A Method of Maneuver Detection Based on Multi-step Innovation

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A Method of Maneuver Detection Based on Multi-step Innovation

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Abstract. One way to improve the processing capability for high-speed mobile anti-ship missiles is to improve the target data tracking rate, so that the Fire Control System can obtain more target information, but the improvement of the data sampling rate will reduce the signal-to-noise ratio of single-step window measurement by the traditional maneuver detection algorithm. In this paper, a maneuver detection algorithm based on multi-step prediction is proposed. The algorithm uses the current measurement value and the multi-step prediction value information, and uses the maneuver detection method based on attenuation memory. Through the simulation calculation method, the relationship between the minimum maneuver detection delay time and the attenuation coefficient, and the prediction step are given. At the same time, the method can also effectively reduce the detection of false alarm rate.

1. Introduction

Maneuvering target tracking mainly included the preprocessing of observation data, the maneuvering target model, the maneuvering detection and motion identification, the filtering and prediction, the tracking coordinate system and the selection of filter state variables which were location and description of target space. The difficulties mainly came from two aspects: the first difficulty was the uncertainty of the target movement, the second difficulty was the noise of observation data. In order to solve this problem, an important step was the maneuver detection[1,2,3].

The main idea of maneuver detection was to conduct a maneuver detection in accordance with a particular criterion or logic with the change of innovation vector $d(k) = Y(k) - H\hat{X}(k/k-1)$ which came from observation data $Y(k)$ and state prediction data $H\hat{X}(k/k-1)$. Based on maneuver detection results, we could adaptive adjust system state noise matrix, estimate and predict the motion state of maneuvering targets at last, achieve to tracking target. Therefore, the performance of maneuvering target tracking could be detected in a reliable and timely detection of target maneuver model.

In 21 century, due to the rapid development of electronic technology, the performance of high-speed target had been greatly improved. In order to improve the Terminal defense system processing capacity of supersonic anti-ship missiles, one way is to improve the fire control system data rate to fully use the tracker's target measurement data. In view of the improvement of system data rate, the traditional maneuver detection method[4,5,6,7] based on single-step innovation is no longer applicable. In this paper, a new method of maneuvering detection based on multi-step innovation was proposed, which can be used to extract the target maneuver information, which is convenient for maneuver detection.
Through simulation calculation, for a given false alarm rate, the detection method gives the relationship between the minimum maneuver detection delay and the attenuation coefficient.

2. Multi-step innovation calculation method

The target dynamic model was used to describe the change of the target state $X$ with the change of time. Linear state space model (discrete time model) was:

$$
\begin{align*}
X(k+1) &= \Phi(k+1|k)X(k) + U(k)\alpha + W(k); \\
Y(k) &= H(k|k)X(k) + V(k);
\end{align*}
$$

(1)

Taking the discrete state equation as an example, $X(k)$, $Y(k)$ and $U(k)$ were the vector of the target state, observation and control inputs at $k$ time; $\Phi(k+1,k)$ and $H(k)$ were the appropriate state transition matrix and observation matrix $W(k)$ and $V(k)$ were system model noise and observation noise, respectively, which were Gauss white noise sequence. Statistical characteristics were:

$$
\begin{align*}
[E[W(k)] = 0; E[W(k)W^T(j)] = Q \cdot \delta_{ij}; \\
E[V(k)] = 0; E[V(k)V^T(j)] = R \cdot \delta_{ij};
\end{align*}
$$

Q and $R$ are system noise and observation noise covariance matrix[8,9], $E[*]$ is expectation operator, if $k=j$, $\delta_{ij}=1$; else $\delta_{ij}=0$.

Innovation was the difference between observation data and forecast data, formula:

$$
d(k) = Y(k) - H(k)\hat{X}(k|k-1)
$$

(3)

In reference [4], the author proved that linear optimal filter innovation sequence $(d(k))$ which based on Kalman filter and prediction was zero mean Gauss white noise.

Multi-step innovation $(d_T(k)^i)$ was the difference between observation variables $Y(k)$ and Multi-step forecast variables $\hat{X}(k|k-1)$ at $T$ step.

$$
d_T(k) = Y(k) - H(k)\hat{X}(k|k-T)
$$

(4)

Here, $T$ was an integer multiple of the system operating cycle. If the target was not maneuvering, for non maneuvering target model, $(d_T(k)^i)$ was also the zero mean Gauss white noise characteristic, the maneuver detection method described in this paper was also based on the characteristic.

3. Maneuver Detection Method

Detection of maneuvering targets was a decision problem, which could be formulated as a hypothesis testing problem.

$H_0$: non maneuvering, $H_1$: maneuvering

According to the characteristics of observation residuals and control inputs, In maneuvering target tracking, we could use testing using the $\chi^2$ detection methods and or quasi $\chi^2$ detection methods. Under the condition of $H_0$ (detection maneuver startment), we estimated whether or not the Statistic was $\chi^2$ distribution. Assuming that under $H_0$ conditions, $\varepsilon$ was $\chi^2$ distribution $\varepsilon \sim \chi_n^2$ with degree of freedom is $n$, and the next equation was is set up, it indicated that the target is maneuvering.

$$
\varepsilon > \lambda = \chi_n^2(\alpha)
$$

(5)

Here $1-\alpha$ was confidence value.

Normalized residual squared was $\varepsilon_i = d'(k)S^{-1}_k d(k)$. $S_k = \text{cov}(d(k))$. In order to reduce the probability of false alarm and false alarm, this used the method of attenuation memory statistics to test the hypothesis. The sum of memory decay was $\varepsilon^\rho_k$.

$$
\varepsilon^\rho_k = \sum_{j=1}^{k} \rho^{k-j} \varepsilon_j = \rho \varepsilon^\rho_{k-1} + \varepsilon_k, \quad 0 < \rho < 1, \quad s_\rho = \frac{1}{1-\rho}
$$

(6)
Here, $\rho$ was attenuation coefficient, $s_\rho$ was the length of the sum of Attenuation memory equivalent window. Because $\varepsilon_k$ was $\chi^2$ distribution $\varepsilon \sim \chi^2_n$ with degree of freedom is $n(\varepsilon_k \sim \chi^2_n, n = \text{dim}(d))$. $\varepsilon_k^\rho$ was not $\chi^2$ distribution, but it could be approximated as a $\chi^2$ variable by weight matching. That was approximate[10]:

$$
\varepsilon_k^\rho \sim \frac{1}{1+\rho} \chi^2_n, \quad n_\rho = n \frac{1+\rho}{1-\rho}
$$

(7)

In application, we used $n = 3$ when tracking in spherical coordinate system. At this point, the maneuvering start can be detected according to the equation (6).

4. Maneuver Detection Delay Time
Generally, the problem of hypothesis testing was expected to get as many measurements as possible to improve the detection probability. But for the problem of maneuver detection, we hoped to get the judgment as soon as possible. That was the minimum delay. In this way, we faced two conflicting goals. That was to increase the detection probability and tried to delay the decision, at the same time we tried to reduce the delay to avoid tracking lag. So, it was very important to obtain the detection delay time accurately under the constant false alarm rate.

According to equation (6), It could be seen that the calculated value $\varepsilon_k^\rho$ was related to the amplitude of maneuver (the value of innovation) and the length of the window ($s_\rho$). Maneuver detection delay time which was $\chi^2$ distribution was the function of the system model, maneuvering range, threshold value ($\alpha$) and window length(equivalent to the size of the attenuation coefficient). Maneuver detection delay time which based on multi-step innovation was the function of the model of the system, the range of motion (with the step length), the confidence and the length of the window.

Confidence value was given according to system requirements, If the $\alpha$ is small, confidence value is high, the threshold value of maneuvering target is higher, therefore, the detection delay is large. So, $\alpha$ was inversely proportional to the detection delay. Maneuvering amplitude also affected detection delay, the large maneuver made the value of the innovation sequence larger. So the statistical value $\varepsilon_k^\rho$ has a larger value. For a fixed detection threshold, it was easy to detect maneuver earlier. In fact, Since the target was unknown, thus, the amplitude of maneuver was unknown in advance, it could not be used for system optimization. When the window length $s_\rho$ was large, randomness of $\varepsilon_k^\rho/s_\rho$ was very weak, detection lag was larger. At the same time, if the step of multi-step innovation was larger, it would also bring detection lag, so the selection of the step size of multi-step innovation, and the window length (attenuation coefficient) could be selected to optimize the system.

5. Simulation Analysis
Considering the complexity of the optimal problem, the simulation method was used here, to guide the choice of step length and attenuation coefficient.

The target simulation route was from the uniform straight line to a certain fixed load to do uniform acceleration motion, a total of 5 target route simulation were used. Target overload capacity was from 1.0g to 5.0g, for each route, the attenuation coefficient ranged from 0.1 to 0.8. Under different overload conditions, the relationship between the minimum detection delay time and attenuation coefficient was shown in Figure 1. It could be seen that the smaller the attenuation coefficient, the longer the delay time. This was also consistent with theoretical analysis.

For each of the above routes in fixed attenuation coefficient, the step size of the multi-step innovation was set from 10 to 60 (the number of operating cycles), and simulated. Simulation results showed: for a highly maneuverable target course (as described in this article), there was no
change in the detection delay time under different step sizes. But it could significantly reduce the false alarm rate of target maneuvering detection, as shown in figure 2.

For weak maneuvering routes, the same transition from uniform straight line to a fixed overload to do uniform acceleration movement, but the target overload is only 0.2g. In the fixed attenuation coefficient conditions, the minimum detection delay time and the relationship between the steps shown in Figure 3. It can be seen that there is an optimal prediction step for the fixed attenuation coefficient.

6. Conclusion
Anti-ship missiles an important direction of development is faster and faster, leaving the end of the defense system response time is getting shorter and shorter. An effective way to improve the handling capacity of anti-ship missiles is to improve the utilization rate of the tracking system for tracking data, that is, to improve the data rate of the end defense system. But the improvement of the data rate will reduce the traditional signal-to-noise ratio based on the single-step new machine
detection window. Based on this, this paper presents a maneuver detection method based on multi-step new information, and adopts the maneuver detection method based on attenuation memory. According to the given maneuver detection threshold, the analysis and simulation show that the false alarm rate can be significantly reduced by the multi-step dynamic detection method. For the simulation route, the minimum detection delay time and attenuation coefficient are given, and the relationship between the delay time and the prediction step is given.

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