Research on bionic composite guidance law considering field of view angle

Jun Li, *Peijie* Wei*, *Chenjun* Su, and *Song* Xue

Army Artillery Air Defense Force Academy, HeFei, China

Keywords: Bionic guidance law, Motion camouflage, Segment guidance, Field of view angle, Strapdown seeker.

Abstract. Due to the use of strapdown seeker in small missiles, a small field of view angle is required to ensure effective tracking and strike of the target during the final interception. Based on the tracking strategy of dragonfly chasing targets, a composite guidance law is studied. In the initial guidance section, the parallax angle is controlled by the sliding mode control law to adjust the missile to the tail following attitude. The final guidance section used the motion camouflage guidance law with the focus at infinity for target tracking,and between the initial guidance and the final guidance. The second-order smooth interface law is used for the transition. The simulation results show that compared with the traditional proportional guidance law, the required overload of the missile in the final guidance is small,and the target is closer to the center of the field of view, which can reduce the missile in the final guidance. The overload and the field of view of the seeker can be used to effectively improve the attack accuracy.

1 Introduction

For missiles with smaller diameters, most are equipped with strapdown imaging seekers to detect targets, and the detection range of the seekers is limited by the dynamics of the projectile. In addition, using traditional guidance laws to intercept oncoming targets, the relatively high relative velocity can lead to the need for normal overload at the end of the missile, resulting in the loss of targets and other issues[1]. A new guidance law based on the field of view angle of the seeker is studied to meet the precise interception requirements of low-cost small missiles.

At present, there are many studies on guidance laws with limited field of view for guidance heads both domestically and internationally, and their processing methods are mainly divided into two categories. One is to design a guidance law that maintains a constant target parallax angle. When the target is about to exceed the field of view of the guidance head, it switches to this guidance law to ensure that the target is always within the field of view [2-4]; Another approach is to directly analyze the maximum perspective of the

* Corresponding author: ljazq1314@163.com

target during the guidance process, and achieve the goal of keeping the target parallax angle within the field of view of the guidance head by limiting the missile's motion state or adding a bias term to the guidance law [5-6]. The above processing methods are mostly aimed at fixed targets, and there is limited research literature on the guidance problem of limited field of view angle for moving targets in the guidance head. Entomologists have found that when dragonflies pursue oncoming fruit flies, they adjust their posture to maintain a tail chasing mode and use a motion camouflage tracking strategy that does not generate relative angular motion with the target in the latter half of the tracking process to capture the target[7]. This strategy can ensure that the dragonfly is in the final stage of pursuing the target, with the target moment within the dragonfly's field of view, and the flight trajectory is relatively straight, requiring less normal overload. Based on this, this article studies the bionic guidance law considering the field of view angle of the seeker. In the initial stage of final guidance, the sliding mode control law is used to adjust the visual angle of the missile and control the missile to intercept the target in a tail chasing manner. In the final attack stage of final guidance, the motion camouflage guidance law with a focus on infinity is used for target tracking to ensure that the trajectory is straight and requires minimal normal overload. The second-order smooth interface law is used for the transition

2 Mathematical model establishment

In order to facilitate the study of space guided missile target rendezvous problems, the following assumptions are made to simplify the 3D motion model: ①Decompose the 3D space guidance problem into a transverse and longitudinal plane, and transform it into a 2D plane problem; ②The missile velocity remains constant during the final guidance process.

Taking the vertical plane as an example, as shown in Figure 1, D is the missile, M is the target, and F is a fixed point arbitrarily selected in the plane, defined as the focal point. r is the distance between the missile and the target, r_d is the distance from the missile to the focal point, v_d and v_m are the velocities of the missile and the target, q is the line of sight angle of the missile and the target, and q_d is the angle at which the missile rotates relative to the focal point, θ_d and θ_m represents the velocity direction angles of the missile and target, respectively, $\alpha$is for the angle of attack, ψ_d is the attitude angle of the missile, ψ_d is the leading angle of the target. The angle between the missile's longitudinal axis and the missile's line of sight is defined as the parallax angle, i.e η_d.

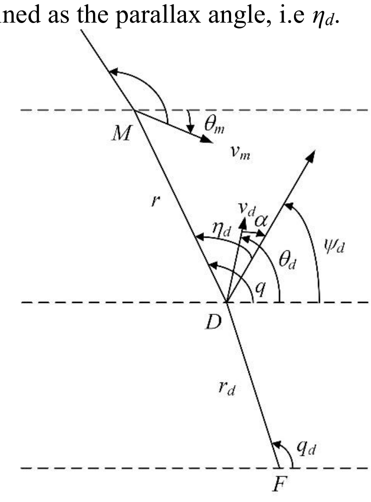

Fig. 1. Relative motion diagram of missile and target in the state of intercepting.

The motion equation of the missile relative to the focal point is

$$\begin{cases} \dot{r}_d = v_d \cos(q_d - \theta_d) \\ \dot{q}_d = -\dfrac{v_d}{\dot{r}_d} \sin(q_d - \theta_d) \end{cases} \quad (1)$$

The relative motion equation of the projectile can be expressed as

$$\begin{cases} \dot{r} = v_m \cos(\theta_m - q) - v_d \cos(\theta_d - q) \\ r\dot{q} = v_m \sin(\theta_m - q) - v_d \sin(\theta_d - q) \end{cases} \quad (2)$$

Target leading angle η_m and parallax angle η_d can be expressed as

$$\begin{cases} \eta_m = q - \theta_m \\ \eta_d = q - \psi_d \end{cases} \quad (3)$$

Determine the interception status based on the absolute value of the target's leading angle [8]:

If $\eta_m < 90°$, the missile is in a tail chasing target state;

If $\eta_m > 90°$, the missile is in a state of engaging the target.

3 Selection of bionic guidance strategies

3.1 Design of initial stage guidance law

Due to the limitations of the missile's power characteristics, it is impossible for the missile to achieve the motion state of transitioning from attacking the target to chasing the target through significant attitude adjustments like a dragonfly. Considering the flight dynamics characteristics of missiles and the field of view angle limitations of detecting targets, the sliding mode principle of controlling target parallax angle is applied to design the Lyapunov function [9].

$$s = \frac{1}{2}(q - \psi_d)^2 \quad (4)$$

Derived

$$\dot{s} = (q - \psi_d)(\dot{q} - \dot{\psi}_d) \quad (5)$$

Order

$$\dot{q} - \dot{\psi}_d = -k(q - \psi_d) \quad (6)$$

Among them, $k > 0$, and $a_d = v_d \dot{\psi}_d$, $\eta_d = q - \psi_d$, the above equation can be obtained through transformation.

$$a_d = v_d \dot{q} + k v_d \eta_d \tag{7}$$

At this time

$$\dot{s} = -k(q - \psi_d)^2 \leq 0 \tag{8}$$

So the initial guidance law is obtained as

$$n_y = a_d / g + \cos\psi_d = (v_d \dot{q} + k v_d \eta_d) / g + \cos\psi_d \tag{9}$$

3.2 Design of terminal guidance law based on "motion disguise"

Figure 2 shows the relative motion diagram of motion camouflage with fixed point at finite place, with *F* as the focus, *D* as the missile, *M* as the target, and *FM* as the camouflage line. Figure 3 shows relative motion diagram of motion camouflage with fixed point at infinite place, where the missile is initially located at D_0, the target is initially located at M_0, and q_0 is the initial line of sight angle of the missile and target. Due to the constant velocity of the missile during the final guidance stage, i.e. the tangential overload of the missile is 0, the final guidance law is to calculate the normal overload of the missile, so that the missile remains on the camouflage line.

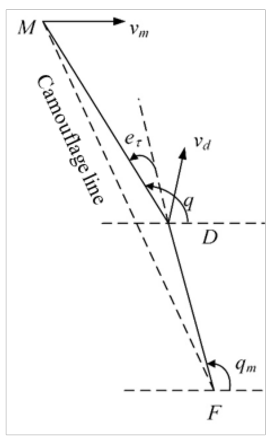

Fig.2. Relative motion diagram of motion camouflage with fixed point at finite place.

For the case shown in Figure 2, the degree to which the missile deviates from the camouflage line can be represented by the angle between the straight line FD and the straight line DT, i.e. the error angle $\mathbf{e}_r$ is

$$e_r = q - q_d \tag{10}$$

For the case in Figure 3, the error angle is the difference between the current bullet line of sight angle *q* and the initial bullet line of sight angle.

$$e_r = q - q_0 \tag{11}$$

Due to the fact that the trajectory of motion camouflage tracking with a focus on infinity is flatter and requires less normal overload, this article mainly adopts motion camouflage bionic guidance in this case [9]. At this point, designing a guidance law is equivalent to designing a closed-loop control law, which controls the missile speed direction to make the error angle er tend to 0. Here, the PID control law is selected, which means

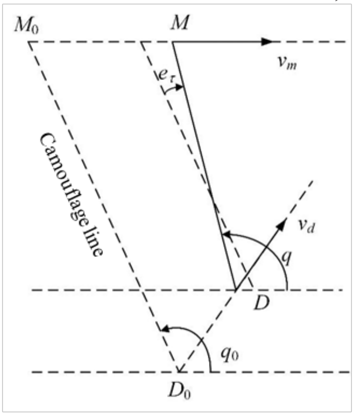

Fig.3. Relative motion diagram of motion camouflage with fixed point at infinite place.

$$\dot{\theta}_m(t) = K_p e_r(t) + K_i \int_0^t e_r(t)dt + K_d \frac{de_r(t)}{dt} \tag{12}$$

In the formula, K_p, K_i and K_d are PID proportional, integral, and differential parameters, respectively; T is the guidance time, so the final stage bionic guidance law based on "motion camouflage" is:

$$n_y(t) = \theta_m(t) v_m / g \tag{13}$$

3.3 Transitional guidance law design

The switching stage guidance law between the initial and final guidance stages mainly focuses on two issues: the selection of the timing for switching between the initial and final guidance stages, and the design of the guidance law during the handover.

The selection of the timing for switching between the initial and final guidance stages is related to the constraint of the field of view angle range of the guidance head. In the initial guidance stage, sliding mode control law is used to control the parallax angle, which can maintain a small target parallax angle. In the final guidance stage, due to the use of motion camouflage bionic guidance with a focus at infinity, $\dot{q} = 0$, the parallax angle η_d is obtained from equation (2) .

$$\eta_d = \arcsin\left(\frac{v_m}{v_d} \sin \eta_m\right) - \alpha \tag{14}$$

Ignoring the influence of the angle of attack, the leading angle is related to the target parallax angle, and the field of view of the missile seeker is set to ［-φ,φ］, so the absolute value of the target leading angle should be less than

$$\eta_{md} = \arcsin\left(\frac{v_d}{v_m} \sin \varphi\right) \tag{15}$$

Table 1. Main parameter table.

Simulation parameters	**Parameter values**
Missile speed $v_d / (m \cdot s^{-1})$	120
Missile initial position $(x_d, y_d, z_d) / m$	0,0,0
Initial ballistic inclination angle of the missile $\theta_d / (°)$	-30
Initial ballistic deviation angle of missile $\psi_{vd} / (°)$	90
Initial pitch angle of missile $\vartheta_d / (°)$	-30
Initial yaw angle of missile $\psi_d / (°)$	90
Target initial position $(x_m, y_m, z_m) / m$	2000,0,200
Target speed $v_m / (m \cdot s^{-1})$	80
Initial ballistic inclination angle of the target $\theta_m / (°)$	0
Initial trajectory deviation angle of the target $\psi_{vm} / (°)$	0
Initial target parallax angle in the vertical direction $\eta_{melv} / (°)$	15
Initial target parallax angle in the horizontal $\eta_{maz} / (°)$	7
Initial target lead angle in the vertical direction $\eta_{telv} / (°)$	-100
Initial target lead angle in the horizontal direction $\eta_{telv} / (°)$	90
Initial sliding mode guidance coefficient k	8
Initial and final guidance handover points $\lvert\eta_{telv}\rvert / (°), \lvert\eta_{taz}\rvert / (°)$	36,36
Total transition time t_{gd} / s	2.5
Final stage PID parameters K_p, K_i, K_d	5,0.01,9

Transition between the initial and final guidance stages to ensure that the guidance head does not lose the target in the field of view. The purpose of adding transitional guidance laws is to achieve a smooth transition of guidance law switching, in order to avoid the need for severe overload oscillations during the switching of initial and final guidance laws. The second-order smooth transition law proposed in reference [10] designs the transition section overload as the weighted sum of the initial guidance section overload and the final guidance section overload,

$$n_{ygd}(\bar{t}) = \lambda(\bar{t}) n_{y1}(\bar{t}) + [1 - \lambda(\bar{t})] n_{y2}(\bar{t}) \tag{16}$$

In the formula, $\bar{t} = t - t_0$ is the time during which the missile is in the transition phase, $n_{ygd}(\bar{t})$ is overloading of the transition section , t_0 is the starting time of the transition period.

$$\lambda(\bar{t}) = 1 - \frac{3}{t_{gd}^2} \bar{t}^2 + \frac{2}{t_{gd}^3} \bar{t}^3 \tag{17}$$

In the formula: $\lambda(\bar{t})$ is the smoothing operator, t_{gd} is the total time consumption of the transition section.

4 Simulation verification

Using bionic segmented composite guidance laws in both vertical and horizontal planes to simulate a small missile with a wingspan of 0.6m and a weight of 10kg intercepting aerial targets. The simulation conditions are shown in Table 1.

During the simulation process, proportional guidance [11] and bionic segmented guidance laws were used to obtain the time-varying curves of overload, target parallax angle, attack angle, sideslip angle, and attitude angle, as shown in Figures 4-11. According to the simulation results, when the velocity ratio of the missile to the target is 1.5, the designed composite guidance law requires a longer interception time, but the required overload of the composite guidance law is smaller, and the target parallax angle during the composite guidance process is always smaller than proportional guidance.

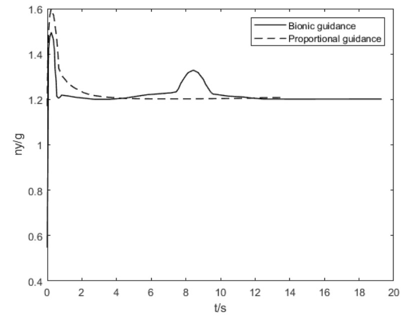

Fig.4. Overload curve on vertical plane.

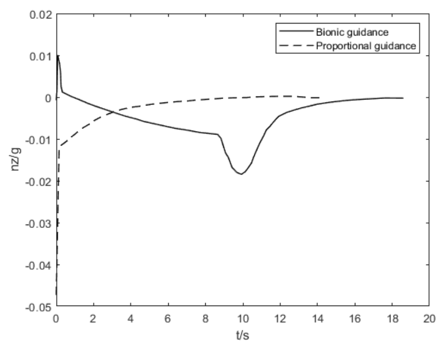

Fig.5. Overload curve on horizontal plane.

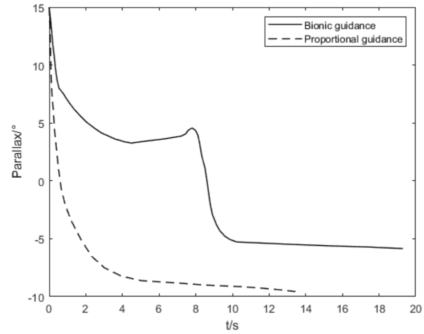

Fig.6. Parallax curve of target on vertical plane.

https://doi.org/10.1051/matecconf/202439501014

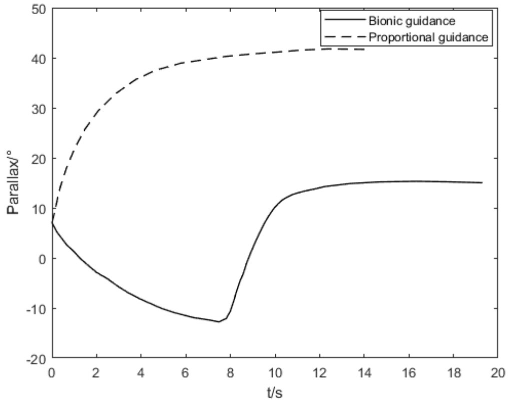

Fig.7. Parallax curve of target on horizontal plane.

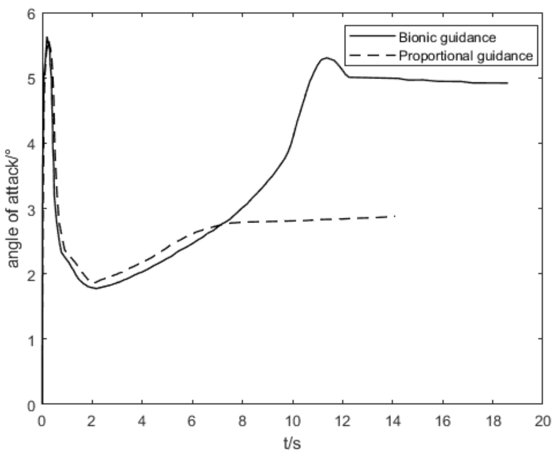

Fig.8. Angle of attack curve.

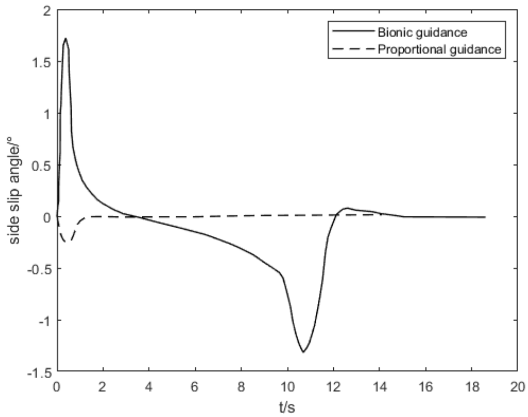

Fig.9. Side slip angle curve.

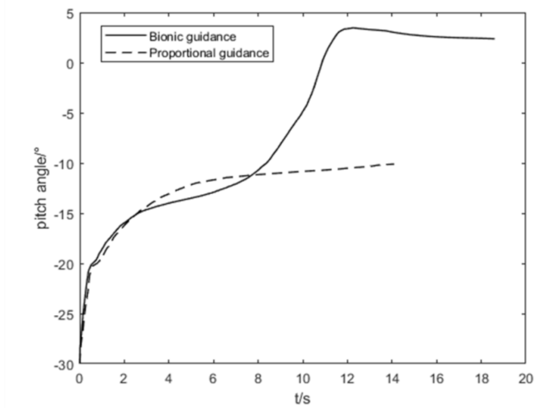

Fig.10. Pitch angle curve.

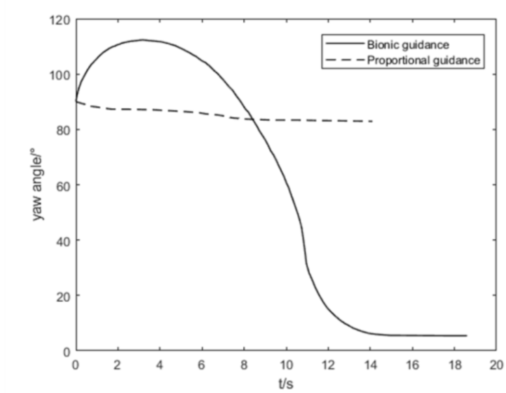

Fig.11. Yawangle curve.

From Figure 9, it can be seen that the maximum parallax angle of proportional guidance reaches over 40 °, which is far beyond the field of view range of the guidance head, resulting in the loss of the target at the end of the guidance. The parallax angle of the segmented composite guidance designed in this article is at (-20 °, 20 °), fully in line with the field of view angle range specified by the strapdown guidance head.

5 Summary

A segmented bionic guidance law similar to the dragonfly maneuver strategy was designed based on the capture strategy of natural flying insects for low-cost small missiles with strapdown optical guidance heads. In the initial stage of the final guidance, a sliding mode control law was used to control the parallax angle, adjusting the missile attitude to the state of tail chasing the target. In the final guidance, a motion camouflage guidance law with straight trajectory characteristics was used for target interception.

The guidance law designed in this article achieves some advantages of dragonflies during their predation of fruit flies. Compared with proportional guidance law, bionic segmented composite guidance requires less overload in terminal guidance, and the target is closer to the center of the field of view, which can reduce the missile's available overload and the guidance head's field of view limitations in terminal guidance, effectively improving guidance accuracy.

References

1. XIONG Junhui,TANG Shengjing, GUO Jie,ct al. Design of On variable structure guidance law for interceptor based of fuzzy variable coefficient strategy[J]. Acta Armamentarii,2014,35(1):134-139.
2. SAND D K,TAHK M J. Guidance law switching logic considering the seeker's field-of-view limits[J].Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,2009,223(8)：1049-1058
3. LIN Peng,SU Zhong,FAN Junfang. Design of guidance law for full strapdown guided ammunition[J].Journal of Projectiles,Rockets,Missiles and Guidance,2015,35(3):1-4.
4. LIN Peng. Research on strapdown guidance method for micro air vehicle[D].Beijing: Beijing University of Information Technology,2015.
5. ZHANG Daochi,SUN Jing,WEN Qiuqiu,et al. Guidance method considering angle of view and falling angleof seeker[J].Transactions of Beijing Institute of Technology,2016,36(5):452-457.
6. XI Jie,YANG Jun,ZHU Xueping. Design of guidance law with angle of fall and angle of view of seeker[J]. Electrooptics and Control,2014,21(9):26-28.
7. WANG Zhengjie, HUANG Weilin, YAN Yonghong. Vision-based bio-inspired guidance law for small aerial vehicle[J].Chinese Journal of Aeronautics,2015,28(1):260-267.
8. HUANG Weilin, WANG Zhengjie. Study on the bionic complex guidance law of micro-miniature cruise missiles[J].Tactical Missile Technology,2018(2):90-94.
9. WANG Zhengjie, CAI Changqing, HUANG Weilin. Study on bionic subsection compound guidance law considering field of view angle of seeker[J]. Transactions of Beijing Institute of Technology,2021,41(2):186-192.
10. ZHANG Lei, FANG Yangwang, GAO Xiang,et al. Research on ballistic transition law of missile mid-and end-guidance[J].Journal of Ballistics,2014,26(2):12-16.
11. QIAN Xingfang, LIN Ruixiong, ZHAO Yanan. Missile flight mechanics[M]. Beijing: Beijing Institute of Technology Press,2008.