Research on Missile Guidance Based on Three-Loop Autopilot Device

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Abstract. In order to improve the speed of the guide head capturing the target in the case of guided missiles with large landing angle and reduce the angular deviation of the start point of terminal guidance, a high control method of missile autopilot design is proposed and the trajectory programming method-constraints of seeker (TPM-CS) is considered with multiple constraints of the guide head. The constraints of end-guidance start point are established according to the maximum detection distance of the seeker. The attack path constraints are established according to the geometric relationship between the projectile and the field of view angle of the guide head, and the objective function of minimizing the front angle and the amplitude of the control variables is established. In order to realize the optimal matching of the initial trajectory inclination and declination of the guided missile, the rocket ignition time, the glide start and control time, the guide head opening time and other parameters, a 5-stage ballistic planning model is established. And Simulink is utilized to simulate the guidance process. The design model of three-loop autopilot, the frequency response of the projectile, the proportional guidance system, the Seeker/Tracker subsystem and the Guidance subsystem model design are considered. The final simulation results show that this missile can operate well compared to conventional methods. The simulation system can show good results.

Keywords: Missile Guidance, Ballistic Planning, 5-segment Model, Guide Head Multi-constraint, Simulink Simulation.

1. Introduction

Precision guidance technology occupies a very important position in the development of modern military high technology. Its creation and development have directly led to the introduction of a large number of precision-guided weapons. The future information war is still a fierce competition between the two sides in the combat system centered on precision-guided weapons. The level of precision guidance technology. Will play a decisive role in the war process and the outcome of the war. Glide extended-range guided missiles are developed on the basis of conventional missiles by adding booster rockets and guidance control systems. It is launched with the help of conventional artillery launch platform. The advantages of high precision and low maintenance cost have been widely emphasized by the world's major military powers [1].

The ballistic optimization design of missile guidance occupies a pivotal position in its entire life cycle. The ballistic optimization problem can essentially be regarded as a trajectory optimization problem. Aiming at this kind of problem, scholars have done a lot of research. Lei Wengui [2] et al. for guidance, using Guass pseudo-spectral method based on the air-to-air missile in the guidance method research. The above experimental simulation model is based on a number of assumptions. In fact, the interception of hypersonic targets by air-to-air missiles is affected by various random factors. It may not be able to meet the mission requirements. Chen Junjie [3] et al. adopt the design method of semi-physical simulation system for guidance control based on RTX. Zhang Kuanqiao [4] et al. based on fixed time stability theory and inverse sliding mode control. A multi-constraint guidance control integration design method considering attack angle constraints, state constraints and control constraints is proposed. Liang Jinxin [5] et al. address the problems of insufficient nonlinear approximation ability and decreased tracking accuracy of traditional filtering algorithms when dealing with complex maneuvers of targets. A strong tracking volumetric Kalman filter (STCKF) method is proposed. Liu Chao [6] et al. For the second-stage booster rocket. The Gaussian pseudo-

spectral method is used to design the optimal flight trajectory to avoid the radar no-fly zone. Changsheng Gao et al. [7] used an adapted pseudo-spectral method to plan the maneuvering breakout flight trajectory for a hypersonic gliding vehicle.

Although scholars have conducted a lot of research on the missile guidance ballistic planning problem. However, up to now, few articles have been published on missile guidance trajectory planning considering guide head constraints. Based on this, this paper takes the glide extended range guided missile as the research object. A programmatic trajectory planning method (TPM-CS) considering multiple constraints of the guide head is designed. For the convenience of differentiation, this paper refers to the full-ballistic scheme ballistic planning method for glide extended range missile guidance, which contains 4 stages, as the traditional glide missile guidance ballistic planning method (TPM) as mentioned in the literature [8-9]. The TPM does not consider the constraints of the guide head. Therefore, the missile guidance follows the programmed trajectory planned by the TPM. The target may not be in the guide's field of view when it arrives at the end-guidance start point. As a result, it is difficult for the guide head to capture the target, even until the missile flies to the end of the trajectory. In view of this, the TPM-CS method designed in this paper divides the full ballistic trajectory of missile guidance into five stages: takeoff section, boost section, ascent section, glide section and final guidance section. In the final guidance section, the constraint of the start point of final guidance is established according to the maximum detection distance of the guide head. The attack path constraint is established according to the field of view angle of the guide head. In order to reduce the distance of target deviation from the center of the field of view of the guide head. Consider penalizing the angle of deviation of the bullet eye line of sight relative to the guide head axis in the objective function. The missile guidance dynamic model is established first. Consider the three-loop autopilot design model, the frequency response of the projectile, the proportional guidance system, the Seeker/Tracker subsystem and the Guidance subsystem model design. Finally the simulation of the missile hitting the target is carried out in Simulink.

2. Dynamic Modeling of the Projectile

This paper establishes a ballistic planning model that considers multiple constraints on the guide head according to the working principle of glide missile guidance. The working principle of glide extended-range missile guidance is as follows: after the frontline reconnaissance unit discovers the target. Send the target position information to the rear missile launch terminal. Missile launch terminal according to the target information and the current battlefield environment conditions to form a program trajectory loaded to the missile guidance system and launch the missile. The missile passes through the takeoff section, boost section, ascent section and glide section as shown in Figure 1 Glide extended-range missile guidance trajectory schematic to reach the point where the guide head opens. The guide head is turned on to search and capture the target. Finally, the missile enters the final guidance to correct the deviation and complete the precision strike on the target.

2.1. Three-Dimensional Simplified Ballistic Modeling of Glide Extended Range Missile Guidance

According to the set of three-dimensional space equations of motion of the missile [10]. A three-dimensional simplified ballistic model for the guidance of glide extended range missiles is established under the small angle assumption:

$$\begin{cases} \dot{v} = \frac{F_p - F_x - mg\sin\theta}{m} \\ \dot{\theta} = \frac{F_y - mg\cos\theta}{mv} \\ \dot{\psi}_v = -\frac{F_z}{mv\cos\theta} \\ \dot{x} = v\cos\theta\cos\psi_v \\ \dot{y} = v\sin\theta \\ \dot{z} = -v\cos\theta\sin\psi_v \\ \dot{m} = -m_c \end{cases} \tag{1}$$

In the formula: v is the velocity. θ is the ballistic inclination. ψ_v is the ballistic declination. m is the mass of the projectile.m_c is the booster rocket mass flow. F_p is the booster rocket thrust. F_x is the aerodynamic drag. F_y is the aerodynamic lift. F_z is the aerodynamic lateral force. (x, y, z) is the coordinates of the missile in the ground coordinate system. The state vector of the model can be expressed as $x = [v \ \ \theta \ \ \psi_v \ \ x \ \ y \ \ z \ \ m]^T$.

The aerodynamic forces in the 3 directions are

$$\begin{cases} F_x = \frac{1}{2}\rho v^2 S C_{x0}(1 + k_c(\alpha^2 + \beta^2)) \\ F_y = \frac{1}{2}\rho v^2 S C_{y\alpha}\alpha \\ F_z = \frac{1}{2}\rho v^2 S C_{z\beta}\beta \end{cases} \tag{2}$$

Where: ρ is the air density. S is the reference area. α is the angle of attack.β is the side slip angle. C_{x0} is the zero-lift drag coefficient. k_c is the coefficient associated with induced drag. $C_{y\alpha}$ is the lift coefficient derivative. $C_{z\beta}$ is the lateral force coefficient derivative. The model control vector can be expressed as $u = [\alpha \ \ \beta]^T$.

2.2. 5-Segment Ballistic Model

As shown in Figure 1. The flight trajectory of the glide extended-range guided missile is divided into five segments, namely, the take-off segment, the boost segment, the climb segment, the glide segment and the final guidance segment.

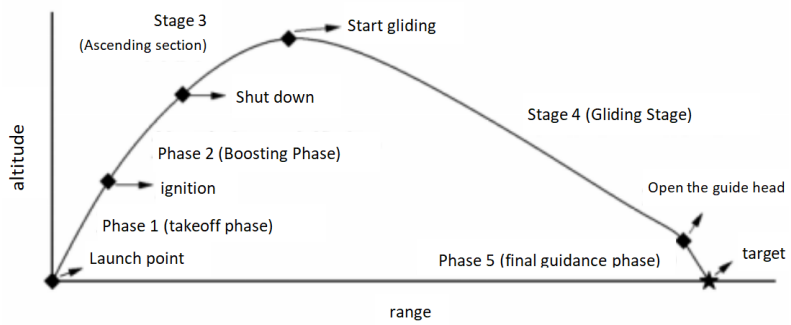


Figure 1. Schematic diagram of glide extended range missile guidance

For ease of labeling the time variables for each segment. Define the pth phase flight time interval as $\left[t_0^{(p)}, t_f^{(p)}\right]$. The duration of the pth phase is

$$t_d^{(p)} = t_f^{(p)} - t_0^{(p)} \tag{3}$$

In Eq: $(\cdot)_0^{(p)}$ is the initial value of stage p. $(\cdot)_f^{(p)}$ is the end value of stage p. $(\cdot)_d^{(p)}$ is the duration of stage p.

The phases in ballistics are defined as follows:

1) Takeoff segment. Begins at the launch position and ends at the booster rocket ignition position. The booster rockets must be ignited after the missile is a certain distance out of the muzzle. So when conducting the planning program trajectory, the variable $t_d^{(1)}$ should be set to a reasonably positive lower bound.

2) Boost segment. Begins at the booster rocket ignition position and ends at the booster rocket shutdown point. $t_d^{(2)}$ Equal to the duration of booster rocket operation.

3) Climb Segment. Begins at the point of booster rocket shutdown and ends at the point of glide initiation. In reality, the perturbation of the booster rocket switching from the working state to the off state will affect the balance of the projectile to a certain extent. Therefore, after the end of the boost, we need to wait for a period of time to restore the balance of the projectile before turning on the rudder to enter the gliding section. Therefore, the lower bound of variable $t_d^{(3)}$ should be set to a reasonable positive number.

4) Glide Segment. Begins at the glide start position and ends at the end guidance start point.

5) Terminal Guidance Segment. Begins at the end-guidance start point and ends at the target point.

2.3. Constraints

2.3.1 Boundary Constraints

The initial velocity of the guided missile is v_0. The initial coordinates are (x_0, y_0, z_0). The initial mass is m_0. So the initial state constraint of the guided missile is established as:

$$\begin{cases} v(t_0^{(1)}) = v_0 \\ x(t_0^{(1)}) = x_0 \\ y(t_0^{(1)}) = y_0 \\ z(t_0^{(1)}) = z_0 \\ m(t_0^{(1)}) = m_0 \end{cases} \tag{4}$$

The coordinates of the stationary target are (x_t, y_t, z_t). To achieve better strike effectiveness. Let the lower bound of the terminal velocity constraint is v_{fL}. The upper bound of fall angle constraint is θ_{fU}. So the end state constraint is established as:

$$\begin{cases} x(t_f^{(5)}) = x_t \\ y(t_f^{(5)}) = y_t \\ z(t_f^{(5)}) = z_t \\ \theta(t_f^{(5)}) \le \theta_{fU} \\ v(t_f^{(5)}) \ge v_{fL} \end{cases} \tag{5}$$

2.3.2 Process Constraints

Guided missiles have different flight characteristics and are subject to different constraints in different flight phases. The booster rocket operates only in the boost section, and the amount of control is zero for the first three flight phases.

Ascending and climbing segment constraints:

$$\begin{cases} F_p = 0 \\ m_c = 0 \\ \alpha = 0 \\ \beta = 0 \end{cases} \tag{6}$$

Boosting segment constraints:

$$\begin{cases} F_p = F_p^* \\ \alpha = 0 \\ \beta = 0 \end{cases} \tag{7}$$

Where F_p^* is the average thrust of the booster rocket.

Glide segment and end-guidance segment constraints:

$$\begin{cases} F_p = 0 \\ m_c = 0 \\ \alpha_{min} \le \alpha \le \alpha_{max} \\ \beta_{min} \le \beta \le \beta_{max} \end{cases} \tag{8}$$

Where $(\cdot)_{min}$ is the lower boundary value of the variable. $(\cdot)_{max}$ is the upper boundary value of the variable.

2.3.3 Continuity Constraints

Multi-stage ballistic planning, which needs to ensure time continuity and continuity of state variables. Namely:

$$\begin{cases} t_f^{(p)} = t_0^{(p+1)} \\ x_f^{(p)} = x_0^{(p+1)} \end{cases} \tag{9}$$

Eq: $(\cdot)^{(p)}$ is the information for stage p (p=1, ..., P-1). where P is the total number of full ballistic segments.

2.3.4 End-guidance Path Constraints

The geometric relationship between the end-guidance process of guided missile is shown in Fig.2. In the figure, M is the guided missile and T is the target. θ_L is the angle of sight inclination. φ_L is the line-of-sight deflection angle.

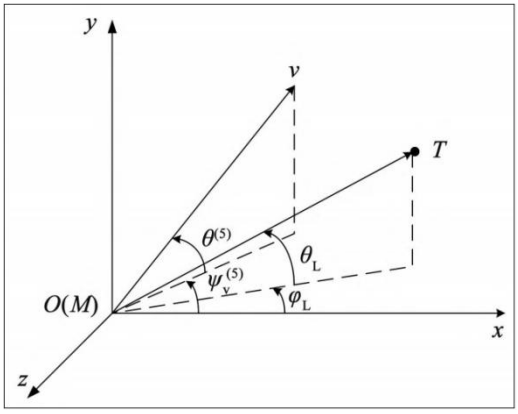


Figure 2. Three-dimensional guidance geometry relationships

It is approximated that the guide head reference axis and the velocity axis coincide. The angle of deviation of the missile target's line of sight in the elevation and azimuth directions with respect to the reference axis of the guide head are respectively:

$$\begin{cases} e_\theta = \left|\theta^{(5)} - \theta_L\right| \\ e_\varphi = \left|\psi_v^{(5)} - \varphi_L\right| \end{cases} \tag{10}$$

Where the angle of sight is calculated as:

$$\begin{cases} \theta_L = \tan^{-1}\left(\frac{y_t - y}{\sqrt{(x_t - x)^2 + (z_t - z)^2}}\right) \\ \varphi_L = -\tan^{-1}\left(\frac{z_t - z}{x_t - x}\right) \end{cases} \tag{11}$$

During the end-guidance process, it must be ensured that the target is within the field of view of the guide head. Let the field of view of the guide head be ε. The target must be guaranteed to be in the field of view of the guide head. Thus, according to the field of view angle, the end-guidance path constraint can be established as:

$$\begin{cases} e_\theta \le \varepsilon \\ e_\varphi \le \varepsilon \end{cases} \tag{12}$$

2.3.5 End-guided Start Point Constraints

The guides have a limited detection range. Turning them on too early wastes on-board power. Turning on the guide head too late will reduce the space and time for the guidance system to correct the deviation of the projectile position. Let the maximum detection range of the guide head is R_s. The distance between the starting point of the final guidance of the guided missile and the target is:

$$R_{MT} = \sqrt{(x_0^{(5)} - x_t)^2 + (y_0^{(5)} - y_t)^2 + (z_0^{(5)} - z_t)^2} \tag{13}$$

The formula, $(x_0^{(5)},\ y_0^{(5)},\ z_0^{(5)})$ is the end-guidance start point.

It is assumed that once the target enters the detection range of the guide head the guided missile enters the final guidance. Therefore, this paper designs the end-guidance start point constraint as:

$$R_{MT} - R_s = 0 \tag{14}$$

2.4. Objective Function

To facilitate the interpretation of the objective function. Firstly, the angle of attack control margin and the sideslip angle control margin are defined as:

$$\begin{cases} \zeta_\alpha = \alpha_{max} - |\alpha| \\ \zeta_\beta = \beta_{max} - |\beta| \end{cases} \tag{15}$$

Then define the sight angle constraint margin as:

$$\begin{cases} \zeta_\theta = \varepsilon - e_\theta \\ \zeta_\varphi = \varepsilon - e_\varphi \end{cases} \tag{16}$$

Guided missiles have limited maneuverability. In order to enhance its anti-jamming capability, a certain amount of control margin and field-of-view constraint margin needs to be reserved for the guidance control system when designing the program trajectory. So this paper establishes the objective function as:

$$J = J_1 + J_2 \tag{17}$$

Among them:

$$J_1 = \sum_{p=4}^{5} \int_{t_0^{(p)}}^{t_f^{(p)}} w_{1,1}\left(\frac{\alpha}{\alpha_{max}}\right)^2 + w_{1,2}\left(\frac{\beta}{\beta_{max}}\right)^2 dt$$

$$J_2 = \int_{t_0^{(5)}}^{t_f^{(5)}} w_{2,1}\left(\frac{e_\theta}{\varepsilon}\right)^2 + w_{2,2}\left(\frac{e_\varphi}{\varepsilon}\right)^2 dt$$

In Eq, $w_{1,1}$, $w_{1,2}$, $w_{2,1}$, and $w_{2,2}$ are the penalty weights. The objective function part 1 J_1 is to minimize the effect of the guidance control system on the control variables α and β of the control variables to increase its control margin. Part 2 of the objective function J_2 serves to minimize the angle of divergence of the eye's line of sight with respect to the guide head's axis, i.e., the precession angle, in order to increase the field-of-view constraint margin.

3. Simulation and Analysis

3.1. Design of Automatic Driving on the Third Ring Road

The missile autopilot controls the normal overload of the missile body. The structure of the autopilot utilizes a three-loop design. It uses measurements from an accelerometer located forward of the center of gravity, and it also uses a rate gyroscope to provide additional damping. Controller gains are scheduled based on angle of incidence and Mach number, and adjusted for robust performance at 10,000 feet altitude.

When designing an autopilot using traditional methods, a linear model of the body pitch dynamics must be derived from a large number of leveling flight conditions. MATLAB can determine the leveling conditions and derive a linear state-space model directly from a nonlinear Simulink model. This approach saves time and helps to validate the model. The behavior of the open-loop frequency (or time) response of the projectile is visualized using functions provided by the MATLAB Control System Toolbox and Simulink Control Design, as shown in Figure 3.

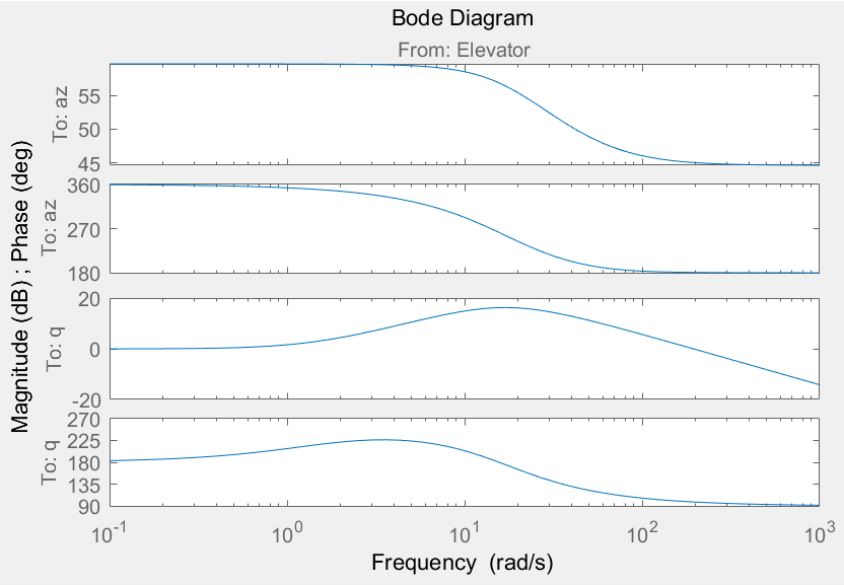


Figure 3. Scheduling of automated driving design for the Third Ring Road

3.2. Frequency Response of Bullet

The autopilot design is based on a large number of linear projectile models derived from a variety of flight conditions over the entire expected flight envelope. In order to implement the autopilot in a nonlinear model, the autopilot gain must be stored in a two-dimensional lookup table and combined with an anti-saturation gain to prevent the integrator from saturating when the flick command exceeds the maximum limit. The autopilot is then tested in a nonlinear Simulink model. Satisfactory performance is shown in the presence of nonlinearities (e.g., actuator tail and rate limiting) and gain dynamics as a function of flight conditions, utilizing the Autopilot subsystem for gain scheduling.

3.3. Seeking Guidance Ring

The seeker guidance loop contains the Seeker/Tracker subsystem, which returns measurements of the relative motion between the missile and the target. The Guidance subsystem generates the normal

overload command passed to the autopilot. The autopilot becomes part of the inner ring of the overall seeker guidance system. As shown in Figure 4, the missile guidance system is modeled in Simulink.

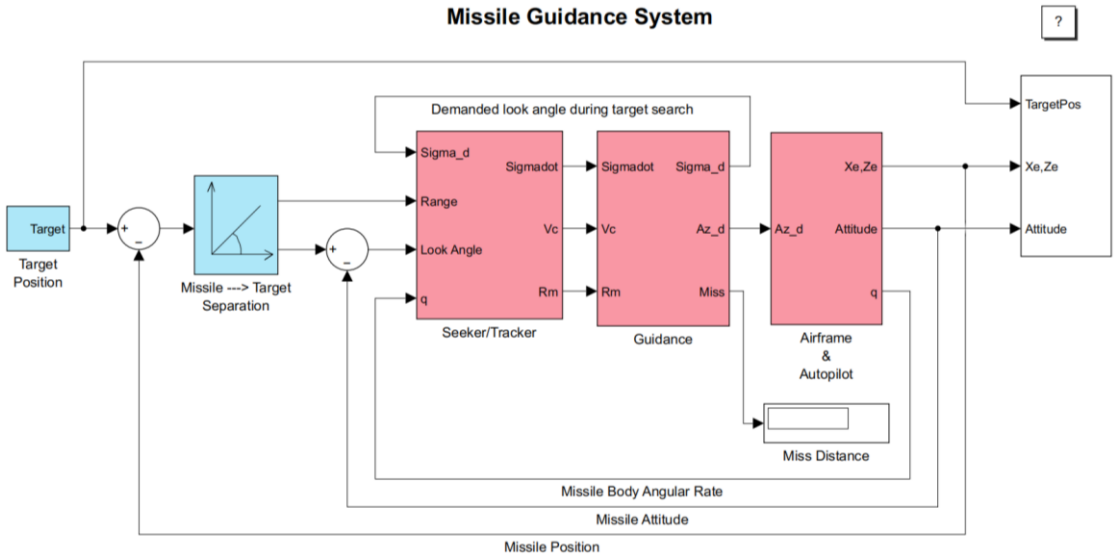


Figure 4. Missile guidance systems

3.4. Guidance Subsystem

The Guidance subsystem generates commands during closed-loop tracking and performs an initial search to localize the target position. The Stateflow diagram controls the switching between these different modes of operation. The switching between modes is triggered by events generated in Simulink or inside the Stateflow diagram, which control how the Simulink model behaves by changing the value of the mode. This variable is used to switch between different control commands. During the target search, the Stateflow diagram directly controls the tracker by sending commands to the guide head gimbal (Sigma). Once the target is within the beamwidth of the guide head (Acquire), the tracker marks the target for capture. After a short delay, closed-loop guidance is initiated. The Stateflow feature allows the system to quickly define all modes of operation. For example, actions to be taken when target lock is lost or when the target is not acquired during target search.

3.5. Proportional Guidance

Once the guidance head acquires the target, the missile is guided using proportional guidance (PNG) law until it hits the target. This form of guidance law has been used to guide missiles since the 1950s and can be applied to radar, infrared, or television guided missiles. A guidance law requires the following data:

1) A measure of approach velocity between the missile and the target (for radar-guided missiles, this can be obtained using Doppler tracking equipment).

2) An estimate of the rate of change of the inertial line-of-sight angle.

3.6. Seeker/Tracker Subsystem and Radome Aberration

The Seeker/Tracker subsystem is used to drive the guide head gimbal, align the guide head dish antenna to the target, and provide an estimate of the line-of-sight rate for the guide law. The tracker ring time constant, tors, is set to 0.05 seconds, a value that takes into account maximizing response speed while keeping noise transmission at an acceptable level. The stabilizer loop is used to compensate for the projectile roll rate. The gain Ks (i.e., the loop crossover frequency) is then set to the highest possible value within the bandwidth allowance of the stabilizing rate gyroscope. The line-of-sight rate estimate is the filtered value of the sum of the following two rates of change: the rate of change of the dish angle measured by the stabilizing rate gyroscope, and the rate of change of the angular tracking error (e) measured by the receiver.

For radar-guided missiles, the generally modeled parasitic feedback effect is radome aberration. Radome aberration occurs when the shape of the protective shield on the guidance head distorts the return signal and gives an incorrect reading of the target viewpoint. Typically, the amount of distortion is a nonlinear function of the current gimbal angle. However, the model uses a Gain module called Radome Aberration to approximate a linear relationship between gimbal angle and distortion magnitude, and models other parasitic effects (such as the sensitivity of the rate gyroscope to normal overload) to test the robustness of the target tracker and estimator filters.

3.7. Operational Guidance Simulation

The target has been defined as traveling at a constant velocity of 328 m/s in the direction of the initial missile heading and is located 500 m above the initial missile position. Simulation results show that capture occurs at 0.69 seconds into the rendezvous and closed-loop guidance begins after 0.89 seconds. The impact with the target occurs at 3.46 seconds and the distance between the two at the closest point of encounter is 0.265 meters.

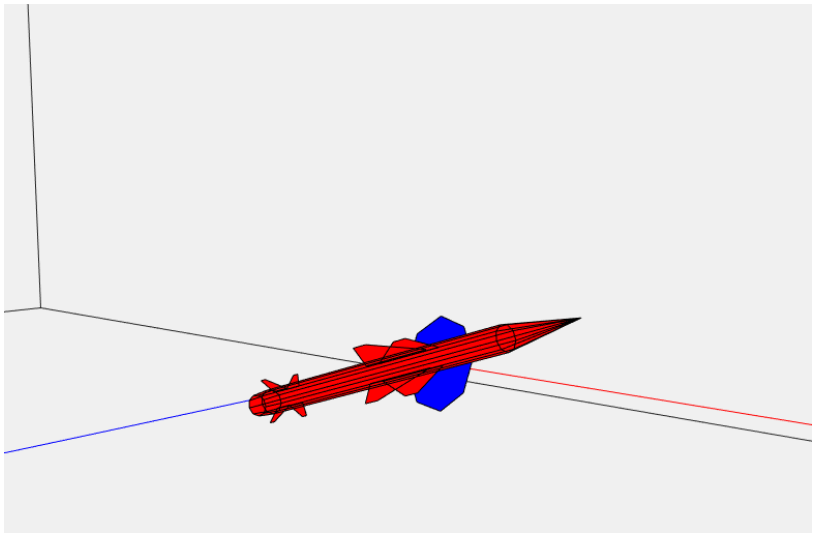


Figure 5. Motion simulation reference diagram

As shown in Fig. 5, the simulation reference diagram of the animation module shows the missile motion state from the beginning to the end.

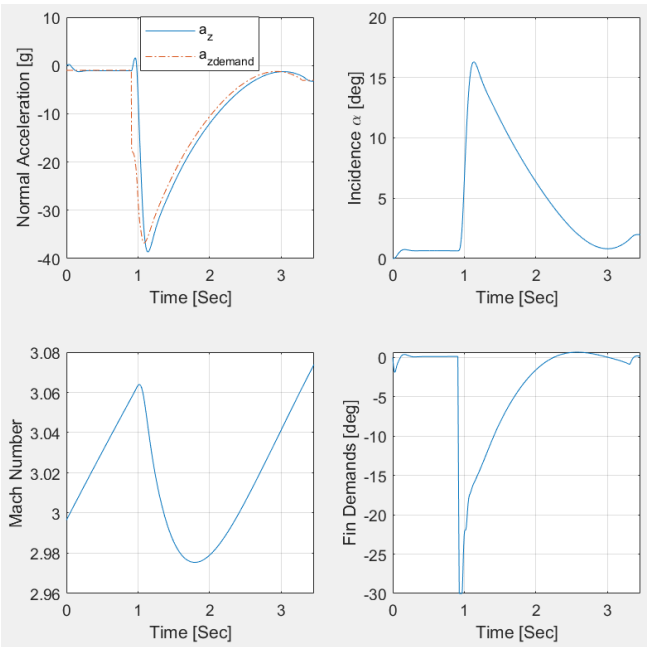


Figure 6. Parameter function diagram

As shown in Fig. 6, the image sequentially represents the normal acceleration, angle of incidence, Mach number, and final output versus time. The Gimbal angle of gyration is shown in Figure 7. A graphical representation of the missile-target trajectory is shown in Figure 8.

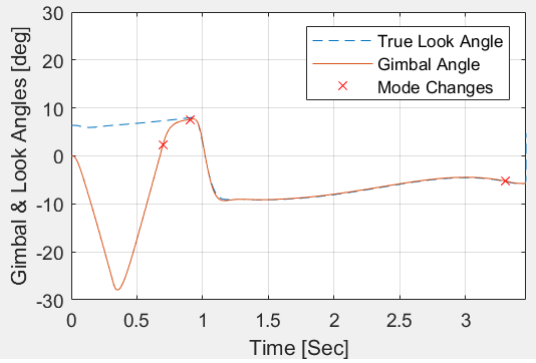


Figure 7. Gimbal turnback angle

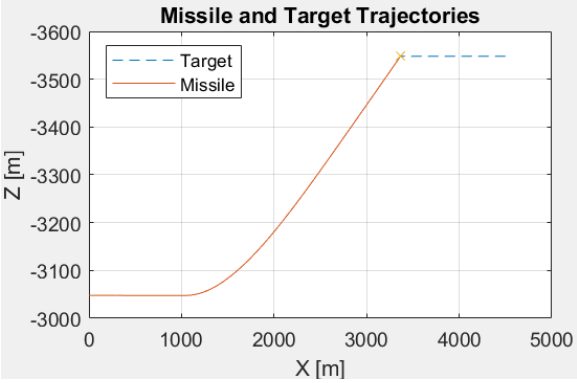


Figure 8. Missile and target trajectory

4. Conclusion

The program trajectories planned using the TPM-CS method proposed in this paper satisfy the maximum detection distance constraints of the guide head and the field of view angle constraints of the guide head, which verifies the effectiveness of the TPM-CS method. This paper proposes a method of missile guidance autopilot and automatic control. In the simulation results, it is shown that the capture occurs at 0.69 seconds of the rendezvous and the closed-loop guidance starts after 0.89 seconds. The impact with the target occurs at 3.46 seconds, and the distance between the two at the nearest meeting point is 0.265 meters, successfully intercepting the target to achieve the final precision strike. The final simulation results show that this missile can work well compared to the traditional method and the simulation system can show good results. The future information war is still a fierce competition between the two sides in the combat system centered on precision-guided weapons, and the level of precision-guided technology will play a decisive role in the process of the war and the outcome of the war. The glide range-extended guided artillery shells are based on conventional artillery shells with additional booster rockets and guidance control systems. Launched with the help of conventional missile launching platforms, they have been widely emphasized by the world's major military powers for their advantages of high strike accuracy and low maintenance costs. In this paper, we have not yet considered the simulation of more situations, and only one sample simulation has been conducted. The next step will be to validate the system by simulation under various conditions.

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