with track id 3 in (a) and track id 7 in (d) is also illustrated. The target almost completely disappears in (b) and (c), where only the relative AIS contacts are depicted with yellow squares.

system (AIS) messages are used as ground-truth. The main parameters used for the signal processing chain are shown in Tab. 1. A set of ad-hoc performance metrics, proposed in [13], are exploited. The time-on-target (ToT), the track fragmentation (N^{TF}) and accuracy (using errors in position ϵ^{pos}, velocity ϵ^{vel}, width ϵ^{wid}, and length ϵ^{len}), and the false alarm rate (FAR) are used for validating both attributes (i.e. the targets' lengths and widths) and kinematic information (i.e. the targets' positions and velocities). Fig. 1 depicts the output of the proposed tracker for four frames of the analyzed dataset. The processing chain is able to properly address the multiple ETT problem. This statement is supported by the evaluation of the performance metrics (see Tab. 2 for details). The overall time-on-target is 0.85. The track fragmentation is almost always equal to 1 in spite of the obscuration phenomenon in Fig. 1, the false alarm rate is limited, and the track accuracy is high by considering the errors mainly due to transponder positions and the radar point spread function effects that are not taken into account in this paper. Finally, the analysis is completed by taking into consideration the execution times. The chain, running on a Quad 3.73 GHz Intel Xeon processor, can process a $3800 \otimes 200$ pixel frame in about 1 s, thus assuring the near real time requirement, which is of great importance for maritime surveillance applications.

4. CONCLUSIONS

A signal processing chain consisting of a pixel-wise detector, a post-processing phase, a clustering step, and a JPDA-UKF tracker, has been presented and tested on real data provided

Table 2. Tracking Metrics

JPDA track id number / **MMSI ship**	1 / 255803790	2 / 247076200	3 / 351361000	6 / 247031200	7 / 351361000	8 / 247222500	**Average Results**
ϵ^{pos} [m]	50.1	17.6	41.8	39.7	65.8	23.1	39.7
ϵ^{vel} [m s^{-1}]	0.53	0.64	3.12	2.70	1.43	0.58	1.50
ϵ^{len} [m]	13.5	6.7	34.5	4.5	104.8	16.3	30.0
ϵ^{wid} [m]	34.5	6.3	22.8	10.4	22.3	9.0	17.5
ToT	1.00	0.95	0.86	0.70	0.86	0.74	0.85
N^{TF}	1.00	1.00	2.00	2.00	2.00	1.00	1.50
FAR [m^{-2} s^{-1}]	4×10^{-8}						

Table 1. Parameter Settings

Parameter	**Value**	**Specification**
λ_t	4.1×10^{-13}	Rate parameter $target$
λ_{nt}	1.8×10^{-9}	Rate parameter $non \quad target$
T_s	2 s	Sampling time
σ_v	0.4 m s^{-2}	Process noise
σ_l	4 m	Process noise
σ_w	4 m	Process noise
σ_{rr}	1 m	St. dev. range
$\sigma_{r\phi}$	1°	St. dev. azimuth
σ_{rl}	4 m	St. dev. length
σ_{rw}	4 m	St. dev. width
$\sigma_{r\theta}$	60°	St. dev. orientation
M/N	$5/6$	Track initialization logic
M^*/N^*	$6/6$	Track termination logic

by an X-band Marine radar located in the Gulf of La Spezia, Italy. AIS position messages have been considered as ground-truth to validate the performance. The outcomes are encouraging and the processing chain reached high tracking performance, evaluated by proper metrics, meeting the critical near real time requirement.

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Keywords

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