SPACE-BASED TACTICAL BALLISTIC MISSILE TYPE IDENTIFICATION

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This work is focused on the space-based tactical ballistic missile type identification. As mentioned in some literatures, the missile types are mainly identified by infrared radiation, missile engine off-time eigenvalue or standard ballistic trajectory. But the infrared radiation is sensitive to weather, light beam and cloud cover; the missile engine off-time eigenvalue are different according to different missile flight programs; the standard ballistic trajectory is not applicable to especially lofted and depressed ballistic trajectory. In this paper, a novel method is proposed to identify the missile types according to the brand new characteristics. By analyzing the law of the missile thrust and the mass changed over time, the paper comes to the conclusion that the maximum range and the ratio of the missile thrust to the mass are the main characteristic information to distinguish the missile types. Next, an algorithm is established to calculate these characteristics from observation data, and the fuzzy pattern recognition algorithm is introduced to fuse these characteristics. Finally, there is discussion of example calculation by use of different methods, and the results show that the method in this paper is more reliable and feasible.

1. INTRODUCTION

At present, some developed countries have been developing their early warning satellite systems. These systems, (e.g. the Defence Support Program (DSP) and the Space-Based Infrared System (SBIRS)), identify the missile types by use of missile characteristic database.

ZHAO [1] gave a method to identify the missile types with three characteristics: the launching location, infrared radiation characteristic and missile engine off-time eigenvalue. But ranges computed by missile engine off-time eigenvalue will always be different if different flight programs are chosen. Using the methods of missile launch parameter estimation mentioned in literature [2] for reference, a method which takes standard ballistic trajectory as characteristic could be established to identify the missile types. However, the standard ballistic trajectory is not applicable to especially lofted and depressed ballistic trajectory.

In this paper, a novel method is proposed to identify the missile types according to the brand new characteristics. By analyzing the law of the missile thrust and the mass changed over time, the paper comes to the conclusion that the ratio of the missile thrust to the mass, called the acceleration of missile thrust, is the characteristic information. However, in the special case that when the curve shapes of thrust acceleration are similar, the uncertain launch time influences the recognition results. To deal with this situation, the acceleration of missile thrust is fused with the maximum range characteristic. Next, an algorithm is established to calculate these characteristics from observation data, and the fuzzy pattern recognition algorithm is introduced to fuse these characteristics. Finally, by changing the missile flight programs the simulation is repeated 1000 times. The accurate recognition rate gained by our method is 72.2%, by the method of the fusion of infrared radiation and missile engine off-time eigenvalue is less than 30.0%, and by the method of the fusion of infrared radiation and standard ballistic trajectory is less than 40.0%.

2. THE ANALYSIS OF MISSILE CHARACTERISTICS

2.1 The Analysis of Thrust and Mass

According to interior ballistics, the rocket engine thrust is as follows:

$$P(t,h) = m_{ci}u_{ei} + S_{ai}(P_{ai} - P_h), \quad t_{ki-1} < t \le t_{ki}, \quad i = 1,\cdots,n \tag{1}$$

where n is missile stages. t_{ki} is the shutdown time of $i-th$ rocket engine, taking flying-off for micro chronometer. m_{ci} is the total propellant flow rate of $i-th$ rocket engine. u_{ei} is the jet speed at nozzle exit of $i-th$ rocket engine. S_{ai} is the section area of nozzle exit of $i-th$ rocket engine. P_{ai} is the pressure of combustion-air flow at nozzle exit of $i-th$ rocket engine. P_h is the static pressure of atmosphere at the position where the missile locates.

The sea level thrust is $P_{0i} = m_{ci}u_{ei} + S_{ai}(P_{ai} - P_N)$, and the vacuum thrust is $P_{vi} = m_{ci}u_{ei} + S_{ai}P_{ai}$; $P_N = 101360 N/m^2$. Therefore,

$$P(t,h) = m_{ci}u_{ei} + S_{ai}(P_{ai} - P_h) = P_{vi} - S_{ai}P_h = P_{vi} - (P_{vi} - P_{0i})P_h / P_N \quad (2)$$

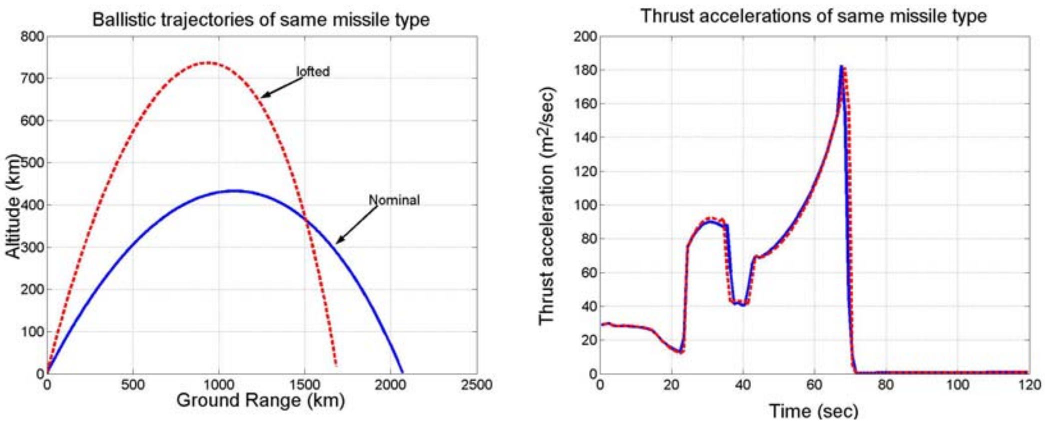
When the missile is detected, its position locates at about 20km height, where $P_h / P_N \approx 5\%$ and relative atmosphere density is less than 8%. So the missile thrust can be considered as vacuum thrust, and the difference of atmosphere influence according to different flight programs can be taken no account of. Therefore, $P(t,h)$ should take on the same law as time varies for the same missile type.

The change law of the missile mass as time varies is as follows:

$$m(t) = m_{0i} - \int_{t_{k,i-1}}^{t} m_{ci}dt, \quad t_{ki-1} \le t \le t_{ki}, \quad i = 1,\cdots,n \quad (3)$$

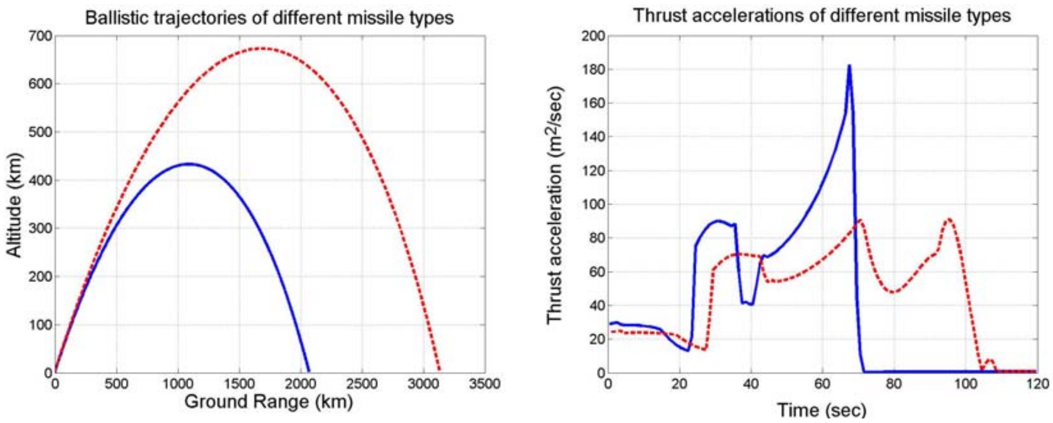
where m_{0i} is lift-off mass of $i-th$ rocket. For the same missile type, m_{0i} and t_{ki-1} are the constants, while m_{ci} takes on the same law as time varies. Therefore, $m(t)$ should take on the same law as time varies.

By doing much calculation, along with analysis of thrust and quality, $P(h,t)/m(t)$, defined as dynamic characteristic (thrust acceleration), takes on the same law as time varies for same missile type. Generally speaking, the result of recognition by use of this characteristic is credible, shown in figure.1 and figure.2.



(a) (b)

Figure 1. (a) Comparison of ballistic trajectories of the same missile type. (b) Comparison of thrust accelerations of the same missile type.



(a) (b)

Figure 2. (a) Comparison of ballistic trajectories of different missile types. (b) Comparison of thrust accelerations of different missile types.

According to literature [5] and literature [7], $P(h,t)/m(t)$ can be calculated from observation data.

2.2 The Analysis of Maximum Range

Define the flight time as τ when the missile is detected by the satellite system. However, the error of τ may influence the results of recognition badly.

The error of τ computed by 4th-order polynomial coefficients, will be very large, so τ can be estimated by comparing with standard dynamic characteristic in database. But if their curve shapes are similar, the dynamic characteristic computed by measurement pairs from satellites may make a deviation to true value. Therefore, it is necessary to give other characteristics for recognition. Generally, different missile types also have different maximum ranges. Consequently, maximum range is defined as another characteristic, called capability characteristic.

Next an algorithm is provided to compute maximum range as follows. Mentioned in literature [4], the maximum range corresponding to the flight program is:

$$\varphi = \begin{cases} \pi/2 & 0 \le u_1 \le 0.05 \\ 6.25(\pi/2 - \varphi_k)(0.45 - u_1)^2 + \varphi_k & 0.05 \le u_1 \le 0.45 \\ \varphi_k & u_1 \ge 0.45 \end{cases} \tag{4}$$

where $u_1 = \int_0^t m_{c1} dt / m_{01}$. The pitch angle, defined as φ_k, is a constant.

Using literature [2] and literature [5] for reference, eq. (5) can be gained.

$$\begin{cases} mgh_{\tau 2} - mgh_{\tau 1} = \frac{1}{2} mV_{\tau 1}^2 - \frac{1}{2} mV_{\tau 2}^2 \\ d_{\tau 2} = (1-1.5l) d_{\tau 1}, \quad h_{\tau 2} = (1+l) h_{\tau 1} \\ tg\varphi_2 \approx \frac{h_{\tau 2}}{d_{\tau 2}}, \quad tg\varphi_1 \approx \frac{h_{\tau 1}}{d_{\tau 1}} \end{cases} \tag{5}$$

where $h_{\tau i}(i=1,2)$ is the height where the missile locates at τ. $V_{\tau i}(i=1,2)$ is the missile speed at τ. $d_{\tau i}(i=1,2)$ is the horizontal distance between launcher and missile position at τ. When pitch angle is changed from φ_2 to φ_1, $V_{\tau 1}$ can be calculated by use of eq. (6).

$$V_{\tau 1} = \sqrt{V_{\tau 2}^2 + \frac{4}{5} g h_{\tau 2} \frac{tg\varphi_2 - tg\varphi_1}{tg\varphi_2}} \tag{6}$$

With $P(h,t)/m(t)$ and eq. (6), engine off-time eigenvalue will be computed. So the maximum range of post-boost phase can be calculated. Then the range of the boost phase is estimated. Consequently, the maximum range can be computed.

3 RECOGNITION BASED ON DATA FUSION

Define the distance of thrust acceleration between the missile to be recognized and standard missile in database as follows:

$$D_i = \sqrt{\left(\sum_{j=1}^{n} (a_i(t_j+\tau) - a(t_j))^2 / n\right) / \min_{i \neq k} \left(\sum_{j=1}^{n} (a_i(t_j+\tau) - a_k(t_j+\tau))^2 / n\right)} \tag{7}$$

where $\{a(t_j)\}_{j=1,\cdots,n}$ is the thrust acceleration sequence of the missile which will be recognized, $\{a_i(t_j+\tau)\}_{j=1,\cdots,n}$ is the corresponding thrust acceleration sequence of standard missile in database.

As mentioned above, define the distance of maximum range R_i, quantity of heat T_i and pixel of infrared imagery L_i (according to [1]) between them as follows:

$$R_i = \frac{|R - R_i^{ok}|}{\min\limits_{j \neq k}(|R_j^{ok} - R_k^{ok}|)}, \quad T_i = \frac{|T - T_i^{ok}|}{\min\limits_{j \neq k}(|T_j^{ok} - T_k^{ok}|)}, \quad L_i = \frac{|L - L_i^{ok}|}{\min\limits_{j \neq k}(|L_j^{ok} - L_k^{ok}|)} \tag{8}$$

Define membership function as follows:

$$y(x) = \frac{1}{1 + (x/a)^n} \tag{9}$$

where $a = 1, n = 2$

So the degree of membership between the missile to be recognized and standard missile in database is: $N_i = a_D \cdot y(D_i) + a_R \cdot y(R_i) + a_L \cdot y(L_i) + a_T \cdot y(T_i)$, where a_D is the weight of thrust acceleration, a_R is the weight of maximum range, a_L is the weight of pixel of infrared imagery, and a_T is the weight of quantity of heat.

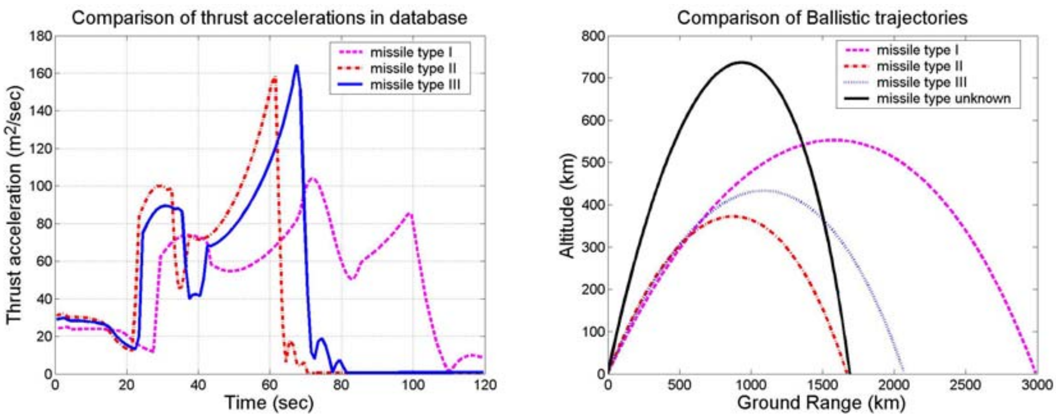
Define that $N = \bigvee\limits_{1 \le j \le m} N_j$, and λ is threshold. If $N \ge \lambda$, it belongs to this type, if $N < \lambda$, it doesn't belong to any type in database.

4 EXAMPLE CALCULATIONS

For convenience, assume that ballistic trajectory is a planar curve and there are three missile types. Table1 describes infrared radiation characteristic and capability characteristic, and figure.3 (a) describes dynamic characteristic in missile database. With comprehensive consideration, the weights of dynamic characteristic and capability characteristic are both set for 40%, while the weights of quantity of heat and pixel of infrared imagery are both set for 10%, Suppose that quantity of heat of the missile to be recognized is 2320 and pixel of infrared is 4.

Table 1 infrared radiation characteristics and capability characteristics in database

Missile type	quantity of heat	pixel of infrared imagery	Maximum range
I	2600	3	3300
II	2200	5	1750
III	2400	4	2300



(a) (b)

Figure 3. (a) Dynamic characteristics in database
(b) Ballistic trajectories displaying in launch geographic coordinates

The different methods are listed as follows:

Method 1: Fusion of missile engine off-time eigenvalue and infrared radiation characteristic

Method 2: Fusion of dynamic characteristic and infrared radiation characteristic

Method 3: Fusion of standard ballistic trajectory and infrared radiation characteristic

Method 4: Fusion of dynamic characteristic, capability characteristic and infrared radiation characteristic

The results of calculations are shown in table 2.

Table2 the results of different methods

Method / Degree of membership (Accuracy of recognition) / Type	Method 1	Method 2	Method 3	Method 4
I	0.183(0%)	0.210(0%)	0.231(0%)	0.179(0%)
II	0.947(52.6%)	0.633(28.5%)	0.702(2.1%)	0.477(5.5%)
III	0.572(25.1%)	0.814(31.9%)	0.721(38.9%)	0.883(72.2%)
results	II	III	III	III

As shown in table 2, by changing the missile flight programs the simulation is repeated 1000 times, the accurate recognition rate gained by our method is 72.2%, while other methods are less than 40%.

5 CONCLUSIONS

Based on the interior ballistics principle and a great deal of experimentations, this paper comes to a conclusion that the acceleration of missile thrust and maximum range characteristic are the main characteristic information for distinguishing the missile types. Furthermore, the fuzzy pattern recognition algorithm is introduced based on weight sum of membership degree. Simulation results show that the accurate recognition rate gained by our method is 72.2%, by the method of the fusion of infrared radiation and missile engine off-time eigenvalue is less than 30.0%, and by the method of the fusion of infrared radiation and standard ballistic trajectory is less than 40.0%.

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