General construction principles and performance features of trajectory processing by data from one radar data source

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Abstract. The general principles of construction and features of the operation of the trajectory processing device based on data from one source of radar information are considered. The tasks performed and structure of the trajectory processing device are discussed.

Introduction
Not a single modern radar complex or station is complete without a trajectory processing system. Currently, there are two main approaches to constructing a trajectory processing system. The first one is that each main function of the trajectory processing system (track detection, plot to track association, filtering, track deleting, etc.) is implemented as a separate algorithm [1, 2]. Such an implementation is convenient and efficient when constructing trajectory processing devices in simple conditions - in the absence of complex interference, grouped, distributed and separating objects, etc. In more complex signal-clutter situations, some of the algorithms (for example, filtering and plot to track association) are implemented jointly and significantly affect each other. This has led to the fact that at present there is a tendency to create combined algorithms that solve several problems at once [2]. In such conditions, the complexity of synchronization and accounting for the influence of algorithms on each other increases significantly. The issues of constructing combined algorithms within the framework of a unified system of trajectory processing are practically not considered in the literature. The report will discuss the general principles of construction and features of the operation of the trajectory processing device based on data from one source of radar information.

1. General principles of trajectory processing based on data from one source of radar data
Tracking information processing consists in combining in time a sequence of radar plots belonging to one object. A radar plot (or simply a plot) is understood as a vector of observed parameters (their one-time estimates) of the detected signal and the time point corresponding to the detection decision. Combining in time single decisions about the presence or absence of an object in a particular resolution element and its class improves the characteristics of detection and recognition. Combining one-time estimates of the coordinates of the observed objects in time reduces measurement errors. Methods for combining time stamps and the processing quality indices achieved thereby constitute the content of the problem of trajectory processing of radar information. The track (trajectory) of the
observed object here means the time sequence of the filtered coordinates of the observed objects and the vector of its velocity.

It should be noted that several objects with different coordinates can be located simultaneously in the radar coverage area. Moreover, the measurement of their coordinates should be carried out independently, i.e. in separate tracks. Before considering the features of constructing a trajectory processing device, it is necessary to determine the tasks to be solved, input and output information.

The input information of the trajectory processing device is the plots that contain the vector of the observed parameters and the time of determining the coordinates of the observed object. The output information of the tracking processor is the trajectory state vector.

The main tasks of trajectory processing of radar information are [1-4] automation of the process of detecting tracks of observed objects; improving the probability of detection decisions when detecting or recognizing observed objects; improving the accuracy of measuring the coordinates of observed objects due to discrete filtering of their plot coordinates; determination of the full velocity vector of the observed objects; determination of extrapolated values of coordinates and motion parameters of observed objects.

Trajectory processing, as a rule, is implemented in software form on a specialized computer that is a part of the radar, the control center or a complex of automation equipment, where the radar is capable of issuing primary radar information. Trajectory processing of radar information is carried out sequentially in time (from scan to scan of the radar) as new plots are received from the device for the primary processing of the received signal. The generalized block diagram of trajectory processing is shown in Fig. 1.

![Fig. 1. Generalized block diagram of the trajectory processing device in the radar](image-url)
Trajectory processing main elements are scan-to-scan selection of moving targets, plot to track association, track detection, track deletion, track buffer. In this case, the track is a separate class responsible for storing data for each individual stream of one-time plots and operations with them. All tracks are stored in a track buffer.

In accordance with the presented diagram, the principle of operation of trajectory processing is as follows. Initially, preliminary processing is performed on the received plots: scan-to-scan selection of moving targets and coordinate conversion. Further, the plots on the current scan are sent to the association device, and the extrapolated coordinates of the tracks, together with the extrapolation errors, are also received there.

Based on these data, a correspondence matrix is formed. The plot numbers are on one side, and trajectory numbers are on the other side. The values of the matrix elements are equal to the weights of the proximity of the plot coordinates to the centers of the path gates. These weights are commonly referred to as likelihoods.

After the distribution of the plots along the track, the filtration of the coordinates and parameters of the trajectory movement is performed, but only those in which the plot fell.

In the tracks that did not include the plots, the criterion for deleting the trajectory from tracking is checked. If the criterion is met, then the track is deleted from tracking, i.e. removed from the track buffer by the corresponding device. New tracks are created based on the plots that did not fall into any of the tracks, and they are added to the buffer.

Thus, the main operations of the trajectory processing at the stages of track detection and tracking are: detecting a new plot in the view area and setting a new track; determination of the full velocity vector; filtering and extrapolation of coordinates and motion parameters of the observed object; strobing - highlighting the area of the likely location of the object in the next cycle of the space scan; association of the plot coordinates and extrapolated tracks and the choice of one of them to continue the track.

2. Features of plot to track association

The plot to track association is the most difficult stage of trajectory processing. This is due to the fact that a multitarget situation with a high degree of uncertainty about the belonging of observations to target trajectories is often observed. At the same time, there is no a priori information about the number of targets in the coverage area. At the same time, clutters are observed, the properties of which change over time.

The following stages of association are conventionally distinguished:

- taking into account the spatial correlation of observations;
- formation of a multi-linked list (database);
- identifying conflict situations (splitting the general list into private ones);
- taking into account the time correlation of observations;
- formation of gating matrices (resource allocation problem);
- analysis of conflict situations (resource allocation problem).

An additional difficulty in solving the association problem is that it must be solved at high speed. Checking for hitting the gate is performed according to [3]:

$$v_k^T R_k^{-1} \sum_{k+1} v_k \leq g_p,$$

where

$$v_{k+1} = \hat{\theta}_{k+1} - H \hat{\alpha}_{k+1},$$

is observation residual vector (the discrepancy between the vector of observed parameters \( \theta_{k+1} \) and the state vector \( \hat{\alpha}_{k+1} \), converted into the coordinate system of the vector of observed parameters using the matrix \( H \));

$$R_{k+1} = R_{0k+1} + HR_{0k+1} H^T,$$

is correlation matrix, including correlation matrix of one-time estimation errors \( R_{0k+1} \) and the correlation matrix of extrapolation errors \( HR_{0k+1} H^T \), converted into a system of a vector of observed parameters;
\( g_P \) – gating threshold (significance level) determined with the probability of hitting a plot in a gate \( P_G(m_0, g_P) \) according to Fig. 2.

![Fig. 2. Strobe factor](image)

The condition for solving the identification problem is the gating matrix \( Q \). The formation of such a matrix becomes more complicated in the presence of several targets and false plots, when situations of detection-measurement-resolution arise. Figure 3 shows the case when two signals are resolved, but there is no trajectory resolution. The crosses show the coordinates of the current estimates numbered I, II, and III, the dots show the forecast estimates numbered 1 and 2. The shaded ellipses around the current estimates correspond to the dimensions of the cross-sections of the mismatch bodies of the sounding signals in coordinates, and the ellipses around the forecast estimates are determined by the forecast errors, current estimation, and maneuverable target capabilities.

![Fig. 3. Trajectory uncertainty situation (a) and gating matrix for it (b)](image)

To form the matrix \( Q \), it is necessary to calculate the likelihood coefficient, which characterizes the measure of the proximity of the \( i \)-th track and the \( j \)-th plot [3]:

\[
L_{i,j} = \frac{(2\pi)^{-m_0/2}}{\sqrt{|R_{\Sigma(k+1)}|}} \exp \left\{ -\frac{1}{2} v_k^T R_{\Sigma(k+1)}^{-1} v_k \right\}.
\]

If it is necessary to create a new trajectory at the \( i \)-th plot, then its weight (measure) of the solution will be determined according to
\[ L_{i,j} = \frac{V}{V_{str}} \]

where \( V_{str} \) – detection gate volume.

The hypotheses for association of plots and tracks reflect all possible options. In this case, the number of hypotheses will be equal to \([3, 4]\):

\[
N_{\text{hyp}} \approx \min\left\{ n, m \right\} \sum_{j=0}^{\min\{n, m\}} \frac{n! \cdot m!}{j!(n-j)!(m-j)!}.
\]

Hypotheses are represented in the form of correspondence matrices \( \mu_s \left( s = 1, N_{\text{hyp}} \right) \), according to the rules [3]:

1. The dimension is the same as the size of the gating matrix \((n \times m)\);  
2. Matrix elements can be zeros and ones, characterizing the correspondence of plots to trajectories;  
3. A unit at the intersection of the \(i\)-th row and \(j\)-th column means the identification of the \(i\)-th track with the \(j\)-th plot   
4. You can bind the \(j\)-th plot to only one track;  
5. \(i\)-th track can be bound to only one plot.

In the situation shown in Fig. 4, a:

- the first plot may be false, belong to the first track or a new track 3;  
- the second plot can be false, belong to the first or second track, or form a new track 4;  
- the third plot can be false, belong to the second track or a new track 5.

Thus, for the situations considered in Fig. 4, \(M = 30\) possible hypotheses of identification can be formed. These hypotheses are summarized in Table 1. The columns of the table correspond to the numbers of plots I, II and III, the rows correspond to the numbers of hypotheses from 1 to 30.

| Hypothesis | I | II | III | Hypothesis | I | II | III |
|------------|---|----|-----|------------|---|----|-----|
| 1          | 0 | 0  | 0   | 16         | 1 | 2  | 5   |
| 2          | 0 | 0  | 2   | 17         | 1 | 4  | 0   |
| 3          | 0 | 0  | 5   | 18         | 1 | 4  | 2   |
| 4          | 0 | 1  | 0   | 19         | 1 | 4  | 5   |
| 5          | 0 | 1  | 2   | 20         | 3 | 0  | 0   |
| 6          | 0 | 1  | 5   | 21         | 3 | 0  | 2   |
| 7          | 0 | 2  | 0   | 22         | 3 | 0  | 5   |
| 8          | 0 | 2  | 5   | 23         | 3 | 1  | 0   |
| 9          | 0 | 4  | 0   | 24         | 3 | 1  | 2   |
| 10         | 0 | 4  | 2   | 25         | 3 | 1  | 5   |
| 11         | 0 | 4  | 5   | 26         | 3 | 2  | 0   |
| 12         | 1 | 0  | 0   | 27         | 3 | 2  | 5   |
| 13         | 1 | 0  | 2   | 28         | 3 | 4  | 0   |
| 14         | 1 | 0  | 5   | 29         | 3 | 4  | 2   |
| 15         | 1 | 2  | 0   | 30         | 3 | 4  | 5   |

After that, the correspondence matrix is assessed as a measure of the cumulative proximity of the plots to the trajectories. Matching matrices are matrices \( \mu = [\mu_{ij}] \) of dimensions \((n+1) \times (m+1)\) (\(n\) is the number of trajectories, \(m\) is the number of plots), consisting of zeros and ones and characterizing the correspondence of plots and trajectories. A unit at the intersection of the \(i\)-th row and \(j\)-th column means the identification of the \(i\)-th trajectory with the \(j\)-th plot. Units in the zero line indicate the hypothesis that the plot is new or false, and in the zero column indicates the omission of the plots for the corresponding trajectories. For each of the rows in Table 1 (i.e., for each identification hypothesis),
its own correspondence matrix is compiled. So, for the 1st, 14th and 29th lines of Table 1 the correspondence matrices are:

\[
\mathbf{\mu}_1 = \begin{bmatrix}
0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}, \quad \mathbf{\mu}_{14} = \begin{bmatrix}
0 & 0 & 1 & 1 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}, \quad \mathbf{\mu}_{29} = \begin{bmatrix}
0 & 1 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
\]

There are two main options for evaluating compliance matrices. The first method is based on the Nearest Neighbor («egoist») algorithm according to [3]:

\[
L_{\mathbf{\mu}}(\mathbf{\mu}) = \prod_{i=1}^{n} \max(Q_{i,j}) \forall \mathbf{\mu}_{i,j} \neq 0; \ j = 1, n.
\]

In this case, the maximum-likelihood estimate is made [3]:

\[
\mathbf{\hat{\mu}} = \arg \max_{\mathbf{\mu}_s} \{L_{\mathbf{\mu}}(\mathbf{\mu}_s)\}, \ s = 1, N_{\text{run}}.
\]

The second method is based on the Global Nearest Neighbor («altruist») algorithm according to [3]:

\[
L_{\mathbf{\mu}}(\mathbf{\mu}) = \prod_{i=1}^{n} \prod_{j=1}^{m} Q_{i,j} \forall \mathbf{\mu}_{i,j} \neq 0.
\]

In this case, the mean value is assessed [3]:

\[
\mathbf{\mu} = \frac{1}{N_{\text{hyp}}} \sum_{i=1}^{N_{\text{hyp}}} P(\mathbf{\mu}_s, \mathbf{\mu}) L_{\mathbf{\mu}}(\mathbf{\mu}_s) \mathbf{\mu}_s.
\]

Evaluation of the correspondence matrix allows us to speak about the unambiguous or probabilistic distribution of plots along the trajectories.

**Difficulties that arise when solving the identification problem:**

1. Exponential growth of computational costs as the number of plots and trajectories increases;
2. Geometric growth of the number of identification hypotheses \(N_{\text{hyp}}\) with an increase in the number of conflicting plots and trajectories;
3. Features of the detection (deletion) of tracks

Tracking detection is understood as the process of acquiring new targets for tracking that appear in the radar coverage area. Tracking detection is carried out based on analysis of the sequence of plots coming from the same target over several scans, and ends with a decision on the presence or absence of a target. There are two main methods for constructing deletion and detection algorithms: block and sequential methods.

In block methods, the size of the analyzed sample \(n\) is determined in advance based on a priori known distributions and specified error probabilities. In this case, the decision to detect or delete is made as a result of the simultaneous analysis of the entire sample. Trajectory detections are usually implemented in a sliding window of size \(n\). After receiving the next measurement, one of three possible decisions is made: track detection, track deletion, or continuation of data collection. The sample size in this case is a random value depending on the incoming data and the required probabilities of detecting trajectories.
Currently, sequential criterion two-stage detectors \(((2 \ of \ n) + (k \ of \ m))\) are the most commonly used. Their main advantages are ease of implementation and intuitive configuration requirements. The disadvantage is that such algorithms do not adapt to the conditional probability of detection \(D\) and false alarm \(F\). Figure 4 shows the probability of trajectory detection depending on the criterion used, range and radar cross section. The figure shows that the «soft» criteria (with \(n > 2\) and \(k \ll m\)) allow increasing the probability of detection, but the probability of false alarm increases. The use of «hard» criteria can reduce these probabilities.

![Figure 4. The probability of correct trajectory detection depending on the criterion used, range and radar cross section (RCS)](image)

Thus, the use of various criteria for target detection, depending on the range, makes it possible to ensure a high value of probability of detection throughout the entire radar coverage area.

When deleting a trajectory, the sequential criterion of the detector is most often used – «\(n\)» passes in a row. Figure 5 shows the dependence of the probability of a false trajectory reset depending on the criterion used, the range and the effective reflecting surface of the target.

![Figure 5. Probability of false alarm of trajectories depending on the criterion used, range and radar cross section](image)

### 4. Features of tracking filtration

To filter the coordinates and motion parameters of maneuvering targets, various modifications based on Kalman filter are most often used [3, 4, 6-10]. The movement of a target in space can be described by various models of movement (with constant speed or acceleration, steady-state turn, etc.). In this case, the moments of change of the motion model and the motion parameters for the observer are not known. To effectively solve this problem, it is advisable to use a trajectory meter (IMM – Interactive...
Multiple Model) adaptive to changing motion model [3, 4, 11-14]. The structure of the IMM is shown in Figure 6.

In accordance with the diagram, the principle of IMM operation is as follows. Current estimate of the observation vector \( \hat{\theta}_{k+1} \) enters all IMM channels that are tuned to different traffic patterns. At the output of the channels, conditional estimates of the state vector are formed \( \hat{\alpha}_{k+j} \) according to refined a priori data \( \hat{\alpha}_{k+j} \), \( \hat{R}_{k+j} \) from the previous measurement step. The device for calculating probabilities calculates the posterior probabilities of the motion model \( P_{k+1}(f_{k+1}') \) and the probabilities of transition from one model to another \( P_{k+1}(f_{k+1}') \). Received probabilities \( P_{k+1}(f_{k+1}') \) are fed to the weight adder to calculate the unconditional estimate of the state vector \( \hat{\alpha}_{k+1} \).

The use of IMM modifications allows adapting the target movement model without inertia, preventing the growth of dynamic error and target disruption from tracking.

Conclusions

The report considers the general principles of construction and features of the operation of the trajectory processing device based on the data from one source of radar information. The main tasks of trajectory processing of radar information are considered. They include automation of the trajectory detection process; improving the probability of detection decisions when detecting or recognizing; increasing the accuracy of measuring coordinates due to discrete filtering of the plot coordinates; determination of the full vector of speed; determination of extrapolated values of coordinates and motion parameters. The features of the devices included in the trajectory processing are considered: the device for identifying plots and trajectories; the trajectory in which the filtration and extrapolation of coordinates is directly carried out; device for creating a new trajectory; trajectory removal device.

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