Near space interceptor on-line correction research based on predictive intercept point

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Abstract. Aiming at the problem of large maneuvering range and difficult target detection of hypersonic target in the near space, according to the maneuvering range of predictive intercept point (PIP), this paper proposes a method to select different correction algorithms. First, The Gauss pseudospectral method is used to solve the trajectory optimization problem and the off-line optimal trajectory is generated. Then, aiming at the situation that the range of predictive intercept point is small, based on neighboring optimal control, the on-line correction method is used to find out the optimal trajectory near the off-line optimal trajectory. Finally, when the interceptor is located in a high airspace, aiming at the situation that the range of target motion is wide and the range of predictive intercept point is large, a direct force correction method based on velocity gain guidance is adopted. Simulation results verify the effectiveness of the proposed methods.

1. Introduction

Near space refers to the airspace 20km ~ 100km away from the ground. Near space hypersonic vehicle is a weapon that flies in the near space for a long time. Although the airspace of the near space is relatively high, the hypersonic vehicle in the near space can still fly for a long time in it according to the unique aerodynamic shape with high lift drag ratio. The vehicle has the characteristics of large combat space, fast flight speed, strong penetration ability and wide damage range, bringing great challenges to the air defense safety in the future. At present, there is no effective intercept method for hypersonic target in the near space. There are few researches on the interception of hypersonic vehicles in the near space, most of researches focus on the attack of hypersonic vehicles in the near space[1]. These also bring some reference to the near space defense operations. After years of research, the scholars have gradually formed three mainstream ideas for the interception of near space interceptors: air-based interception, ground-based interception and near space-based interception [1,2,3,4,5,6,7]. This paper is mainly talking about the ground-based.

Ballistic design is an important part of interception based on ground. The traditional air defense interceptor does not need to design the trajectory specially. The guidance law adopted by it can determine the trajectory. However, due to the high altitude, strong maneuverability, difficult target information acquisition and prediction, and the need for long-distance interception of target, the traditional way of intercepting by using guidance law to determine the trajectory and tracking the target in the whole process will limit the range and flight state of interceptor. At the same time, when the guidance law dominates the trajectory, in the initial launch phase, the interceptor will mainly fly straight to the target area. At same time, the target flight height is high, which will greatly increase the
interceptor flight time in the dense atmosphere. In contrast, if the interceptor is launched vertically at first, it will quickly cross the dense atmosphere at the bottom layer, and then it will fly to the target area after turning, which will greatly save energy. Therefore, the trajectory of interceptor is designed separately to meet the constraints of each stage and achieve the desired performance index, so that in the actual flight, the off-line optimized trajectory can be tracked by adjusting the control quantity to achieve the purpose of interception.

Aiming at the trajectory planning and trajectory correction of the interceptor in the near space, a lot of scholars have done related work: literature [8] studies the problem of front angle constraint, and the guidance law designed can get the optimal angle of the corresponding plane. In literature [9] and [10], indirect methods are used to study the trajectory optimization of spacecraft, but to guess the initial value of the covariates is necessary; in literature [11], the guidance law with angle constraint is studied with the view angle of the seeker as the constraint. In reference [12], the problem of trajectory optimization in the vertical ascent of solid rocket is solved by the indirect method. References [13,14,15,16] linearized the missile-target motion model, designed the optimal guidance law based on the trajectory shaping guidance idea, deduced the optimal trajectory model by using the Gauss pseudospectral method. In reference [17], the integrated control law of cooperative attack guidance and control is designed by using the inversion control theory. The disturbance observer is introduced and the angle constraint of seeker is taken as the constraint condition of guidance law design. In order to avoid the limitation of Gauss pseudospectral method in solving complex optimization problems, the HP adaptive pseudospectral method is used to study the problem of multi constraint and multi-stage trajectory optimization design in reference[18], which obtained good results. Reference[19] designed the integrated guidance and control algorithm based on the inversion control theory, compared with the traditional design, the proposed method has better robustness.

However, when the target is maneuvering, the optimal trajectory generated offline will no longer meet the constraints. Therefore, the original terminal constraints are no longer applicable, and the trajectory of interceptor needs to be corrected. Considering the characteristics of long time, small overload and large area of near space target, the trajectory correction algorithm of guidance in near space interceptor should have the following characteristics:

(1) Rapidity, for the disturbance generated on the basis of the reference trajectory, the algorithm should has the ability of fast correction and planning, to ensure that the trajectory change period is greater than the trajectory correction period.

(2) Accuracy, according to the change of the predicted intercept point and other constraints, which can generate the corresponding optimal trajectory in real time, so as to ensure the smooth completion of the shift handover at the end of the middle term.

(3) Robustness, we must ensure non-singularity of the algorithm in the wide range, and avoid the singularity in the trajectory correction process.

(4) Selectivity, according to the different predicted intercept points in different ranges, there is no universal solution, so it is necessary to choose a reasonable correction method according to specific scenarios.

Based on the above research and analysis, the following scenarios are made for the optimization and correction methods of the missile middle track:

Before the interceptor is launched, according to the target prediction information, the predicted intercept point is determined, and the interceptor angle constraint at the time of the transition of the middle and terminal guidance is taken as the terminal state constraint to establish the dynamic terminal constraint model. At the same time, the optimization indexes of trajectory, such as heat flow density constraint, angle of attack constraint, dynamic pressure constraint, terminal velocity of interceptor, vertex height of high throw trajectory and required energy, are taken as process constraints. The trajectory optimization algorithm is used to solve off-line to obtain the optimal trajectory data base pointing to the predicted intercept point, which is bound to the interceptor missile computer. If the predicted trajectory information of the target is accurate and the predicted intercept point does not change, the interceptor carries out flight control according to the trajectory database instruction of the
missile computer; if the predicted intercept point changes in a small range, the online trajectory optimization algorithm based on neighboring optimal control is applied to obtain the optimal trajectory; if the predicted intercept point changes in a large range, the first condition is to ensure that the interceptor meets the position constraints under the fixed flight time, and the direct force correction is used based on the velocity gain guidance algorithm.

2. The motion model of interceptor

The longitudinal plane motion model of interceptor is established as follows:

\[ \dot{\alpha} = \frac{P \cos \alpha - C_\alpha q S}{m} - g \sin \theta \]
\[ \dot{\theta} = \frac{P \sin \alpha + C_\beta q S}{mV} - \frac{g \cos \theta}{V} \]
\[ x = V \cos \theta \]
\[ y = V \sin \theta \]

Where \( V \) is the velocity of interceptor, \( P \) is the thrust acting on interceptor, \( q \) is the dynamic pressure, \( S \) is the reference area and \( g \) is the acceleration of gravity. \( \theta \) is the trajectory angle, \( m \) is the interceptor mass, \( x, y \) are the missile position in the earth inertial coordinate system. \( C_\alpha, C_\beta \) are drag coefficient and lift coefficient, can be expressed as functions of Mach number \( Ma \) and angle \( \alpha \) of attack respectively:

\[ C_\alpha = C_{\alpha 0} (Ma) \alpha \]
\[ C_\beta = C_{\beta 0} (Ma) + K (Ma) \cdot C_\beta^2 \]

Where \( C_{\alpha 0} \) is the coefficient of zero lift resistance, \( C_{\alpha 0} \) is the partial derivative of lift to angle of attack, and \( K \) is the coefficient of induced resistance.

In order to make the interceptor have more maneuverability and direct force damage effect at the end, the maximum velocity at the end time is generally taken as the optimization index \( J \). The geometric center coordinates of the predicted intercept area at the terminal time are expressed as \((x_f, y_f)\). In order to ensure the good conditions, the target value of the trajectory inclination at the terminal time is set as \( \theta_f \). Then the terminal constraints can be expressed as:

\[ \psi_f = [\theta - \theta_f, x - x_f, y - y_f]^T = 0 \]

The angle of attack is taken as the control quantity, and the process constraint is set to \( \| u \| \leq u_{\max} = 20 \text{deg.} \)

3. The generation of off-line trajectory

3.1. Trajectory optimization problem description

The state equation of interceptor is expressed as follows:

\[ \dot{X}(t) = f(X(t), u(t), t) \quad t \in [t_0, t_f] \]

Where, \( X(t) \in u^n \) is the \( n \) dimensions vector, represents the interceptor state vector. \( u(t) \in u^m \) is the \( m \) dimensions vector, represents the interceptor control vector. \( t_0 \) indicates the starting time and \( t_f \) is terminal time. The boundary condition constraints formed by the start time and the end time can be expressed as,

\[ \psi(X(t_0), t_0, X(t_f), t_f) = 0 \]

In the middle time, the path constraints that need to be considered can be expressed as,

\[ C(X(t), u(t), t) \leq 0 \quad t \in [t_0, t_f] \]

\[ J = \phi(X(t_0), t_0, X(t_f), t_f) + \int_{t_0}^{t_f} g(X(t), u(t), t) dt \]
\( f(X(t_0), t_0, X(t_f), t_f) \) represents the terminal performance index that the interceptor state needs to meet at the beginning and the end, and \( g(X(t), u(t), t) \) represents the integral performance index that needs to be considered in the whole optimization process. The definition field and value field of the function \( f, \psi, C, \phi, g \) are as follows,

\[
\begin{align*}
\phi(X(t_0), t_0, X(t_f), t_f) &\equiv \phi(x^n, u^m, t^l) \rightarrow x^n \\
\psi(X(t), u(t), t) &\equiv \psi(x^n, t^l, x^n, t^l) \rightarrow x^n \\
C(X(t), u(t), t) &\equiv C(x^n, u^m, t^l) \rightarrow x^n \\
\phi(X(t_0), t_0, X(t_f), t_f) &\equiv \phi(x^n, t^l, x^n, t^l) \rightarrow x^n \\
g(X(t), u(t), t) &\equiv g(x^n, u^m, t^l) \rightarrow x^n
\end{align*}
\]

Generally, the control variables are thrust control variables or aerodynamic control variables, and the constraints and performance indexes are related to the missions in different stages. In the off-line optimal trajectory generation, the angle of attack is selected as the control variable.

3.2. Trajectory optimization generation based on Gauss pseudospectral method

The time domain of the optimal control problem is \([t_0, t_f]\), transformed into \([-1, 1]\), the interval of discrete point distribution of Gauss pseudospectral method, and a new time variable \( \tau \) is introduced for transformation,

\[
\tau = \frac{2t - t_f + t_0}{t_f - t_0} \quad (13)
\]

Record \( dt \) and \( d\tau \) as the differential of time \( t \) and variable \( \tau \), \( \frac{dt}{d\tau} = \frac{t_f - t_0}{2} \).

By substituting formula (27) into the equation of state for time domain transformation \([t_0, t_f] \rightarrow [-1, +1]\), there will be

\[
\frac{dX}{d\tau} = \frac{t_f - t_0}{2} f(X(\tau), u(\tau), \tau) \quad \tau \in [-1, +1] \quad (14)
\]

\[
\psi(X(-1), t_0, X(+1), t_f) = 0 \quad (15)
\]

\[
C(X(\tau), u(\tau), \tau) \leq 0 \quad \tau \in [-1, +1] \quad (16)
\]

\[
\min_{u(\tau), \tau \in [-1, +1]} J = \int f(X(-1), t_0, X(+1), t_f) + \frac{t_f - t_0}{2} \int_{-1}^{+1} g(X(\tau), u(\tau), \tau) d\tau \quad (17)
\]

After parameterizing the state quantity, control quantity, state equation and index function in turn, the continuous optimal control problem in the time domain is transformed into the NLP problem with discrete parameters in the domain defined by pseudospectral method. Details in reference [20] using the software package developed by Gill as the solver of NLP problem [21].

4. On-line correction algorithm of interceptor

4.1. Small range on-line correction algorithm of interceptor

After the obtaining of the baseline optimal trajectory, if the predicted intercept point changes a little, the interceptor will fly along the baseline trajectory \( X'(t) \) according to the baseline control quantity \( u'(t) \). However, due to the uncertainty of hypersonic target flight path prediction in the near space, especially in the case of long-distance detection and tracking, it is very difficult to predict its flight path with high precision. With the interceptor flying, the target information measured by interceptor
will be more and more accurate, and the predicted intercept point will be constantly updated. At this
time, the state constraint of the midcourse guidance terminal $\psi$ will change. Note that the terminal
constraint deviation is $\delta\psi_f = \psi - \psi'$, the optimal trajectory correction algorithm can use the
information of the benchmark optimal trajectory to calculate a series of control variables $\delta u = u - u'$, 
adjust its state variables, meet the adjusted terminal constraint conditions, and ensure that the
optimization index $J$ can still maintain a certain optimality.

First of all, according to the first-order optimality conditions of the benchmark optimal trajectory,
the first-order variational operations are performed on it, and the following equations are obtained:

$$
\delta x = \frac{\partial^2 H}{\partial \lambda \partial x} \delta x + \frac{\partial^2 H}{\partial \lambda \partial u} \delta u
$$

(18)

$$
\delta \lambda = -\frac{\partial^2 H}{\partial \lambda \partial x} \delta x - \frac{\partial^2 H}{\partial \lambda \partial u} \delta u
$$

(19)

$$
0 = \frac{\partial^2 H}{\partial u \partial x} \delta x + \frac{\partial^2 H}{\partial u \partial \lambda} \delta \lambda + \frac{\partial^2 H}{\partial u \partial \lambda} \delta u
$$

(20)

$$
\delta \lambda(t) = \left[\frac{\partial^2 \phi}{\partial x^2} + v^T \frac{\partial^2 \psi}{\partial x^2}\right] \delta x + \frac{\partial \psi}{\partial x} \delta \nu
$$

(21)

$$
\delta \psi_f = \left[\frac{\partial \psi}{\partial x} \delta x\right]
$$

(22)

Where, $\delta \nu$ is the adjustment amount of the terminal multiplier. If $\frac{\partial^2 H}{\partial \lambda \partial u}$ is not singular in the
whole design process, then the expression of the control quantity correction $\delta u$ can be obtained
according to the formula (20) as follows:

$$
\delta u = -\left(\frac{\partial^2 H}{\partial u \partial x}\right)^{-1} \left(\frac{\partial^2 H}{\partial u \partial \lambda} \delta x + \frac{\partial^2 H}{\partial u \partial \lambda} \delta \lambda\right)
$$

(23)

By substituting formula (23) into formula (18) and formula (19), the dynamic equation of sum can be obtained $\delta x$ and $\delta \lambda$ as follows:

$$
\delta \dot{x} = A(t) \delta x - B(t) \delta \lambda
$$

(24)

$$
\delta \dot{\lambda} = -C(t) \delta x - A^T(t) \delta \lambda
$$

(25)

Where

$$
A(t) = \frac{\partial^2 H}{\partial \lambda \partial x} - \frac{\partial^2 H}{\partial \lambda \partial u} \left(\frac{\partial^2 H}{\partial \lambda \partial \lambda} \right)^{-1} \frac{\partial^2 H}{\partial \lambda \partial x}
$$

(26)

$$
B(t) = \frac{\partial H}{\partial \lambda \partial u} \left(\frac{\partial^2 H}{\partial \lambda \partial \lambda} \right)^{-1} \frac{\partial^2 H}{\partial \lambda \partial \lambda}
$$

(27)

$$
C(t) = \frac{\partial^2 H}{\partial x^2} - \frac{\partial^2 H}{\partial x \partial u} \left(\frac{\partial^2 H}{\partial \lambda \partial \lambda} \right)^{-1} \frac{\partial^2 H}{\partial x \partial \lambda}
$$

(28)

According to the expressions of equations (21) and (22), $\delta \lambda$ and the correction amount of the
terminal constraint $\delta \psi_f$ are expressed as a linear expression about the adjustment amount of the
terminal multiplier $\delta \nu$:

$$
\delta \lambda(t) = S(t) \delta x(t) + R(t) \delta \nu
$$

(29)

$$
\delta \psi_f = R^T(t) \delta x(t) + Q(t) \delta \nu
$$

(30)

Where, $S(t)$, $R(t)$ and $Q(t)$ are introduced time-varying matrices. By deriving the time from
formula (29) and formula (30). The $\delta \nu$ and the $\delta \psi_f$ are constant matrices, we can get:

$$
\delta \dot{x} = S \delta x + S \delta x + R \delta \nu
$$

(31)

$$
0 = R^T \delta x + R^T \delta x + Q \delta \nu
$$

(32)

Substitute equation (29) into equation (24):
\( \delta \dot{x} = (A - BS) \delta \dot{x} - BR \delta \nu \) \hspace{1cm} (33)

By substituting formula (33) into formula (31) and combining with formula (25), we can get the dynamic equation to be satisfied by the variables \( S(t) \) and \( R(t) \) as follows:

\[
S = -C - A^T S - SA + SBS
\]

\[
R = -(A^T - SB) R
\]

Similarly, by substituting formula (33) into formula (32), we can get that the variable \( Q(t) \) needs to satisfy the dynamic equation:

\[
\dot{Q} = R^T BR
\]

By comparing we can get the terminal constraints of variables \( S(t), R(t) \) and \( Q(t) \):

\[
T = -C A S S + S S B S
\]

\[
T = -C A S B R
\]

\[
T = -Q
\]

\[
R = 0
\]

According to the terminal constraint variable \( S(t), R(t) \) and \( Q(t) \) in formula (37)–(39), integrate the dynamic equation (34)-(36) background until the initial time \( t_0 \)

\[
\delta \nu = Q_0^{-1}(\delta \psi_t - R_0 \delta x_0)
\]

Where the subscript 0 represents the variable value corresponding to the initial time. By substituting formula (40) into formula (29), we can get the initial adjustment amount of the covariance \( \delta \lambda_0 \):

\[
\delta \lambda_0 = [(S - RQ^{-1} R^T) \delta \dot{x} + RQ^{-1} \delta \psi_t]_{t_0}
\]

It can be seen from the formula (41), the adjustment quantity \( \delta \lambda \) is expressed by \( \delta \dot{x} \) and \( \delta \psi_t \), and \( \delta \dot{x} \) and \( \delta \psi_t \) can be calculated by the sensitive measurement device on the interceptor or the ground detection device, which ensure the feasibility of the optimal trajectory correction algorithm.

The steps of applying NOC to solve the optimal trajectory correction method can be summarized as follows:

Step1: Set \( \psi_t \) as the adjustment of the terminal trajectory constraints and compare it with the terminal constraints of the benchmark optimal trajectory, get the adjustment amount of the terminal constraints \( \delta \psi_t = \psi_t - \psi_t' \). Since the trajectory state at the initial time is not adjusted, set \( \delta x_0 = 0 \);

Step2: The matrix \( S, R, Q \) are calculated by formula (37)–(39), and they are substituted into formula (24) as the initial value for inverse integration to the initial time \( t_0 \), and \( S_{t_0}, R_{t_0}, Q_{t_0} \) are obtained;

Step3: Substituting \( S_{t_0}, R_{t_0}, Q_{t_0}, \delta x_0 \) and \( \delta \psi_t \) into the formula (40)–(41), we get the \( \delta \nu \) and \( \delta \lambda_0 \);

Step4: The \( \delta \dot{x} \) and \( \delta \lambda_0 \) are integrated into the formula (24)–(25), and then the \( \delta x(t) \) and \( \delta \lambda(t) \) are integrated into the formula(13), and the adjustment of the control quantity \( \delta u(t) \) is obtained;

Step5: The adjusted trajectory is obtained by adding the adjusted control quantity \( \delta u(t) \) and the reference control quantity, it will be \( u = \delta u + u' \), substituting the control instruction into the dynamic equation of interceptor.

4.2. A large-scale online correction algorithm for Interceptor

When the target moves in a large range, the original predictive intercept point is not applicable in a small range, and the original off-line optimal trajectory is not applicable. At the same time, when the altitude of interceptor is low, the air density in the airspace is large, which can provide power for interceptor maneuvering. However, if the airspace of interceptor is high and the atmosphere is thin, the
maneuverability brought by aerodynamic force is extremely limited. Therefore, a new on-line correction method is needed to meet the large-scale maneuvering of interceptor. Considering that the interceptor is located in a higher airspace and the aerodynamic force of large-scale maneuvering space-time is less overloaded, which can not meet the maneuvering demand, the following direct force correction method is designed.

The basic idea of revision is as follows:

As shown in Figure 1, $A$ is the initial position of the diversion guide section, $P$ is the predictive intercept point, $V_0$ is the initial speed before the diversion, and $V_r$ is the required speed for the diversion. First, according to the initial state of the interceptor, the uncontrolled trajectory is fitted and predicted to obtain the predicted landing point $P_1$ and calculate the deviation $P$ of the predicted terminal point relative to the predictive intercept point; Secondly, in order to eliminate the deviation, the deviation is compensated to the terminal of the flight, the virtual intercept point $P_2$ is determined, and a compensation trajectory $L_2$ from the initial point $A$ of the guidance section to the virtual intercept point $P_2$ is planned; the orbit change required speed $V_r$ is obtained by solving the Lambert problem of two bodies. In order to improve the accuracy, the above operations are repeated for many times for the initial speed $V_0$ before orbit change, so that the final virtual intercept point converges to the given predictive intercept point, and the final required speed of orbit change is determined as the optimal required speed of orbit change, which is corrected by the speed gain $\Delta V = V_r - V_0$.

![Figure 1. Modified guidance strategy.](image)

The specific strategies are as follows:

Step 1 Design the trajectory $L_0$ according to the initial point $A$, point $P$ and flight time $t_f$ in the diversion guidance section, and calculates the required speed $V_r$ of the diversion at the point $A$.

Step 2 Predicts the trajectory quickly according to the trajectory fitting method, and obtains the end point $P_1$ of the predicted trajectory $L_1$.

Step 3 Record the coordinates, the predicted trajectory end point $P_1 (x_1, y_1)$ and the predictive intercept point $P (x, y)$. The deviation between $P_1$ and the actual predictive intercept point $P$ is to compensate the deviation to the target point to get the virtual predictive intercept point $P_2$. The virtual intercept point is determined by the coordinate of the $P_1$ and $P$

$$P_{2x} = 2P_x - P_1x$$
$$P_{2y} = 2P_y - P_1y$$  \(42\)

Step 4 Determine a trajectory from the initial point $A$ to $P_2$, solves the two body Lambert problem, and obtains the required velocity $V_r$.

Step 5 Keep the position of the point $A$ unchanged, predicts the trajectory again for the initial velocity base on $V_r$, and repeats step 2 to step 4 until the virtual intercept $P_2$ converges to the predictive intercept point $P$.

Step 6 Obtains that the final value of the required speed $V_r$ as the optimal required speed for track change.
Step 7 According to the speed increment $\Delta V = V_f - V_0$ obtained by $V_0$ and $V_f$, the engine start-up time is $\Delta t$, and the engine thrust is $F$
\[
\Delta t = \frac{m \Delta V}{F}
\] (43)

5. Simulation verification

5.1. Simulation verification of small range change of predictive intercept point

It is noted that the initial height of the interceptor is 60km, and the terminal height of the off-line optimal trajectory of the interceptor is 30km. In order to conform to the situation that the predictive intercept point is updated, the radius of the maximum error domain shall be recorded as $\varepsilon$, assuming that the predictive intercept point is initially updated within the maximum error domain, with a large dispersion range. As the missile target rendezvous proceeds, the error domain is continuously reduced, and finally converges to 0, so that the predictive intercept point converges to the final predictive intercept point. The correction ability of interceptor in 1km and 2km is verified. Note that the predictive intercept point is updated every 5 seconds. The altitude constraint of the final predictive intercept point is 28km.

![Figure 2. Longitudinal plane track diagram when $\varepsilon = 1km$.](image)

![Figure 3. Longitudinal plane track map when $\varepsilon = 2km$.](image)
Figure 4. Angle of attack when $\epsilon = 1km$.

Figure 5. Angle of attack when $\epsilon = 2km$.

Figure 6. Trajectory inclination when $\epsilon = 1km$. 
From the simulation results, it can be seen that the trajectory online correction based on neighboring optimal control can realize the online correction of interceptor near the reference trajectory when the terminal constraint changes little. However, when the predictive intercept points
are constantly updated as shown in Fig. 4 and Fig. 5, as the control quantity, the angle of attack needs to be changed frequently, and at the same time, the requirements of changing the angle of attack in a small range in an instant should be met, but which will bring great challenges to the stability of the interceptor, and this situation only meets the situation when the interceptor height is low. Therefore, the direct force correction method is needed to adjust when the target moves in a large range and the predictive intercept point changes in a large range.

5.2. Simulation and verification of large-scale change of predictive intercept point

The initial altitude of the interceptor is 150km. In order to meet the actual situation of the missile target rendezvous in flight, it is necessary to predict the update of the interceptor and verify the correction ability of the interceptor in different maximum error areas. Note that the predictive intercept point is updated every 5 seconds.

Figure 10. longitudinal track diagram under direct force correction

Figure 11. engine on-off curve
From Figure 10, it can be seen that under the condition that the predictive intercept point of the interceptor under the direct force correction is constantly updated, the interceptor requirements can be realized on the trajectory, and the resulting trajectory is relatively smooth. At the same time, figure 11 shows the law of switching on and off of rail control engine. Figure 12 shows the change rule of speed increment $\Delta V$, which converges to 0 as a whole. The sudden change is due to the information update of PIP point, which results in the change of the required speed of track change, which leads to the $\Delta V$ change from 0 to non-0 value. However, with the engine start-up adjustment, the speed increment $\Delta V$ tends to zero again, indicating that the speed of interceptor keeps approaching the actual required track change speed.

6. Conclusion

In this paper, the problem of on-line trajectory correction of hypersonic target interceptor in near space is studied. In order to adapt to complex interception scenarios, different correction algorithms are proposed for different scenarios. The simulation results show the effectiveness of the proposed algorithm. But in the direct force correction, the trajectory optimization can not be guaranteed, which will be the focus of the follow-up research.

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