Radar target tracking in cluttered environment based on particle filtering

N. Huansheng, C. Weishi and L. Jing

The Aeronautical Journal / Volume 114 / Issue 1155 / May 2010, pp 309 - 314
DOI: 10.1017/S0001924000003754, Published online: 03 February 2016

Radar target tracking in cluttered environment based on particle filtering

N. Huansheng **C. Weishi**
ninghuansheng@buaa.edu.cn **wishchen@ee.buaa.edu.cn**
School of Electronics and Information Engineering
Beihang University
Beijing, China

L. Jing
Center of Aviation Safety Technology, CAAC
Beijing, China

ABSTRACT

This paper deals with the problem of radar target tracking in cluttered environment from plane position indicator (PPI) radar images collected by low-cost incoherent radar. For this purpose a new five-step technique is proposed, including background subtraction, clutter suppression, measurements extraction, tracking and data fusion; the tracking step uses a particle filtering based data association method. Radar measurements, including target information and clutter interference, are checked whether it belongs to tracking target by data association with Kalman predicted state. If the measurement is generated by target, target state is updated by Kalman filter, and vice versa the predicted state keeps invariant. Moreover, smoothed tracks are given by Kalman smoothing of filtering results. The performance of the tracking algorithm is deeply investigated against Monte Carlo simulations. Finally, the overall multi-frame-based technique is applied to two sets of live PPI radar images, and the results show the effectiveness of the proposed approach.

1.0 INTRODUCTION

The complexity of radar target tracking in clutter environment is that one must solve the problem of data association firstly, deciding which of the received multiple measurements to use to update track or due to clutter. After data association, standard filtering technology can be used for tracking. Methods for solving the data association problems are typically divided into two classes[1,2]: unique-neighbor data association (such as multiple hypothesis tracking (MHT)) and all-neighbor data association (such as joint probabilistic data association (JPDA)) methods. The main difference between them is that in the former each measurement is associated with one of the previously created tracks, and in the latter all measurements are used for updating all tracks. In MHT, each measurement is associated with an existing track, or a new track is formed according to some criterion. Instead of only one track configuration several hypothesis are simultaneously formed and maintained as the data associations are not necessarily unique. Likelihoods of the measurements and the posterior hypotheses are calculated, and according to these only the most probable hypotheses are stored. Particle filtering (PF) based data association method can be considered as a generalisation of MHT as every particle represents different data association hypothesis[3].

There have been plenty of papers all over the world discussing target tracking, especially data association methods. However, little study has been reported on specific techniques for radar target tracking from plane position indicator (PPI) radar images produced by incoherent radar. In this paper, starting from the approach followed in Ref. 3, we propose a novel radar target tracking technique consisting of five steps, which is the kernel for low-cost radar surveillance system. The performance of the overall technique is deeply investigated against two sets of live PPI radar images.

This paper is organised as follows. After describing the PF based tracking algorithm, Section 2, and deep investigation against simulated data, Section 3, the overall radar target tracking technique based on PPI radar images is explained in detail in Section 4. Finally, results obtained against two sets of live images are reported in Section 5 showing the performance achievable in a practical application of the proposed technique. Some conclusions in Section 6 close the paper.

Paper No. 3468. Manuscript received 12 June 2009, revised version received 16 November 2009 accepted 10 January 2010.

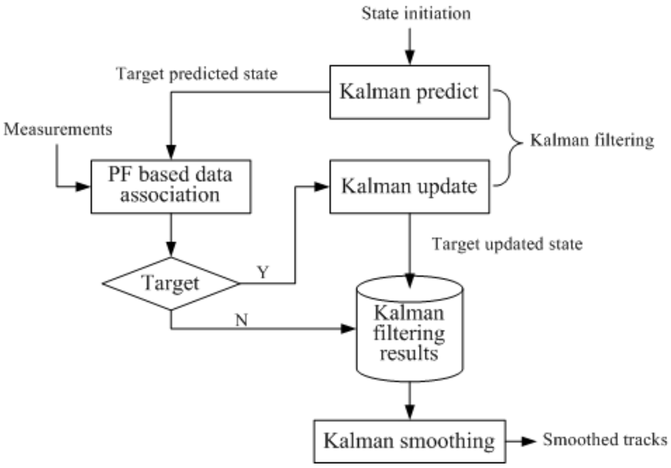


Figure 1. PF based tracking algorithm in cluttered environment.

2.0 PF BASED TRACKING ALGORITHM

The problem of target tracking in clutter environment involves PF based data association and Kalman filtering. The algorithm framework is shown in Fig. 1. Whether the real-time measurement is produced by the tracking target is judged by data association based on Kalman predicted state. If the measurement belongs to the target, target state is modified by the measurement and updated state is obtained, otherwise the state remains unchanged. Judgment method is based on theory of particle filtering, and the results are represented as a discrete set of samples. Finally, all Kalman filtering results are processed by Kalman smoothing, so smoothed tracks are obtained.

Kalman filtering has two steps[4]: the prediction step, where the next state of system is predicted given the previous estimation, and the update step, where the current state of the system is estimated given the measurement at the current time step.

Data association is significant for target tracking in clutter environment, and prerequisite for Kalman state update. Method in this paper is based on the theory of PF. N times of association judgments are stored in variable ind, with the same initial weight for each particle $\{w_k^{(i)} = 1/N,\ i = 1,\dots,N\}$. Association probability for each measurement $P = (P_{tar}, P_{clu})$, includes two elements: target associated probability P_{tar} and clutter associated probability P_{clu}, which are computed as follows[5]:

$$P_{tar} = (1-cp)\cdot P_{lh}, \quad P_{clu} = cp\cdot cd \qquad \dots (1)$$

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

$$P_{lh} = N(\mathbf{y}_k \mid \mathbf{T},\mathbf{S}) \qquad \dots (2)$$

The association probability P is normalised as $P^* = (P^*_{tar}, P^*_{clu})$, where

$$\begin{aligned} P^*_{tar} &= P_{tar}/(P_{tar}+P_{clu}) \\ P^*_{clu} &= P_{clu}/(P_{tar}+P_{clu}) \end{aligned} \qquad \dots (3)$$

Monte Carlo sampling method is used for judgment of whether the measurement is produced by target. A random number $u\sim U(0,1)$ is produced. If u is less than P^*_{tar}, the measurement is determined as target $ind_k^{(i)} = 1$, otherwise it is determined as clutter ($ind_k^{(i)} = 0$). New weight of each particle is computed as;

$$w_k^{(i)} = \begin{cases} w_{k-1}^{(i)}\cdot P_{lh}/P^*_{tar} & ind_k^{(i)} = 1 \\ w_{k-1}^{(i)}\cdot cd/P^*_{clu} & ind_k^{(i)} = 0 \end{cases} \qquad \dots (4)$$

Then, the weight is normalised as

$$w_k^{*(i)} = \frac{w_k^{(i)}}{\sum_{i=1}^{N} w_k^{(i)}} \qquad \dots (5)$$

and the effective number of particles is estimated as

$$n = \frac{1}{\sum_{i=1}^{N}\left(w_k^{*(i)}\right)^2} \qquad \dots (6)$$

If n is too low (i.e. $n<N/4$), perform resampling[6]. For each new particle $\{w_k'^{(i)} = 1/N,\ i = 1,\dots,N\}$, a random number $u\sim U(0,1)$ is generated, the smallest index i` is found to satisfy the following equation

$$\sum_{j=1}^{i'} w_k^{(j)} \ge u \qquad \dots (7)$$

and set

$$\begin{aligned} ind_k'^{(i)} &= ind_k^{(i')} \\ w_k'^{(i)} &= 1/N \end{aligned} \qquad \dots (8)$$

Kalman smoothing[7] is also known as the Rauch-Tung-Striebel (RTS) smoothing. The difference between Kalman filtering and smoothing is that the recursion in filtering moves forward and in smoothing backward. In smoothing, the recursion starts from the last time step.

3.0 TRACKING SIMULATION OF DYNAMIC MODEL

The algorithm's effectiveness is proved by tracking a single target in two dimensions with cluttered measurements, and the simulation results are evaluated and analysed.

3.1 Dynamic model

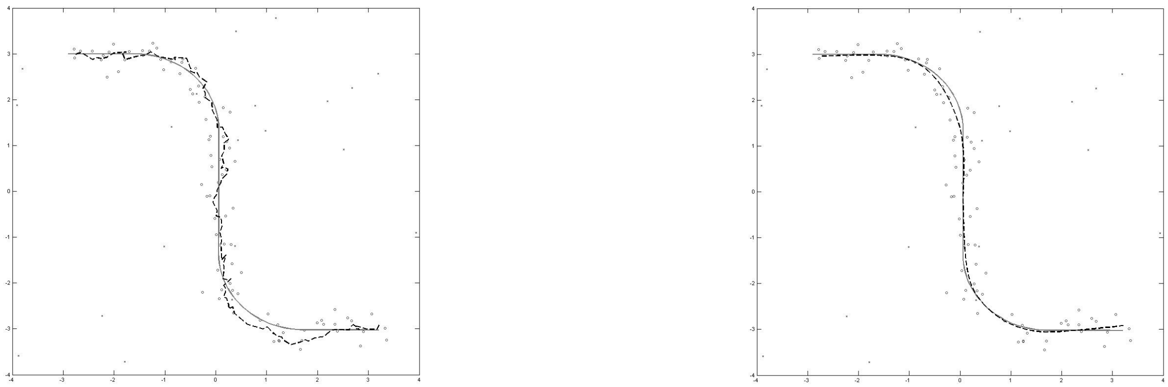
The state of the target can be written as

$$\mathbf{m}_k = (x_k \quad y_k \quad \dot{x}_k \quad \dot{y}_k)^T \qquad \dots (9)$$

where (x_k, y_k) is the target's position and $(\dot{x}_k, \dot{y}_k)$ the velocity in two dimensional Cartesian co-ordinates. $\mathbf{A}$, $\mathbf{Q}$ and $\mathbf{R}$ in Equation (1) are represented as

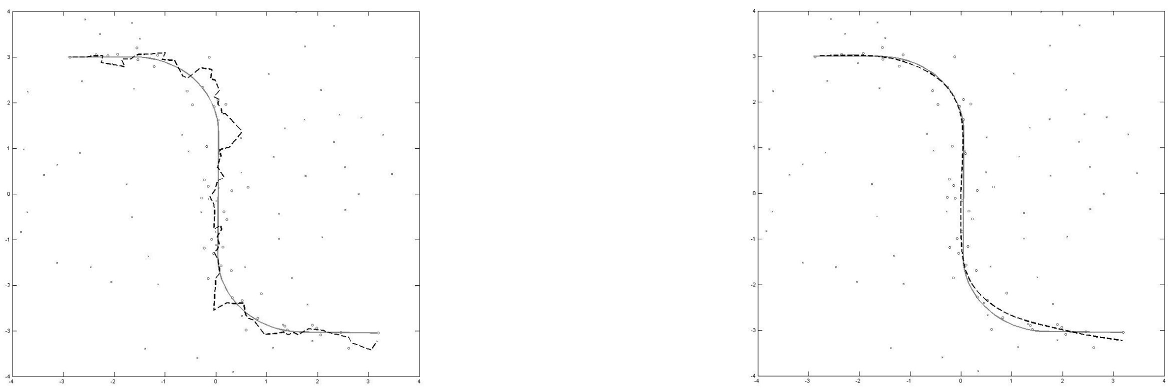
$$\mathbf{A} = \begin{pmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{Q} = \begin{pmatrix} \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 \\ \frac{1}{2}\Delta t^2 & 0 & \Delta t & 0 \\ 0 & \frac{1}{2}\Delta t^2 & 0 & \Delta t \end{pmatrix} q$$



(a) Filtering results (b) Smoothing results

Figure 2. Single target tracking with clutter (cp = 0·2).



(a) Filtering results (b) Smoothing results

Figure 3. Single target tracking with clutter (cp = 0·6).

$$\mathbf{R} = \begin{pmatrix} 0\cdot 05 & 0 \\ 0 & 0\cdot 05 \end{pmatrix}$$

where Δt = 0·1 and q = 0·1. The target starts from (–3,–3), moves at the uniform speed of (1,0) in 0~1·4s, completes right turning in 1·5~4·0s, moves at the uniform speed of   in 4·1~6·7s, completes left turning in 6·8~9·3s, and moves at the uniform speed of (1,0) in 9·4~10·8s. Real target track is shown with solid line in Fig. 2, where target measurements are represented by "∘" and clutter measurements are represented by "×". Target measurement model in linear with additive Gaussian noise. The clutter measurements are defined to be uniformly distributed in space [–4,4] × [–4,4], so cd is set at 1/64.

3.2 Simulation result analysis

In data association, particle number is 10. The value of cp denotes the proportion of clutter in measurements. The higher the value is, the more difficult the tracking is. In Fig. 2, dash line represents filtering and smoothing results for single target tracking when cp = 0·2, and smoothing estimation is closer to real target track. Fig. 3 shows the tracking results when cp = 0·6, so it can be seen that the algorithm still keeps good performance under strong cluttered condition.

Root mean square error (RMSE) for filtering and smoothing results of target's position is calculated using the equation:

$$E_{\text{RMSE}} = \sqrt{\frac{\sum_{k=1}^{T} \left| (x_k, y_k) - (\hat{x}_k, \hat{y}_k) \right|^2}{2T}} \qquad \text{. . . (10)}$$

where (x_k, y_k) is the target's real position on time step k, and $(\hat{x}_k, \hat{y}_k)$ is the corresponding filtering or smoothing result. Average values of RMSE on 100 Monte Carlo simulations with different cp are listed

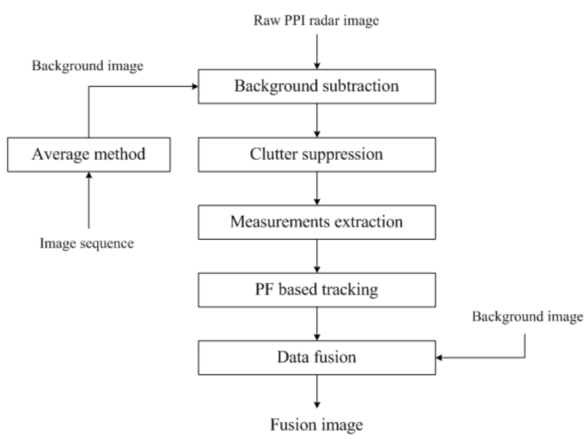


Figure 4. Radar target tracking scheme in PPI images.

in Table 1. It is likely that RMSEs of filtering and smoothing increase with the increase of *cp*, and smoothing estimation result is always better than that of filtering.

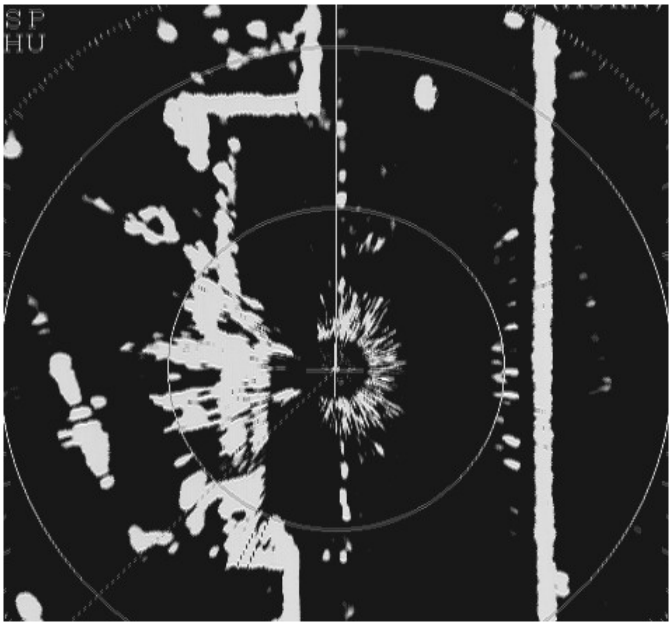
Table 1
RMSE over 100 Monte Carlo simulations

cp	RMSE (Filtering)	RMSE (Smoothing)
0·2	0·1296	0·0636
0·4	0·1523	0·0763
0·6	0·2496	0·1271

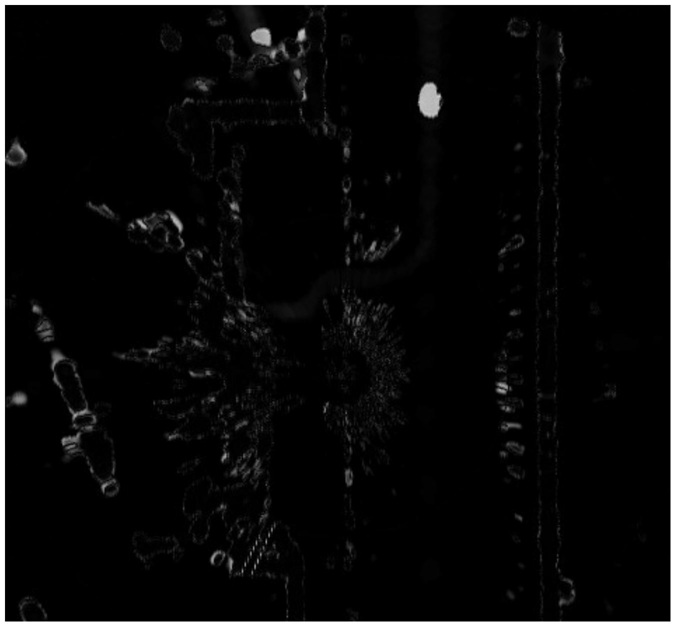
4.0 RADAR TARGET TRACKING TECHNIQUE

Low-cost radar surveillance systems have been developed for home security applications[8] or bird-aircraft strike avoidance[9]. The systems consist of a conventional marine radar, a capture card that digitises the radar signals, and a computer that makes processing. The system provides all-weather, day-night, wide-area awareness with automated detection, localisation and warnings of flying birds, vessels and aircrafts etc. in low-altitude airspace.

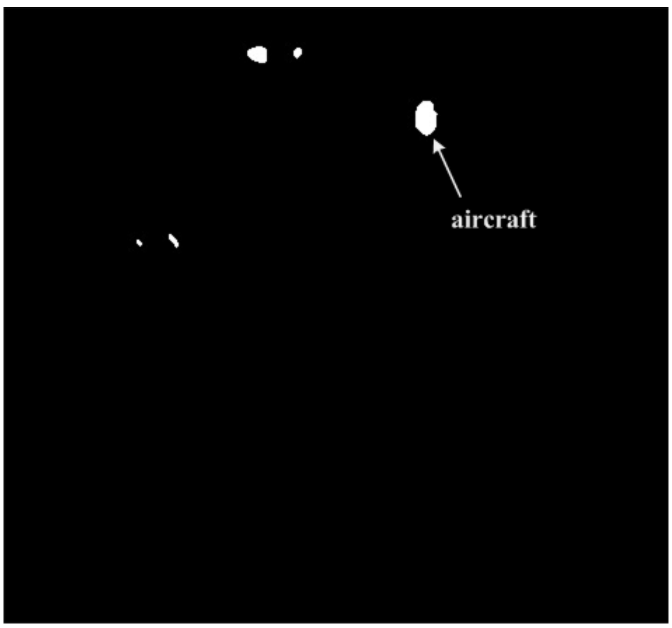
With the cooperation of Center of Aviation Safety Technology CAAC, a radar experimental surveillance system was developed by



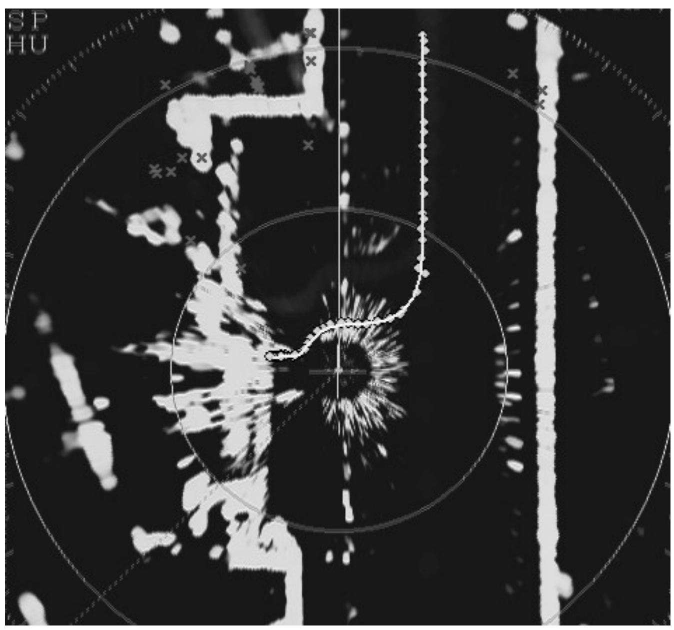
(a) Raw radar image



(b) Subtracted radar image

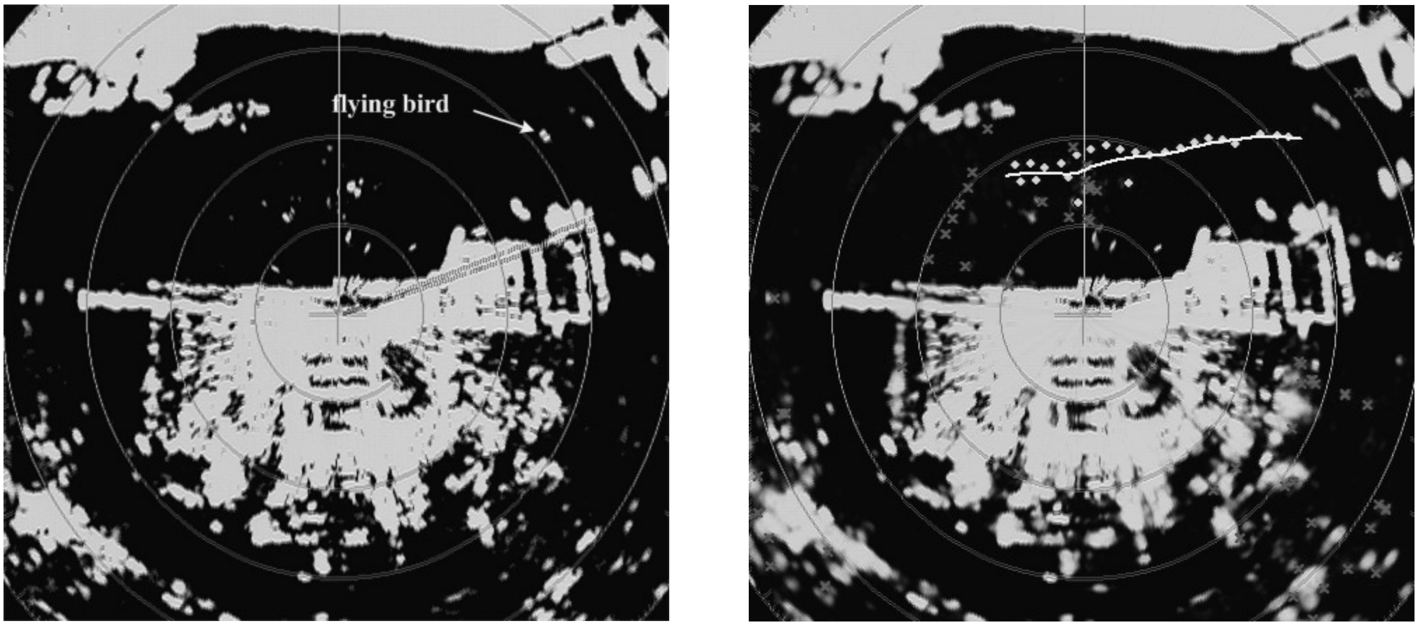


(c) Clutter-suppressed radar image



(d) Fusion image

Figure 5. Aircraft target tracking based on PPI images.



(a) Raw radar image (b) Fusion image

Figure 6. Flying bird target tracking based on PPI images.

Beihang University[10]. PPI images collected by the system are processed by radar target tracking scheme shown in Fig. 4, which is composed of background subtraction, clutter suppression, measurements extraction, PF based target tracking and data fusion.

Background subtraction is the first crucial step in bird targets detection. Therefore, it is essential to construct a pure background image. Since the background changes with time due to variations of surrounding environment, the background image is usually built up as a time averaged version of the input image sequence with programmable time constant in engineering applications.

After background subtraction, there is still a large quantity of clutters in the image, especially much marginal clutter randomly distributed around the edge of the background, so further clutter suppression is absolutely necessary. Threshold calculation is the basic step for clutter suppression, since if the thresholds are too high no targets will be seen and if the thresholds are too low the system will be swamped with false alarms from clutter. A fixed threshold is the simplest and most efficient method, but does not provide any dynamic response to changes in the input images. So, cell-averaged constant false alarm rate (CFAR) method is used to select threshold value adaptively. The threshold is based on the average value of a local area around the sample of interest, automatically responding to dynamic changes in the input image.

After the above two steps, isolated bright areas are left in PPI radar image, whose information is extracted by region labeling and area measurement. By means of region labeling, pixels of each disconnected target area in the binarised PPI image are labeled with the same number. On this basis, center coordinates (ρ, θ) and the sizes of each target represented by pixel number n are extracted.

After the above processing steps, measurements are still mixed with some false alarms since threshold is usually set comparatively low. In order to minimise false alarms, a PF based tracking module is added to the algorithm. The tracking problem is complicated because we do not know which measurements are associated with the existing track, and which measurements are due to clutter. So before standard filtering technique (e.g. Kalman Filter) is applied for each target, data association is necessary.

Data fusion is the last step of the algorithm. In this step, the processed data are displayed on background image in real time and also recorded to databases for detailed post-processing and further analysis.

5.0 APPLICATION TO LIVE PPI RADAR IMAGES

The above technique has been applied to two sets of live PPI radar image data collected by experimental system containing low-altitude targets: more specifically, one set with aircraft and the other with flying bird.

5.1 Aircraft tracking

A series of 112 PPI images with measurement range of 0·25 nautical miles (nmi) were at Nanyang Airport, Henan province, central China on 15 October 2008. The tracking target is a 733 passenger aircraft running from runway to the apron. During the tracking of the aircraft target, measurements from vehicles and staff in and around the airport belong to clutter.

Table 2
Radar measurements

number	ρ (m)	θ (°)	n
1	838·6	104·9	110
2	820·7	97·3	22
3	679·2	68·7	267
4	539·3	146·1	19
5	618	151·7	5

Figure 5 shows the whole processing of the radar image sequence. Figure 5(a) is raw radar image dominated by background due to buildings, trees, shoal and dam besides the flying bird target. After subtraction, Fig. 5(b) is obtained with most of the background removed but still large amounts of marginal clutter left. Figure 5(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 n are extracted and presented in Table 2. Among the five groups of given measurements, the third one with the biggest size is the aircraft, which is also labeled in the figure. In the tracking step, new track is initiated due to its big size, and then target measurements are selected and associated to the existing track to update its present state, when clutters are rejected successfully. Figure 5(d) is the fusion image, where target is indicated by "•" and clutters by "×" in polar coordinates. The smoothed trajectory shows that the aircraft is moving slowly to the apron.

5.2 Flying bird tracking

Another series of 26 PPI images with measurement range of 0·5nmi were collected on the north bank of Shahe Reservoir on 29 March 2007. The tracking target is a small bird flying across the reservoir.

Figure 6(a) is the raw radar image with the target indicated, and Fig. 6(b) is the processed fusion image. Radar detecting range partly depends on the radar cross section (RCS) of the targets of interest. Single bird typically has mean RCS from $1cm^2$ to $100cm^2$, which is even smaller than that of a stealth aircraft(11). Under such conditions, segmentation in the step of clutter suppression has to be set low enough to detect target due to its weak echo signal, and the clutters introduced meanwhile are rejected by PF based tracking algorithm.

6.0 CONCLUSIONS

A new technique for target tracking in cluttered environment from PPI radar images has been proposed. The technique is based on the use of PF based data association, Kalman filtering and smoothing methods. Results obtained by processing live PPI images have also been shown. The analysis on live data proved that the overall tracking scheme is effective for low-cost radar surveillance system. However, radar target tracking is a so sophisticated problem due to the variation of target number, the death of existing targets, the birth of new targets and clutter interference. Such knowledge is still very rarely available in practice, so intensive model has to be built to associate measurements with all known and potential targets and then standard filtering technology can be used for estimating the states of the targets independently. Therefore, unknown birth and death events need to be considered in future work. Otherwise, the technique proposed in this paper belongs to research scope of radar data processor, which is based on echo data obtained by signal processor. The technique is effective for targets moving in area with less clutters, and useless when targets of interest move in the area dominated by background. Under this condition, the detecting and tracking of targets from strong background clutters can only be achieved by Doppler radars.

ACKNOWLEDGEMENTS

This work is jointly funded by National Natural Science Foundation of China (NSFC) and Civil Aviation Administration of China (CAAC) (60879025), and supported by CNS/ATM Labs, CAAC. The authors also wish to acknowledge the financial support from the National High-Tech Research and Development Program of China (2008AA04A101).

REFERENCES

1. BLACKMAN S.S. Multiple hypothesis tracking For multiple target tracking(J). *IEEE Aerospace and Electronic Systems Magazine*, 2004, **19**, (1-2), pp 5-18.
2. Kirubarajan, T. and Bar-Shalom, Y. Probabilistic data association techniques for target tracking in clutter. Proceedings of the IEEE, 2004, **92**, (3), pp 536-557.
3. SÄRKKÄ S., VEHTARI A. and LAMPINEN J. Rao-Blackwellized particle filter for multiple target tracking, *Information Fusion*, 2007, **8**, (1), pp 2-15.
4. RENHONG, Z., ZHONGLIANG, J. and PEIDE, W. *Maneuvering Target Tracking*. Beijing, China: National Defense Industry Press, 1991 (in Chinese).
5. SÄRKKÄ, S. Recursive Bayesian Inference on Stochastic Differential Equations. Doctoral dissertation, Helsinki University of Technology, Helsinki, Finland, 2006.
6. SÄRKKÄ, S., TAMMINEN T. and VEHTARI, A., *ET AL* Probabilistic methods in multiple target tracking–Review and Bibliography, B36. ISBN 951-22-6938-4. Helsinki University of Technology, Helsinki, Finland, 2004.
7. BAR-SHALOM, Y., LI X.R. and KIRUBARAJAN, T. *Estimation with Applications to Tracking and Navigation*, Wiley Interscience, New York, USA, 2001.
8. WEBER, P., PREMJI, A. and NOHARA, T., *ET AL* Low-cost radar surveillance of inland waterways for homeland security applications, IEEE Radar Conference, Philadelphia, Pennsylvania, USA, 26-29 April 2004.
9. NOHARA, T.J., WEBER, P. and UNKRAINEC, A., *ET AL* An overview of avian radar developments–past, present and future. Kingston: Bird Strike Conference, 10-13 September 2007.
10. WEISHI, C., HUANSHENG, N. and WENMING, L., *ET AL* Flying bird targets detection and information extraction based on radar images, *Systems Engineering and Electronics*, 2008, **30**, (9), pp 1624-1627. (in Chinese)
11. MERRILL, I.S. *Introduction to Radar Systems* (3rd ed), New York, USA, McGraw-Hill Companies, 2001.