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Group Tracking of Flock Targets in Low-altitude Airspace

Weishi Chen Hong Liu Sha Hu Huansheng Ning
School of Electronics and Information Engineering, Beihang University
Beijing, China
E-mail: wishchen@buaa.edu.cn

Abstract—**Bird-strike avoidance system usually uses marine radar with limited resolution for surveillance of low-altitude airspace. When the target of interest is flock in high target density, the targets are so closely spaced so one cell on the radar display always represents several birds. Therefore, it is sometimes not necessary to detect and track individual target with accuracy. In this paper, a central group-target tracking algorithm is proposed to track the overall flock behavior, and we consider several criteria of splitting and merging based on clustering method. We experimentally compare the central group-target tracking algorithm with the multi-target tracking algorithm, which are complementary parts of the flying bird targets detecting and tracking scheme. It is shown that the proposed algorithm gives encouraging results with high efficiency, overcoming the data association problem with multi-target tracking for closely spaced targets. In addition, we include an application example on real radar data.**

Keywords-bird-strike; radar; group-target tracking; multi-target tracking

I. INTRODUCTION

Bird strike avoidance has been a problem in the field of aviation safety. Traditional methods of artificial bird observation and driving are increasingly unable to meet the requirements of the airport, waiting for the support of relevant techniques. Avian radar detection is an important technical means for bird observation, which is unrestricted by factors such as invisibility and bad weather, so it can be operated all-weather automatically. After 30 years of development, several airport-based avian radar systems are available. The most typical ones are Merlin[1] developed by DeTect Inc. and Accipiter[2] developed by Sicom Systems Ltd. Beihang University built an Experimental Avian Radar System (BHEARS), with numerous outfield experiments based on bird targets scattering characteristics analysis, and the key problems involved have been initially solved[3]. Flying bird targets detecting and tracking algorithm is the main technique of avian radar system and belongs to the problem of multi-target tracking (MTT) in clutter environment. Flock is the most threatening disaster for flight safety, and is also the most difficult to track. This is because the tracking targets are so close to each other and their moving trends are almost the same; there are so many eco-waves of the targets whose association gates overlap each other frequently. Therefore, it is such a difficult task to track the flock targets precisely. When nearest neighbor method is used, mistakes between target tracks cannot be avoided and state estimation error increases significantly [4]; when joint probabilistic data association (JPDA) or multiple hypothesis testing (MHT) is used, the algorithms are too complex for real-time operation [5]. Overall, when the tracking target consists of multiple individuals, the main characteristic they represent is group behavior, which leads to a new problem in the target tracking: group-target tracking. If these targets with certain rules are regarded as a group to track, the problems with general MTT methods can be avoided while better tracking results with less radar resources can be achieved as well.

There have been some researches on group-target tracking or extended-target tracking of multiple observations. When the observations are produced by multiple targets moving in common formation, it is known as group-target tracking; when they are produced by a single target, it is known as extended-target tracking. However, the tracking approaches are almost the same. Shyu [6] discussed the group tracking algorithm targets on the sea surface by 2-D search radar. A modified cluster-seeding method was used to define the group and deal with the splitting and mering of group. Gilholm and Salmond [7] developed a spatial distribution model for tracking extended objects in clutter, whereas the number of observations from the target was assumed to be Poisson distributed. This considerably simplified the filter and gave a substantial computational savings in a particle filter implementation. Mahler [8] proposed a random-set filtering approach for tracking group targets, and described a particle filter implementation of the Probability Hypothesis Density (PHD) filtering for tracking a bulk of targets [9]. Clark developed a method for group tracking with the Gaussian mixture PHD filter, explicitly identifying group targets and their constituent members by creating a graph of connected components [10]. The purpose of this paper is to solve the group-target tracking problem in avian radar detection. A practical algorithm is proposed to track flock targets in low-altitude airspace from avian radar data.

The paper is organized as follows. In Section Ⅱ, we discuss the core technique of typical avian radar system: the flying bird targets detecting and tracking scheme based on plane position indicator (PPI) radar images. Section Ⅲ is the main contribution of the paper where

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we present the central group-target tracking (CGTT) algorithm and discuss several criteria of group association, splitting and merging based on Kalman filter with clustering method. In Section Ⅳ, simulation experiments are given to compare the CGTT algorithm with the MTT algorithm, showing the improvements of the proposed algorithm. Furthermore, the CGTT algorithm is applied to real radar data in Section Ⅴ, and the last section concludes the paper.

II. AVIAN RADAR SYSTEM

Typical avian radar system adopts two marine radars: one for X-band vertical scanning, installed on the end of the runway responsible for the area above the runway (5000 feet); the other for S-band horizontal scanning, installed near the airport center responsible for the low-altitude airspace in and around the airport (2-3nmi). The two radars work independently, and the PPI images separately collected are processed by two computers in real time. After the processing of embedded algorithm, vertical and horizontal fusion images are provided.

Flying bird targets detecting and tracking is the core technique of the typical avian radar system, whose flow chart is illustrated in Fig. 1.

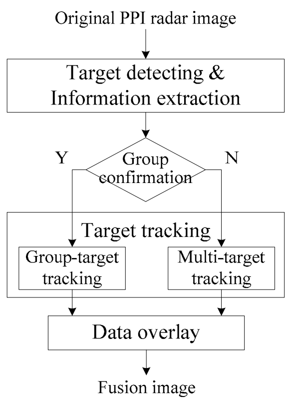


Figure 1 Flying bird targets detecting and tracking scheme

Firstly, original PPI radar image is processed by the target detecting and information extraction algorithm. Then, the tracking scheme is selected by the group confirmation step and the flying bird trajectory extracted from complex radar images is overlapped on satellite map, generating fused image that improves the observation. In the algorithm, the target detecting and information extraction step (background subtraction, clutter suppression, measurement information extraction) [11] is the first part, which separates flying bird location information from original images. To improve the detection rate, lower threshold is generally set in clutter suppression, introducing dozens of false alarms. Excellent tracking algorithm, as an addition to flying target detection algorithm, can eliminate these false alarms while tracking dim targets. Its purpose is to track unknown number of targets at the same time, making the system to track targets with high detection rate and low false alarm rate in cluttered environment.

In the above scheme, the target tracking part includes two complementary modules: group-target tracking and multi-target tracking. Before target tracking, group confirmation is added to make the decision. If the concerned targets satisfy the following conditions, including “move in the same direction”, “the distance between each other is less than a certain threshold”, and “the speed is almost the same”, they should be confirmed to be a target group and the corresponding group-target tracking algorithm is chosen. Otherwise, each target is tracked individually with the MTT algorithm which is given in [11], where multi-target tracking in a cluttered environment can be divided into three parts of track initiation, track deletion and track maintenance according to different states of a target. With birth events modeling for track initiation and death events modeling for track deletion, all possible associated events are enumerated in the track maintenance stage.

III. CENTRAL GROUP-TARGET TRACKING

Group target tracking of flying birds adopts CGTT algorithm using the group center to track. This algorithm associates the predicted group track center with the measurements, then updates the group target center with the associated measurements, and finally estimates the group velocity. In this section, the group center association algorithm is proposed based on Kalman filtering and the separation and merging schemes are discussed.

A. Group Association

Group association is the selection of radar measurements with the estimation of group target state predicted by Kalman filtering. The group target state is updated with the center of the radar measurements. Targets after clustering are regarded as one group, whereas group association is equivalent to clustering problem.

K-means algorithm is a typical clustering algorithm based on distance measurement, taking distance as the similarity indicator; namely, it is believed that closer distance between the two objects means higher similarity. This algorithm supposes that one cluster is composed of objects close to each other, so obtaining compact and independent clusters is the ultimate goal. The initial clustering center selection greatly affects the clustering result, because the first step in this algorithm is to randomly select k objects as the primary clustering center. This algorithm reassigns each object remaining in the data set of iteration to the nearest clustering according to its distance to the clustering centers. The iteration is finished after all the objects are inspected, and a new clustering center is obtained then. If the evaluation indicator changes little after the iteration, it is indicated that the solution has converged.

The kernel technique of the K-means algorithm is the initial selection of cluster centers. Group clustering method used in this paper combines K-means algorithm with Kalman filtering, taking the group predicted state value as the clustering center in each period, whereas the distance segmentation threshold is set based on the characteristics of the target group. The overall algorithm is described as follows:

1) Kalman prediction is completed by

$$\begin{aligned} \mathbf{m}_k^- &= \mathbf{A}_{k-1}\mathbf{m}_{k-1} \\ \mathbf{P}_k^- &= \mathbf{A}_{k-1}\mathbf{P}_{k-1}\mathbf{A}_{k-1}^T + \mathbf{Q}_{k-1} \\ \mathbf{T}_k &= \mathbf{H}_k\mathbf{m}_k^- \\ \mathbf{S}_k &= \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T + \mathbf{R}_k \end{aligned} \tag{1}$$

where $\mathbf{m}_k^-$ and $\mathbf{P}_k^-$ are the predicted state mean and variance in the k^{th} step before measurements obtained. $\mathbf{A}_k$, $\mathbf{Q}_k$, $\mathbf{R}_k$ and $\mathbf{H}_k$ indicate transfer matrix, process noise matrix, measurement noise matrix and measurement model matrix. $\mathbf{T}_k$ and $\mathbf{S}_k$ represent the predicted state mean and variance.

2) We use the predicted state value as the group center and set a distance threshold TH. All the distances between measurements and the predicted center are calculated. If the distance is less than TH, it is classified into the group; otherwise, it is considered as clutter. If the number of the predicted centers is more than one, under the assumption that the distance is less than TH, measurement samples are classified into the nearest group, and then each new group measurement center $\mathbf{Y}_k$ after clustering is done.
3) Using measurement center $\mathbf{Y}_k$ to update:

$$\begin{aligned} \mathbf{v}_k &= \mathbf{Y}_k - \mathbf{T}_k \\ \mathbf{K}_k &= \mathbf{P}_k^-\mathbf{H}_k^T\mathbf{S}_k^{-1} \\ \mathbf{m}_k &= \mathbf{m}_k^- + \mathbf{K}_k\mathbf{v}_k \\ \mathbf{P}_k &= \mathbf{P}_k^- - \mathbf{K}_k\mathbf{S}_k\mathbf{K}_k^T \end{aligned} \tag{2}$$

where $\mathbf{m}_k$ and $\mathbf{P}_k$ are the predicted state mean and variance in the k^{th} step after update. $\mathbf{v}$ is the measurement correction value and $\mathbf{K}$ is the filter gain, which defines the extent of how much the predicted value should be revised.

B. Group Splitting

Group splitting is a new problem brought by group tracking, equivalent to target tracking initialization, generating a new clustering center during the process of group-target tracking. A group-target splitting judgment method is proposed in this paper, illustrated in Fig. 3, where solid dots are measurements and hollow dots are group target center predicted locations. Note that Y_1 is the predicted value of group target center in the current scanning period. The group is separated if the valid measurement number N_k and the number N_{k-1} obtained from the last scanning less than the threshold TH range (black solid dots in Fig. 2) satisfy the following relationship:

$$N_{k-1} - N_k > n \tag{3}$$

Note that n in equation (3) is usually set to be 10% ~ 30% of N_{k-1}. Firstly, the distance of each measurement outside Y_1 gate to Y_1 is calculated and a new gate (dotted circle in Figure 2) with the center of Y_{new} which is the closest to Y_1 is given. Then the central point Y_2 of all the measurements in the new gate is found, where a new track is initialized to finish the group splitting.

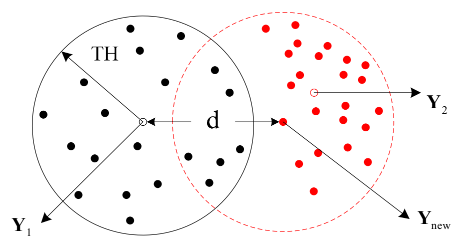


Figure 2 Group splitting illustration

C. Group Merging

Group merging is the inverse problem of group splitting, reducing the two clustering centers to one, equivalent to target tracking termination problem. A merging judgment method is proposed and illustrated in Fig. 3, where dots represent the measurements of group 1 and triangles represents the measurements of group 2. In the current scanning period, whether the centers of the two groups Y_1 and Y_2 should be converged to one are judged by the following three criteria:

1) $d< S_d$, d represents the distance between Y_1 and Y_2, and S_d is the distance threshold;
2) $N_{12}>S_N$, N_{12} represents the number of the measurements appearing both in the gates of Y_1 and Y_2, S_N is the number threshold;
3) The velocities of the two groups $\mathbf{v}_1$ and $\mathbf{v}_2$ are opposite in direction.

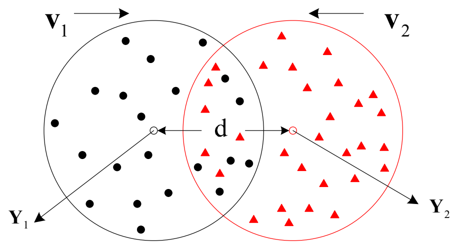


Figure 3 Group merging illustration

Once the above criteria are satisfied, the midpoint of Y_1 and Y_2 are chosen as the new group center and the group merging is done.

IV. SIMULATIONS AND ANALYSIS

In sub-section A, the demonstration of target state modeling is given. Then, we compare the behaviors of the MTT algorithm and the CGTT algorithm against the same model in sub-section B. Finally, we consider the situations of group-target splitting and merging in sub-section C.

A. Targets modelling

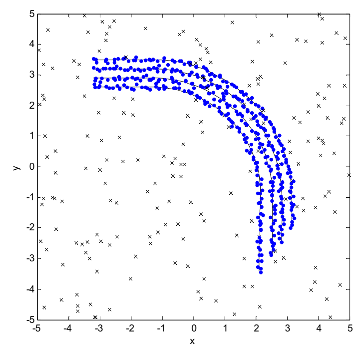
We shall establish a model in which we are tracking several to tens of targets in two dimensions having cluttered measurements randomly distributed. The state of the target can be written as

$$\mathbf{m}_k = (x_k \quad y_k \quad \dot{x}_k \quad \dot{y}_k)^T$$

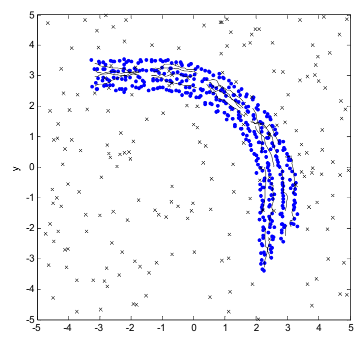
where (x_k, y_k) denotes the target position and $(\dot{x}_k, \dot{y}_k)$ the velocity in two dimensional Cartesian coordinates. The likelihood of clutter measurements is defined to be uniform in space [-5, 5] × [-5, 5]. The prior probability of a measurement being due to clutter is controlled. In Fig. 4 and Fig. 5, the target measurements are represented by "•" and clutter by "×".

B. Algorithm comparison

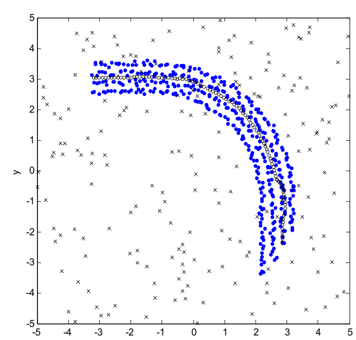
We consider a scenario, in which we are tracking four closely spaced targets with turnings. The model is simulated 100 time steps and each target is given slightly randomized accelerations such that a turning is achieved and plotted in Fig. 4. The target trajectories and measurements are shown in Fig. 4(a). The clutter prior probability is set to cp=0.2. The four targets start from the positions of (-3.3, 3.5), (-3.3, 3.2), (-3.3, 2.9) and (-3.3, 2.6) at the speed of (1, 0), and complete the turning in 2.1~9.0s, 2.1~8.5s, 2.1~8.0s and 2.1~7.5s. Obviously, the target in the inner circle completes the turning in shorter time. We track the targets with two algorithms: multi-target tracking and group-target tracking. Fig. 4(b) presents the tracking result (dotted line) by MTT algorithm. We can see that the algorithm suffers from large target densities and noise added to measurements, leading to serious false data associations. In certain cases, it is sometimes not necessary to detect and track individual targets with accuracy, where the overall distribution of target group is of greater interest. Therefore, we use the proposed CGTT algorithm. The four targets are treated as a group, whose center is tracked and labeled with "◦" in Fig. 4(c). The experiment explicitly shows that the tracked trajectory given by group-target tracking algorithm lies in the center of the measurements, helping to avoid the data association problem.



(a)



(b)

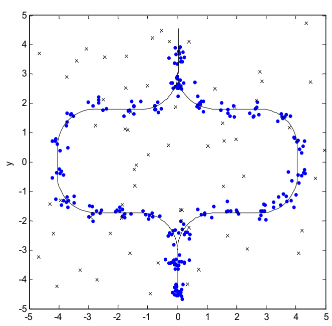


(c)

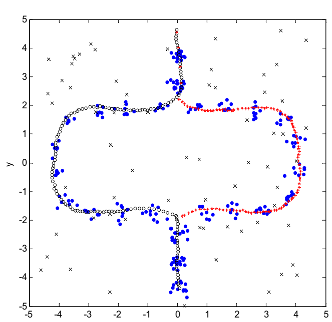
Figure 4 Tracking four closely spaced targets with two algorithms: (a) Target trajectory and the simulated measurements, (b) Tracking results with multi-target algorithm, (c) Tracking results with central group-target tracking algorithm.

C. Group splitting and merging

In this experiment, 20 independent targets constitute one group. The distances between each target and group center satisfy the Gaussian distribution with a certain range. Fig. 5(a) shows the target trajectory and the simulated measurements. The model is simulated 150 time steps when the measurements (target and clutter) are displayed every 10 periods. In 0~1.5s, the group starts from (0, -4.5) and moves at the speed of (0, 1); at 1.6s, the group splits into two groups, each is composed of 10 targets; in 1.6~3.5s, group 1 finishes the left turning and group 2 finishes the right turning; in 3.6~5.0s, group 1 moves at the speed of (-1, 0) and group 2 moves at the speed of (1, 0); in 5.1~7.0s, group 1 finishes the right turning and group 2 finishes the left turning; in 7.1~8.0s, the two groups both move at the speed of (0, 1); in 8.1~10.0s, group 1 finishes the right turning and group 2 finishes the left turning; in 10.1~11.5s, group 1 moves at the speed of (1, 0) and group 2 moves at the speed of (-1, 0); in 11.6~13.5s, group 1 finishes the left turning and group 2 finishes the right turning; at 13.6s, the two groups merge into one group again and moves at the speed of (0, 1) in 13.7~15.0s.



(a)



(b)

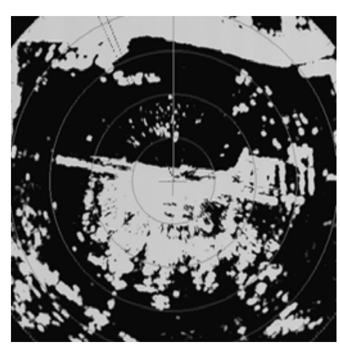
Figure 5 Group splitting and merging in group-target tracking: (a) Target trajectory and the simulated measurements, (b) Tracking results with central group-target tracking algorithm.

In Fig. 5(b), we plot the tracking results with CGTT algorithm. When there is one group, the estimated centers are labeled by "◦"; and by "◦" and"*" when there are two groups. For judgment of the group splitting, n in equation (3) is set to n=2, and the estimated time of splitting is 2.7s (true splitting time is 1.6s); for judgment of the group merging, s_d is set to s_d=0.2 and s_N is set to s_N=4, and the estimated time of merging is 12.8s (true merging time is 13.6s). Note that the judgment of splitting and merging time can vary according to different setting of n, s_d and s_N.

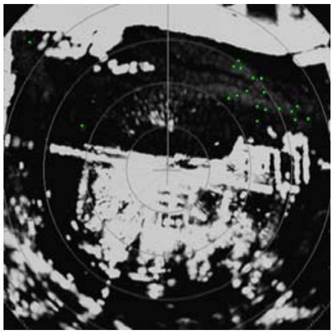
V. APPLICATIONS ON REAL RADAR DATA

We have applied the CGTT algorithm to a sequence of radar images captured by BHEARS with comparison to the MTT algorithm. The radar captures 24 frames of PPI image every minute with a scanning range of 0.5nmi. The capture card transforms the radar data received as function of range and azimuth into an x-y format. The processed image is a 480×480 pixel selection of the central part of the radar display, collected during the experiments on the north bank of Shahe Reservoir, Beijing. The grey value of each pixel of the image lies in [0, 255]. The spatial resolution of the PPI image, which is the distance between two pixels, is set to 4m, so more than one target may appear in the same pixel.

A sequence of 24 horizontal PPI images is processed by the group-target tracking algorithm. The target of interest is a flock flying across the reservoir. Fig. 6 shows the whole processing of the first image of this sequence. Fig. 6(a) is a raw radar image, including the background information and flock targets. By target detecting and information extraction, measurements of the birds can be extracted and labeled in Fig. 6(b). When the number of the measurement is not large enough, MTT algorithm should be used to track all the flying bird targets individually. However, the real-time application is difficult to realize as the number of the measurements is too large (more than 20 in this image). Moreover, for the spatial resolution of the image is 4m, more than one bird may appear in the same pixel. Hence, the CGTT algorithm should be substituted to track the whole target group as a whole. The flight path is shown in Fig. 6(c). The flock moves from west to east and the estimated centers of the group are marked on satellite map with small squares.



(a)



(b)

(c)

Figure 6 Processing of PPI radar images with the CGTT algorithm: (a) Original PPI radar image, (b) Labeled image after target detecting and information extraction, (c) Fusion image with flock flight trajectories.

VI. CONCLUSION

In this paper, we have proposed a central group-target tracking algorithm, enabling flock tracking in PPI radar images. The algorithm combines the clustering method with Kalman filtering, realizing group-target center association, splitting and merging. The resulting algorithm, namely CGTT, is experimentally compared with the MTT algorithm. The tracking result shows that the proposed algorithm focuses on the overall behavior of the target group, while the MTT algorithm focuses on individual targets. The two algorithms are complementary in flying bird targets detecting and tracking. CGTT avoids the data association problem of MTT in clutter environment, bringing a great decrease of the problem complexity. Furthermore, the algorithm is also applied to a PPI radar image sequence to obtain the flock flight path in real time.

Main consideration for future work is to take account of the flock behavior [12] in group-target tracking. Birds in a flock influence each other during flight. Each bird adjusts its velocity by adding to it a weighted average of the differences of its velocity with those of other birds. These characteristics should be considered for the predicted group motion.

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