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Radar target tracking in cluttered environment based on particle filtering

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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: 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.

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.
Then, the weight is normalised as
\[
W_k^{(i)} = \left\{ \begin{array}{ll}
\frac{w_k^{(i)} \cdot P_{\text{tar}}}{P_{\text{tar}}^*} & \text{if } \text{ind}_{k}^{(i)} = 1 \\
\frac{w_k^{(i)} \cdot P_{\text{clu}}}{P_{\text{clu}}^*} & \text{if } \text{ind}_{k}^{(i)} = 0
\end{array} \right.
\] 

(4)

and the effective number of particles is estimated as
\[
n = \frac{1}{\sum_{i=1}^{N} \left( W_k^{(i)} \right)^2}
\]

(5)

If \( n \) is too low (i.e. \( n < N/4 \)), perform resampling \( 6 \). For each new particle \( \{ w_k^{(i)} = 1/N, \; i = 1, \ldots, N \} \), a random number \( u \sim \mathcal{U}(0,1) \) is generated, the smallest index \( \bar{i} \) is found to satisfy the following equation
\[
\sum_{j=1}^{\bar{i}} W_k^{(j)} \geq u
\]

(6)

and set
\[
\text{ind}_{k}^{(\bar{i})} = \text{ind}_{k}^{(i)}
\]

\[
w_k^{(\bar{i})} = 1/N
\]

(7)

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.

\section{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.

\subsection{Dynamic model}

The state of the target can be written as
\[
\mathbf{m}_k = \left( x_k, y_k, \dot{x}_k, \dot{y}_k \right)^T
\]

(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. \( A, Q \) and \( R \) in Equation (1) are represented as
\[
A = \begin{bmatrix}
1 & 0 & \Delta t & 0 \\
0 & 1 & 0 & \Delta t \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
Q = \begin{bmatrix}
\frac{1}{2} \Delta t^3 & 0 & \frac{1}{2} \Delta t^2 & 0 \\
0 & \frac{1}{2} \Delta t^3 & 0 & \frac{1}{2} \Delta t^2 \\
\frac{1}{2} \Delta t^2 & 0 & \Delta t & 0 \\
0 & \frac{1}{2} \Delta t^2 & 0 & \Delta t
\end{bmatrix}
\]

(8)
\( \Delta t = 0.1 \) 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 \((0,1)\) 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 \([-4,4] \times [-4,4]\), so \( c_d \) 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:

\[
E_{\text{RMSE}} = \sqrt{\frac{1}{2T} \sum_{k=1}^{T} (x_k, y_k) - (\hat{x}_k, \hat{y}_k)^2}
\]

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.
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>
<thead>
<tr>
<th>$cp$</th>
<th>RMSE (Filtering)</th>
<th>RMSE (Smoothing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.1296</td>
<td>0.0636</td>
</tr>
<tr>
<td>0.4</td>
<td>0.1523</td>
<td>0.0763</td>
</tr>
<tr>
<td>0.6</td>
<td>0.2496</td>
<td>0.1271</td>
</tr>
</tbody>
</table>

4.0 RADAR TARGET TRACKING TECHNIQUE

Low-cost radar surveillance systems have been developed for home security applications or bird-aircraft strike avoidance. 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
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

<table>
<thead>
<tr>
<th>number</th>
<th>$\rho$ (m)</th>
<th>$\theta$ (°)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>838.6</td>
<td>104.9</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>820.7</td>
<td>97.3</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>679.2</td>
<td>68.7</td>
<td>267</td>
</tr>
<tr>
<td>4</td>
<td>539.3</td>
<td>146.1</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>618</td>
<td>151.7</td>
<td>5</td>
</tr>
</tbody>
</table>

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 ($\rho$, $\theta$) 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 1cm² to 100cm², which is even smaller than that of a stealth aircraft(13). 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 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.

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