Main problems of trajectory processing and approaches to their solution within the framework of multitarget tracking

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Abstract. The main problems of trajectory processing of radar data are considered. Within the framework of the task of multitarget tracking, approaches are proposed that effectively solve the following problems: assignment problems; detection (reset) of trajectories; trajectory measurement of coordinates and motion parameters of the observed objects; highlighting trajectory features.

1. Introduction

Trajectory processing in the general case consists in combining in time the results of the primary processing of the received signals: one-time estimates of coordinates, single decisions about the presence and class of observed objects for trajectory detection, recognizing their classes, and specifying coordinates and motion parameters. Combining one-time estimates of the coordinates of the observed objects in time reduces measurement errors. Combining in time single decisions on the presence or absence of the observed object in a particular resolution element and its class improves the characteristics of detection and recognition. The decision to detect one object with its measured coordinates and the time of the decision is called a plot. Primary radar data (see fig. 1) is understood as a set of plots from the output of the primary processing device for a fixed time interval (space survey period). Trajectory processing allows automation of separating the sequences (streams) of plots from various objects in time with simultaneous measurement of their coordinates and motion parameters. Trajectory processing is an important stage of radar data processing and one of the most difficult.

The problem of developing the stages (elements) of trajectory processing of radar data is widely covered in literature. The most important works include the publications by S. Blackman and R. Popoli [1], Ya. Bar-Shalom and Li X.-R. [2], S.Z. Kuzmin [3], A. Farina and F. Studer [4], Ya.D. Shirman [5], A.A. Konovalov [6] and others. Nevertheless, due to the complexity of the observation conditions, interference environment and multitarget situations, the final solution of the main problems in trajectory processing cannot be found yet.

The difficulty of trajectory processing of radar data for specific targets is due to the need to:
• observe many targets;
• observe a group of closely located objects, subject to their regular or irregular resolution;
• observe objects distributed in space;
• observe maneuvering objects;
• account for nonlinear transformations over estimates of the observation vector;
• detect objects with different reflective properties throughout the coverage area of the radar station;
• take into account the limited time for making decisions about detecting a trajectory and deleting it from tracking;
• detect the event of an object with an unknown radar cross-section leaving the radar station coverage area.

2. Features of trajectory processing
The main tasks of trajectory processing of radar data include:
• automation of the target trajectory detection process;
• improving the probability of detection or recognition of targets;
• improving the accuracy of measuring the target coordinates due to discrete filtering of the coordinates of the plots;
• determination of the full vector of target speed and additional parameters;
• extrapolation of values of coordinates and parameters.

In accordance with the tasks to be solved, the following stages of trajectory processing are distinguished:
• scan-to-scan selection of moving targets;
• track detection (initiation and confirmation);
• track deletion;
• plot to track association;
• data association;
• detection of trajectories of objects in a cluttered environment;
• filtering and prediction (estimate of the coordinates and parameters of the target motion with the selection of track signs).

A plot is understood as the result of observing the target for one contact (one scan, one data refresh interval). The track is understood as a regular sequence (flow) of time and space plots belonging to the same target.

The use of trajectory processing improves the quality of solving problems of radar surveillance for the following two reasons. First, the combination in time of single decisions on the presence or absence of a target in a particular resolution element and its class improves the characteristics of detection and recognition. Second, combining one-time estimates of target coordinates in time reduces measurement errors.

The input information for trajectory processing on the \((k+1)\)-th scan is \(M\) plots, which include: a vector of one-time estimates of the observed coordinates; time of making a decision on detection of a reflected signal; additional signs (number of plot channel, solution of a radar recognition device, etc.).

The output information of the trajectory processing on the \((k+1)\)-th scan is \(N\) state vectors, which include: smoothed (filtered) trajectory coordinates and the time of their generation; trajectory signs («physically realizable trajectory», «high-speed target», «clutter», etc.); additional information (course, full speed, acceleration, etc.).

The complexity of trajectory processing is due to the fact that:
• several \(N\) targets are observed in the radar coverage area (usually – \(N \gg 1\));
• the number \(N\) of plots in most cases is not equal to the number \(M\) of trajectories (\(N \neq M\));
• target observation conditions are difficult.

The difficulty of observing targets is due to the presence of a large number of target-like false plots – discrete interfering reflections (see Fig. 2).

Fig. 2. Fragment of recording radar plots (targets and clutters)
Figure 2 shows a fragment of a record of radar plots for 25 scans of a real radar station at ranges from 0 to 150 km and in the azimuth sector from 0 to 360 degrees. This figure shows the residuals of compensation for concentrated local objects at ranges up to 15 km, hydrometeor clouds at ranges of 5...24 km and azimuths 80...160 degrees, mountains overgrown with forests at ranges of 60...94 km and azimuths 250...300 degrees.

Fragment A in Fig. 2 (enlarged) shows the radar plots caused by the exceeding of the detection threshold by the residuals of compensation of disturbing reflections from mountains. It clearly shows areas of concentration of plots, fluctuating in position. One of these areas is outlined with an ellipse.

Fragment B in Fig. 2 (enlarged) shows the residuals of the compensation of interfering reflections from hydrometeor clouds. A number of highly fluctuating moving sequences of discrete interfering reflections are observed here. One of these sequences is highlighted with an ellipse. The motion of the residuals of interfering reflections from the cloud compensation has one direction, however, a scatter of velocities is observed. A large number of residuals from compensation is due to the small dynamic range of the receiving path of the radar (no more than 30 dB) and the imperfection of the device for selecting moving targets. The presence of a large number of residuals of interference compensation significantly complicates the process of trajectory processing.

In addition, in the course of trajectory generation, false trajectories are inevitable because of discrete interfering reflections and observation of a group of closely spaced targets.

3. Problems of trajectory processing and approaches to their solution

When implementing trajectory processing, 8 main problems can be distinguished. Below are their essences and suggested solutions.

The first problem is associated with the need to detect trajectories of targets with a small radar cross-section at long ranges. When solving this problem, it is necessary to resolve the contradiction. On the one hand, for high-quality detection, it is necessary to increase the time for making a decision on trajectory detection. On the other hand, an increase in time will lead to an increase in the probability of detecting trajectories at false plots. A possible way to solve this problem is to use a trajectory detector adaptive to the range to the target and to the intensity of the flow of false plots.

This method allows
- reducing the average number of false trajectories by 2-4 times;
- increasing the probability of correct detection of trajectories of targets with a small radar cross-section by 10-35% compared to a non-adaptive detector.

The second problem is related to the need to timely delete target trajectories from the tracking. When solving this problem, a contradiction also arises. On the one hand, it is necessary to reduce the time for making a decision to reject the trajectory. On the other hand, it is necessary to increase this time when detecting targets with a small radar cross-section to prevent premature rejection from the trajectory tracking. A possible way to solve this problem is to use a trajectory deletion algorithm adaptive to the range to the target (or to the probability of its correct detection) and to the intensity of the flow of false plots.

This method allows
- reducing the average number of false trajectories by 1.4-2 times;
- increasing the probability of correct rejection of trajectories of targets with a small image intensifier by 5-23% in comparison with a non-adaptive rejection algorithm.

The third problem is related to the need to estimate the coordinates and parameters of maneuvering targets. When solving this problem, the following contradiction arises. On the one hand, if the order of the sensor is less than the order of the target motion model, the probability of the target disengaging from tracking is high due to the appearance of a dynamic error. If the opposite situation arises, then the fluctuation error of filtration and the duration of transient processes in the filter increase. A possible way to solve this problem is to use Interactive Multiple Model (IMM) adaptive to the change of motion model [14-16].
This method allows:  
• inertialess adapting the model of the target motion to prevent the growth of the dynamic error and exclusion of the target from tracking;  
• reducing the likelihood of tracking loss by 90-95% in comparison with non-adaptive filters;  
• reducing the filtering error by 50-90% compared to the primary estimate.

The fourth problem is related to the need to distribute plots along trajectories (it is formulated as a nonlinear problem of resource allocation among consumers – the assignment problem). The difficulty in this case lies in the exponential growth of computational costs as the number of plots and tracks increases. A possible way to solve this problem is to use a resource allocation algorithm adaptive to the dimensionality of the assignment problem (combined auction or JV) [8].

This method allows:  
• reducing the time to solve the assignment problem by 10-100 times compared to the Hungarian method;  
• maintaining a high quality solution to the assignment problem.

The fifth problem is connected with filtering the coordinates and parameters of a group of closely spaced targets, with their regular and irregular resolution from scan to scan. The difficulty in this case lies in the fact that the presence of such a group leads to a delay in the detection time of trajectories and the appearance of false tracks. A possible way to solve this problem is to use an algorithm adaptive to hypotheses of assigning plots along trajectories with JPDA-IMM (Joint Probability Data Associations with IMM) [1, 9] and reducing the number of hypotheses using the Viterbi and Murty’s algorithm [1, 10].

This method allows:  
• reducing the duration of transient processes by 3-10 times, compared to the non-adaptive algorithm (Hungarian algorithm);  
• significant reduction of the number of false trajectories when observing a group of periodically resolved objects.

The sixth problem is related to the observation of multiple targets against the background of simulating artificial and natural interference. The difficulty in this case lies in the fact that the interference becomes a source of a large number of false plots concentrated in space and regularly appearing from scan to scan. A possible way to solve this problem is using a device for scan-to-scan selection of moving targets (based on clutter maps) against the background of clutters adaptive to the flow rate of false plots [17, 18, 19, 20].

This method allows:  
• increasing the coefficient of suppression of discrete interfering reflections and response-simulating interference up to 0.7-0.95;  
• adaptation to the time-varying parameters of the discrete interfering reflections.

The seventh problem is related to the trajectory of targets included in the zone of intensive clutters (discrete interfering reflections). The difficulty in this case lies in the regular hitting of several plots in the trajectory strobe from scan to scan and a high degree of uncertainty as to which of the plots is true. A possible way to solve this problem is to use the probabilistic data fusion algorithm at the stage of measuring the coordinates and parameters of the target’s motion PDA-IMM (Probability Data Associations and IMM).

This method allows:  
• increasing the probability of trajectory passing through the area of intense interference by 10-50% in comparison with non-adaptive algorithms;  
• adaptation to the number of false plots in the trajectory strobe.

And finally, the eighth problem is connected with checking the physical realizability of the tracked trajectory, since in the process of trajectory tracking, a situation may arise when the parameters of the trajectory movement do not fit into the permissible range (permissible speeds, overloads, etc.). The difficulty in this case lies in the fact that the direct recalculation of the state vector estimate gives significant distortions of the physical realizability parameters, the spread of which is difficult to
predict. A possible way to solve this problem is to obtain a numerical Monte Carlo approximation of the probability density of the parameters of physical realizability through a nonlinear transformation over the Gaussian probability density of the state vector estimate [22].

This method allows
• making a decision on the compliance of the trajectory with the physically realizable one with a given confidence level;
• adaptation to errors in the measurement of the state vector.

4. Conclusion
The report considers the main problems of trajectory processing of radar information and approaches to their solution within the framework of the task of multitarget trajectory. The ways to solve the problems of trajectory processing include:
• application of new methods for solving the assignment problem (Auction, JVC, Viterbi and Murty);
• use of Interactive Multiple Model (IMM);
• application of JPDA-IMM (Joint Probability Data Associations with IMM);
• application of PDA-IMM (Probability Data Associations with IMM);
• use of new methods for scan-to-scan selection of moving targets in cluttered environment;
• application of adaptive maintenance of distributed objects;
• introduction of algorithms for detecting and deleting trajectories adaptive to observation conditions;
• search for new approaches to the calculation of signs of observed objects (based on Monte Carlo method).

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