Detecting and Tracking of Small Moving Target in Avian Radar Images

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Abstract— **A sequence of plane position indicator (PPI) images containing a small moving target is collected using an experimental avian radar surveillance system, which is constructed by modifying a standard marine radar. Smoothing trajectory of a small moving target is separated from the image sequence after background subtraction, clutter suppression, measurements extraction and tracking. The background image is generated by Fast Independent Component Analysis (FastICA). Low segmentation value is set in clutter suppression to improve detecting rate at the cost of introducing a great deal of clutters. Therefore, false alarm rate need to be reduced by tracking. Meanwhile, a modified Hough transform method is applied for track initiation. Monte Carlo data association is proposed for track maintenance and Kalman filtering is adopted for target state prediction and update. Finally, the trajectory is smoothed and then fused with a satellite map for further observation.**

Keywords— **radar, tracking, FastICA, Hough transform, data association**

I. INTRODUCTION

Birds pose a threat to aviation safety and cost air carriers and insurance companies approximately $2 billion each year. More than 60% of these collisions occur within the confines of airfields, where airfield managers can reduce the chances of a strike by making the operations area unattractive to birds and by harassing or removing individual birds that remain despite airfield manipulations [1]. Avian radar, which for detecting flying birds, has developed into an important research direction in the field of modern radar due to its advantage of continuous, day-night, all-weather, wide-area surveillance with little limitations of low visibility and poor weather [2]. X-band Marine radar is chosen for our experimental avian radar surveillance system due to its easy operation and low cost. The outputs from the radar are digitized and processed in real-time by the digital processor, with resulting tracks stored locally in a database. Sometimes, echo intensity of flying birds are even weaker than clutters due to its special posture, so effective small targets detecting and tracking algorithm is required for the digital radar processor software.

In this paper, a practicable detecting and tracking scheme based on plane position indicator (PPI) radar images is described in Section II, and results against a set of PPI images are reported in Section III. Some conclusions in Section IV close the paper.

II. DETECTING AND TRACKING SCHEME

PPI radar images were collected by capture card after every scanning period (2.5s) of the radar antenna and then processed in real-time by detecting and tracking scheme shown in Fig. 1. The algorithm mainly contains two steps of detecting and tracking. The detecting algorithm consists of background subtraction, clutter suppression and measurements extraction.

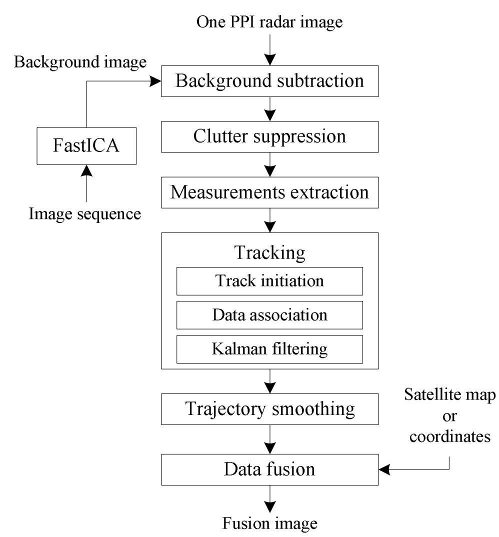

Fig. 1 Detecting and tracking scheme based on PPI radar images

PPI image composed of complex background and a small target can be regarded as mixture signals, so independent components (background and flying bird) could be separated from the image sequence by Fast Independent Component Analysis (FastICA) [3]; this is a new application of FastICA. Clutter suppression adopts constant false alarm rate (CFAR) segmentation method. To improve detecting rate, lower threshold is used in CFAR, and large quantity of clutters are introduced. After

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clutter suppression, radar measurements including targets and clutters are preliminarily extracted from radar images. Perfect tracking algorithm, as a supplement to detecting, can track small targets and reject clutters simultaneously. Tracking step is composed of track initiation, data association and Kalman filtering. With the assumption that the bird was flying in a straight line at the beginning of the track, modified Hough transform (HT) is applied for track initiation. Monte Carlo data association method is used for discrimination of targets based on state updates given by Kalman filtering. Moreover, the tracking result is smoothed. Finally, smoothing bird trajectories are fused with satellite map or coordinates, so a fusion image is given for further observation.

In the following three sections, algorithms used in the above scheme including FastICA, modified HT and Monte Carlo data association will be discussed in detail respectively.

A. Fast Independent Component Analysis

Independent Component Analysis (ICA) is a method for blind source separation [4]. Its goal is to find a linear representation of non-gaussian data so that the components are statistically independent, or as independent as possible. The ICA model is shown in equation (1). Observed data denoted by $\mathbf{x}$ is a group of vectors with elements $\mathbf{x}_1,\ldots,\mathbf{x}_n$. Source data denoted by $\mathbf{s}$ cannot be observed directly. $\mathbf{A}$ is the mixing matrix.

$$\mathbf{x} = \mathbf{A}\mathbf{s} \tag{1}$$

Let us assume that the components s are statistically independent. After estimating the matrix $\mathbf{A}$, we can compute its inverse or generalized inverse, say $\mathbf{W}$, and obtain the independent components simply by

$$\mathbf{s} = \mathbf{W}\mathbf{x} \tag{2}$$

Main methods for ICA estimation include nongaussianity (e.g. high-order moment and negentropy), maximum likelihood estimation and minimization of mutual information. Before applying ICA on the experimental data, some preprocessing should be done first. All the following techniques could make the ICA estimation simpler and better conditioned.

- Centering

Given $\mathbf{x}$ as observed data, its mean vector $\mathbf{u} = E\{\mathbf{x}\}$ is subtracted so as to make it a zero-mean variable.

- Whitening

The observed variables should be whitened before the application of ICA. The components of a white matrix $\tilde{\mathbf{x}}$ are uncorrelated and their variances equal unity, i.e.

$$\mathbf{E}\left\{\tilde{\mathbf{x}}\tilde{\mathbf{x}}^T\right\} = \mathbf{I} \tag{3}$$

Eigen-value decomposition is applied on the covariance matrix $\mathbf{E}\left\{\tilde{\mathbf{x}}\tilde{\mathbf{x}}^T\right\}$ for whitening, so $\tilde{\mathbf{x}}$ is obtained by

$$\tilde{\mathbf{x}} = \mathbf{E}\mathbf{D}^{-1/2}\mathbf{E}^T\mathbf{x} \tag{4}$$

where $\mathbf{E}$ is the orthogonal matrix of eigenvectors of $\mathbf{E}\left\{\tilde{\mathbf{x}}\tilde{\mathbf{x}}^T\right\}$ and $\mathbf{D}$ is the diagonal matrix of its eigenvalues. Then mixing matrix is transformed into a new orthogonal matrix $\tilde{\mathbf{A}}$

$$\tilde{\mathbf{x}} = \mathbf{E}\mathbf{D}^{-1/2}\mathbf{E}^T\mathbf{A}\mathbf{s} = \tilde{\mathbf{A}}\mathbf{s} \tag{5}$$

This can be easily approved by

$$\mathbf{E}\left\{\tilde{\mathbf{x}}\tilde{\mathbf{x}}^T\right\} = \tilde{\mathbf{A}}\mathbf{E}\left\{\mathbf{s}\mathbf{s}^T\right\}\tilde{\mathbf{A}}^T = \tilde{\mathbf{A}}\tilde{\mathbf{A}}^T = \mathbf{I} \tag{6}$$

Whitening reduces the number of parameters to be estimated. The number of observed signals could be reduced to the number of source signals by whitening.

FastICA finds a direction to maximize nongaussianity which is measured by negentropy. The approximate function for negentropy measurement in [5] is

$$\mathbf{N}_g(\mathbf{Y}) = \{\mathbf{E}[g(\mathbf{y})] - \mathbf{E}[g(\mathbf{Y}_{gauss})]\}^2 \tag{7}$$

where $g(\cdot)$ are some non-quadratic functions. The basic form of the FastICA algorithm is as follows:

- Choose an initial weight vector $\mathbf{w}(0)$, and let $k=1$;
- Let $\mathbf{w}^+(k) = \mathbf{E}\left\{\mathbf{x}g\left(\mathbf{w}^T(k-1)\mathbf{x}\right)\right\} - \mathbf{E}\left\{g'\left(\mathbf{w}^T(k-1)\mathbf{x}\right)\right\}\mathbf{w}(k-1)$;
- Let $\mathbf{w}(k) = \mathbf{w}^+(k)/\left\|\mathbf{w}^+(k)\right\|$;
- If not converged, let $k = k+1$ and go back to 2.

B. Modified Hough transform

The HT is a well-known technique used to identify straight lines in a noisy environment. It maps a point (x, y) in the Cartesian coordinates onto a curve in the parameter space ρ – θ, by the relationship

$$\rho = x\cos\theta + y\sin\theta \tag{8}$$

The points which lie on a straight line in Cartesian coordinate space intersect at a common point in ρ – θ after the transformation given by (8). After the radar accumulates data over several scans, the number of points within a certain bin is therefore higher if there is a straight line relationship between the points.

When there are a sufficiently large number of scans, the standard HT performs satisfactorily. However, in a real tracking environment, track initiation using a large number of scans is impractical. It is difficult to distinguish peaks associated with real tracks from peaks due to clutters in a few scans. Therefore, a modified HT method was proposed [4]. Suppose we receive three reports $\mathbf{r}_n$, $\mathbf{r}_{n+1}$, and $\mathbf{r}_{n+2}$ at scans $n, n+1$, and $n+2$. Based on these three data points, we obtain three curves ρ_n, ρ_{n+1} and ρ_{n+2} in parameter space. The difference function is formed as

$$\Delta\rho_n = \rho_n - \rho_{n+1} \tag{9}$$

Two criteria are established for track initiation:

1) The algebraic distance between zero crossing points must be small, i.e.,

$$\left|\theta_{\Delta\rho_n(0)} - \theta_{\Delta\rho_{n+1}(0)}\right| \le \sigma_\theta \tag{10}$$

2) The slopes of the vectors at the zero crossing points $\theta_{\Delta\rho_n(0)}$ and $\theta_{\Delta\rho_{n+1}(0)}$ must have the same sign.

By denoting the distance between point $\mathbf{r}_{n+1}$ and point $\mathbf{r}_{n+2}$ as $d_{n+1,n+2}$ and defining the acute angle between vectors $(\mathbf{r}_{n+1}-\mathbf{r}_{n+2})$ and $(\mathbf{r}_{n+2}-\mathbf{r}_{n+3})$ as α_{n+2}, two more criteria are developed for testing.

3) Since the acceleration of targets is limited by physical constants, the value of $d_{n+1,n+2}$ and $d_{n+2,n+3}$ should be of the same order, i.e.,

$$\left|d_{n+1,n+2}\right| \le c \times d_{n+2,n+3} \quad (11)$$

where c is constant which is determined by the maximum acceleration that targets are known to undergo.

4) If a number of points approximate a straight line, the angle between line segments must be subject to the constrain

$$\beta_1 \le \alpha_{n+2} \le \beta_2 \quad (12)$$

where β_1 and β_2 are limiting angles. β_1 and β_2 are chosen so as to prevent initiation of V-shaped tracks at the intersect of two three point groups.

In the four criteria are satisfied for the assumed track, points $\mathbf{r}_n$, $\mathbf{r}_{n+1}$, $\mathbf{r}_{n+2}$, $\mathbf{r}_{n+3}$ and $\mathbf{r}_{n+4}$ form a track.

C. Monte Carlo Data Association

Data association method in this paper is based on the theory of Monte Carlo. N times of association judgments are stored in variable ind, with the same initial weight for each one. Association probability for each measurement P = (P_j, P_c, j=1,…,n) includes n+1 elements: P_j belongs to target j and P_c belongs to clutter, which are computed as

$$\begin{aligned} P_j &= (1-cp)\cdot P_{lj} \\ P_c &= cp\cdot cd \end{aligned} \quad (13)$$

where cp and cd are clutter prior probability and clutter density value, and P_{ij} denotes the Kalman filter measurement likelihood evaluation, which satisfies Gaussian distribution with parameters $\mathbf{T}_j$ and $\mathbf{S}_j$:

$$P_{lj} = N(y_k \mid \mathbf{T}_j, \mathbf{S}_j) \quad (14)$$

The association probabilities of measurements to targets or clutter are normalized as

$$P^* = (P_j^*, P_c^*, j = 1, ..., n).$$

Monte Carlo sampling method is used for judgment of whether the measurement is produced by target. A random number is generated as

$$u \sim U(0,1).$$

If

$$u < \sum_{k=1}^{j} P_k^*,$$

the measurement is associated to target j, or else it is due to clutter. Weight of each sample is computed as follows:

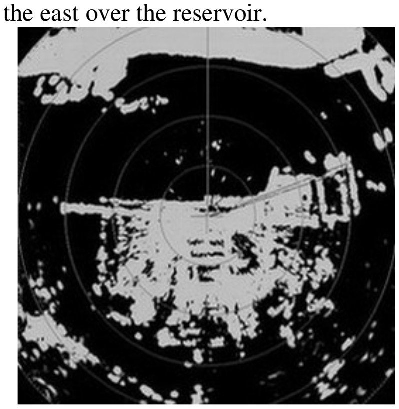
$$w_k^{(i)} = \begin{cases} w_{k-1}^{(i)} \cdot P_{lj} / P_j^* & ind_k^{(i)} = \mathrm{j} \\ w_{k-1}^{(i)} \cdot cd / P_c^* & ind_k^{(i)} = 0 \end{cases} \quad (15)$$

Then, the weights are normalized and effective number n is computed [6]. If n is too low (i.e. n<N/4), then we perform resampling.

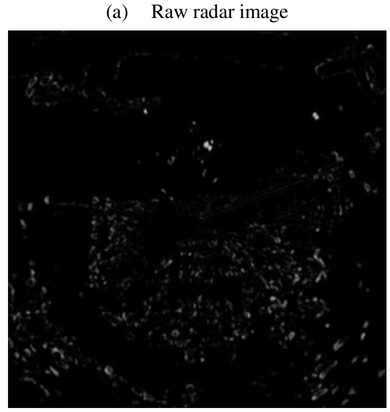
III. EXPERIMENT RESULT ANALYSIS

A sequence of 26 avian PPI radar images with the measurement range of 0.5nmi was collected by the experimental system [7] on the north bank of Beijing Shahe Reservoir on 29 March 2007.

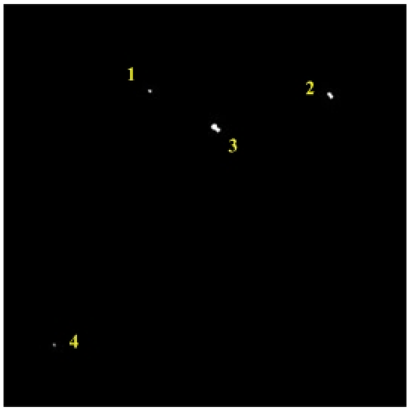
Fig. 2 shows the whole processing of the first image of the sequence. Fig. 2(a) is raw radar image dominated by background due to buildings, trees, shoal and dam besides the flying bird target. After subtraction, Fig. 2(b) is obtained with most of the background removed but still large amounts of marginal clutter left. Fig. 2(c) is the result after clutter suppression, when high bright domains in the image are our interesting areas. Radar measurements including polar coordinate positions (ρ, θ) and size (pixel number n) are extracted and presented in TABLE I, while their serial numbers are marked in Fig. 2(c). Four groups of measurements are given, and final association judgments have to be made by tracking algorithm. The track of a small target is initiated by modified HT, and then target measurements are selected and associated to the existing track to update their present states, when clutters are rejected successfully. From the tracking result, we know that measurement 2, whose size is 31, is the target and the other three measurements are clutters whose sizes are even bigger than the target sometimes (e.g. size of measurement 3 is 62). Fig. 2(d) is the fusion image, where target is indicated by "•" and clutters by "×" in polar coordinates, the initial point is labeled. The smoothed trajectory shows that a bird is flying to the east over the reservoir.



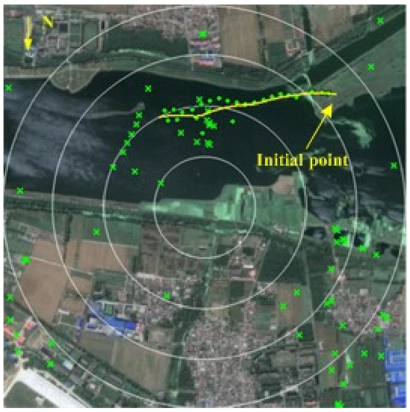
(a) Raw radar image



(b) Radar image after subtraction



(c) Radar image after clutter suppression



(d) Fusion image

Fig. 2 Processing of avian PPI radar images

TABLE I
RADAR MEASUREMENTS

Number	ρ(m)	θ(º)	n
1	598.8	115.6	9
2	770.3	42.2	31
3	372.8	83.5	62
4	937.2	221.8	5

IV. CONCLUSIONS

A detecting and tracking scheme is developed for avian radar surveillance system. Low segmentation is always set for small target detecting, and an effective tracking method including modified HT, Monte Carlo data association and Kalman filtering is supplemented to reject clutters. Results obtained by processing live PPI images containing a small flying bird have also been shown. Generally, tracking problems consist of three parts: track initiation, track maintenance and track deletion. However, in this paper, only the first two parts are considered, because the tracking certainly ends as the image processing comes to the last frame. In real application, tracking targets might escape from the scanning region at any time, so tracking deletion cannot be neglected [8]. Otherwise, multiple-model methods such as interactive multiple models (IMM) filter should be used for maneuvering targets [9]. Therefore, advanced filtering and track deletion methods should be further researched.

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