1st International Conference on Autonomous Unmanned Systems Sept.24-26, 2021

ICAUS-21-A2.2C.2(x0059)

TCLF-based Obstacle avoidance path planning for HSV using Pigeon-inspired Optimization

Rugang Tang[1] and Xin Ning[1,2,*]

[1] School of Astronautics, Northwestern Polytechnical University, Xi'an, PR China
[2] National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an, PR China
nx_nwpu@163.com

Abstract. This paper proposes an obstacle avoidance planning method based on the penalty function of the truncated Coulomb-like force (TCLF) for Hypersonic vehicle (HSV) in multiple threat zones. The main point of the proposed method is to to put forward a TCLF so that an flight-fit trajectory is obtained which can avoid obstacles autonomously while ensuring landing accuracy. Analogous to the Coulomb force, this paper proposes a TCLF penalty function to characterize the impact of the threat zone on ballistic planning. The pigeon swarm algorithm is used to solve the ballistic impact point optimization problem with penalty function. The simulation results show that the method can automatically generate the bank angle sequence and the angle of attack sequence to form a trajectory, effectively solving the problem of obstacle avoidance for HSV.

Keywords: HSV obstacle avoidance , path planning , PIO.

1 Introduction

Compared with aviation aircraft, unmanned aerial vehicles and other aircraft, HSV have the characteristics of weaker maneuverability and greater difficulty in stealth, so their obstacle avoidance problems are rarely considered. With the complexity of combat missions, the improvement of HSV maneuverability and the expansion of attack range, the problem of obstacle avoidance in path planning of HSV has gradually been discussed and certain results have been achieved, which has become a key technology in HSV planning, especially for cruise missiles.

Traditional path planning methods are mainly divided into two categories [1], One type is a global path planning method that relies on known environmental information, such as genetic algorithm [2], A* algorithm [3], Ant Clony Optimization [4], Artificial Neural Networks [5] and so on. These methods can achieve good planning results, but ignores the threat of unknown obstacles in the environment. The other is local path planning methods that rely on the perception of the surrounding environment, such as artificial potential field method [6], velocity obstacle method [7], dynamic window method [8]. The main defect of this type of method is the lack of grasp of the global information, so that the result is often not the global optimum, and the target unreachable phenomenon may occur in serious cases.

Many scholars have devoted themselves to applying the path planning algorithm with obstacle avoidance to the research of HSV trajectory planning. Li Shiyong et al. [10] used an improved ant colony algorithm to plan a better-performing trajectory in a discrete space; Huang Jun et al. [11] took the A* algorithm as the basic framework and considered the constraints of cruise missiles to obtain the path with the smallest cost.

Although such a wealth of results have been achieved, the research on the penalty function of optimization of guidance signals is rarely mentioned, especially for HSV. The trajectories obtained by previous researchs are all waypoint sequences, which are not actual flight-fit trajectories. Based on the above analysis, this paper studies the problem of trajectory planning. Compared with previous studies, the main features of this paper can be summarized as:

- Benefiting from the introduction of TCLF，this paper construct a novel method of the obstacle avoidance，which can adapt the situation of HSV in multi-threat areas.
- Through the TCLF-based algorithm, we can achieve obstacle avoidance and penetration in multi-threat zones, and obtain real Guidance signals.
- In addition, Pigeon-inspired Optimization algorithm (PIO) is used to efficiently solve the optimization problem.

2 Problem Description

The space trajectory calculation equation is established in the launch coordinate system [12], considering gravity, centrifugal inertial force, Coriolis inertial force and aerodynamic force, as shown in equation (1).

$$
\begin{aligned}
m\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} &= \begin{pmatrix}\cos\varphi\cos\psi & -\sin\varphi & \cos\varphi\sin\psi\\ \sin\varphi\cos\psi & \cos\varphi & \sin\varphi\sin\psi\\ -\sin\psi & 0 & \cos\psi\end{pmatrix}\begin{bmatrix}P_e\\ Y_{1c}\\ Z_{1c}\end{bmatrix}\\
&+\begin{pmatrix}\cos\theta\cos\sigma & -\sin\theta & \cos\theta\sin\sigma\\ \sin\theta\cos\sigma & \cos\theta & \sin\theta\sin\sigma\\ -\sin\sigma & 0 & \cos\sigma\end{pmatrix}\begin{bmatrix}-C_x qS_M\\ C_y^{\alpha} qS_M\alpha\\ -C_y^{\alpha} qS_M\beta\end{bmatrix}+m\frac{g_r'}{r}\begin{bmatrix}x+R_{0x}\\ y+R_{0y}\\ z+R_{0z}\end{bmatrix} \qquad (1)\\
&+m\frac{g_{\omega e}}{\omega_e}\begin{bmatrix}\omega_{ex}\\ \omega_{ey}\\ \omega_{ez}\end{bmatrix}-m\begin{pmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{pmatrix}\begin{bmatrix}x+R_{0x}\\ y+R_{0y}\\ z+R_{0z}\end{bmatrix}-m\begin{pmatrix}b_{11} & b_{12} & b_{13}\\ b_{21} & b_{22} & b_{23}\\ b_{31} & b_{32} & b_{33}\end{pmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix}
\end{aligned}
$$

In which, m represents the mass of the missile; x, y, z represent the coordinates in the launch coordinate system; the first term on the right side of the equation is the thrust P_e and control forces Y_{1c} and Z_{1c}; the second term represents the aerodynamic force; the third and fourth terms represent the gravity of the earth; the fifth and sixth terms are centrifugal inertial force and Coriolis force respectively. In addition, φ represents the pitch angle, ψ represents the drift angle, θ represents the flight path angle, and σ represents the track yaw angle.

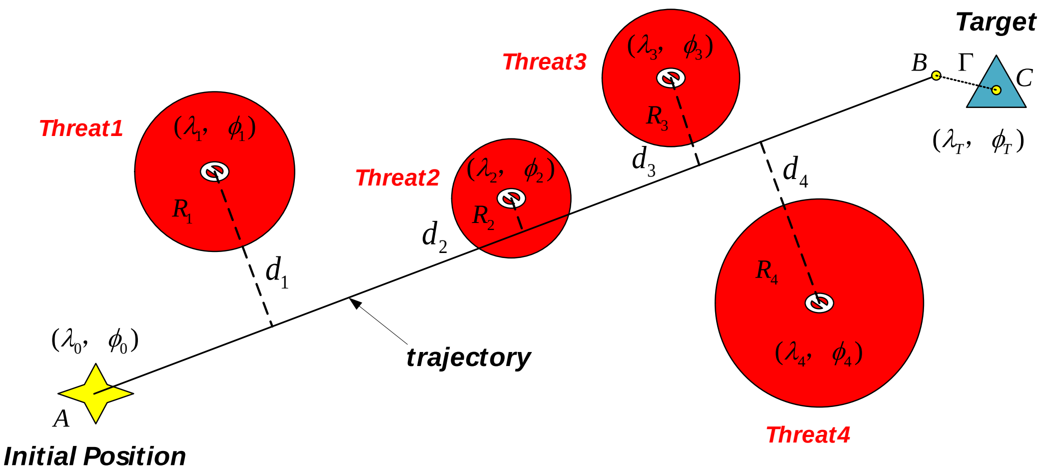

Fig. 1. missile obstacle avoidance problem

Fig. 1 shows a schematic diagram of the missile obstacle avoidance problem. $A(\lambda_0,\phi_0)$ and $C(\lambda_T,\phi_T)$ are the missile launch position and target position (latitude and longitude) respectively. Set the number of threat zones (red area) to N and the center coordinates of the cylindrical threat zones (latitude and longitude) to $Threat1(\lambda_1,\phi_1)$, $Threat2(\lambda_2,\phi_2)\cdots ThreatN(\lambda_n,\phi_n)$, the corresponding threat radius is R_1、$R_2\cdots R_N$; $A-B$ is a trajectory of the missile, d_1, $d_2\cdots$ d_N are the distances between the trajectory and the center of each threat zone. The distance between the actual landing point B of the missile and the target position C is Γ, which is called the landing error.

Assumption 1. It is supposed that the target is in the range of the HSV.

Assumption 2. The threat zone radius is between 100-500 km.

Problem 1. Under the above definition, the purpose of this paper is to find a trajectory where the landing error Γ satisfies the accuracy requirement and obstacles are effectively avoided as $d_i > R_i (i=1,2,\cdots,N)$.

3 Guidance strategy design

When the vehicle enters a certain range of the target position, the preliminary mission is considered to be completed. Therefore, this paper ignores the terminal guidance, and designs the guidance strategy for the gliding section and the turning section respectively.

3.1 Guidance Design for Gliding Section

In the gliding section, considering the influence of heat flow, the structural strength of the missile and other restrictions on aerodynamics, the angle of attack is taken as a given angle of attack profile that varies with speed as the method in reference [13]:

$$\alpha=\begin{cases}40^\circ & v>4570m/s\\ 40^\circ-k(v-4570)^2 & v\le 4570m/s\end{cases}\tag{2}$$

where $k=(40°-14°)/(v_f-4570)^2$, v_f represents the terminal speed.

3.2 Guidance Design for Turning Section

First, define the desired rate of change of ballistic deflection angle:

$$\xi=-k_1\left(\sigma-\sigma_d\right)\tag{3}$$

and set the design goal as:

$$\dot{\sigma}=\xi\tag{4}$$

Similarly, the design goal of the flight path angle is:

$$\dot{\theta}=-k_2(\theta-\theta_d)\tag{5}$$

The equation in the ballistic coordinate system is:

$$\dot{V}=\frac{F_{aero,x3}}{m}+g_{x3},\dot{\theta}=\frac{F_{aero,y3}}{mV}+\frac{g_{y3}}{V},\dot{\sigma}=-\frac{F_{aero,z3}}{mV\cos\theta}-\frac{g_{z3}}{V\cos\theta}\tag{6}$$

in which, the subscript 3 represents the ballistic coordinate system, and F_{aero} is the aerodynamic force. The aerodynamic force can be obtained according to equation (6):

$$\begin{aligned} F_{aero,y3} &= mV\dot{\theta} - mg_{y3} \\ F_{aero,z3} &= -mV\dot{\sigma}\cos\theta - mg_{z3} \end{aligned} \tag{7}$$

The corresponding relationship between the lift coefficient and the drag coefficient in the body coordinate system of the aerodynamic force obtained by the above formula is:

$$\begin{bmatrix} \cos\gamma_v & \sin\gamma_v \\ -\sin\gamma_0 & \cos\gamma_0 \end{bmatrix} \begin{bmatrix} F_{y_3} \\ F_{z_3} \end{bmatrix} = \begin{bmatrix} C_y^\alpha \alpha qs \\ -C_y^\alpha \beta qs \end{bmatrix} \tag{8}$$

Assume that the missile adopts the BBT turning method, that is $\beta = 0$. Then, the command of the angle of attack and the angle of bank can be obtained by solving the binary equations of the above formula about γ_v and α.

Therefore, the tracking of the target can be transformed into a multi-variable single-objective optimization problem of ballistic deflection angle gain and flight path angle gain. The objective function is the distance Dis to the target point. When the optimal objective function value is within the allowable distance, it is considered that the missile successfully finds the target and starts terminal guidance and other follow-up actions.

4 Obstacle avoidance optimization model

4.1 Penalty function based on TCLF

Consider the situation where there are N threat zones $Threat1(\lambda_1,\phi_1)$, $Threat2(\lambda_2,\phi_2)\cdots$ $ThreatN(\lambda_n,\phi_n)$ between launch position A and target position B. This paper proposes a penalty function based on the truncated Coulomb-like force, and introduces the penalty function on the distance d_1、$d_2 \cdots d_N$ between the trajectory and each threat zone into the optimization problem in **Section 2**.

The penalty function is set as $\sum_1^N 1/d_i^2$, and according to the radius of the threat zone, the penalty function influence threshold distance is set proportionally. This paper takes it as 1.5 times, that is, $1/d_i = 0,\ if\ \ d_i > 1.5R_i$.

In order to improve the calculation efficiency, the trajectory is divided into three stages, which are the launching section, the maneuvering section and the target section in sequence.

The Launching Section. Keep bank angle at 0 when the missile is far from the obstacle zone;

The Maneuvering Section. When the distance between the missile and the obstacle zone is $d < d^0$ (d^0 is the preset distance threshold), the independent variable is set to a sequence of bank angle commands. The sequence is optimized to complete the lateral maneuver;

The Target Section. After the missile successfully avoids obstacles, in order to improve the calculation efficiency, the design variables are updated to the deflection angle gain k_1 and the flight path angle gain k_2.

The optimization model can be summarized as follows：

$$\begin{cases} \min\ \ \mathrm{f} = \Gamma + \sum_{i=1}^{N} \dfrac{1}{\mathrm{d}_i^{\,2}} \\ s.t.\quad 0 \le \alpha \le \overline{\alpha} \\ where\ \ \dfrac{1}{\mathrm{d}_i^{\,2}} = 0,\ \text{if}\quad \mathrm{d}_i > 1.5R_i \end{cases} \tag{9}$$

4.2 Obstacle avoidance optimization based on Pigeon-inspired Optimization algorithm

Aiming at the above optimization model, this paper adopts the pigeon swarm algorithm to optimize the solution.

Algorithm Mechanism. Pigeon-inspired Optimization algorithm (PIO) is a swarm intelligence optimization algorithm designed to simulate the homing behavior of pigeons. The pigeons will find their destinations according to the sun, the geomagnetic field, and the landscape during the different stages of homing. PIO is based on this behavior of the pigeons. In the optimization process, the compass operator (based on the geomagnetic field and the sun) and the landmark operator (based on the landscape) are proposed.

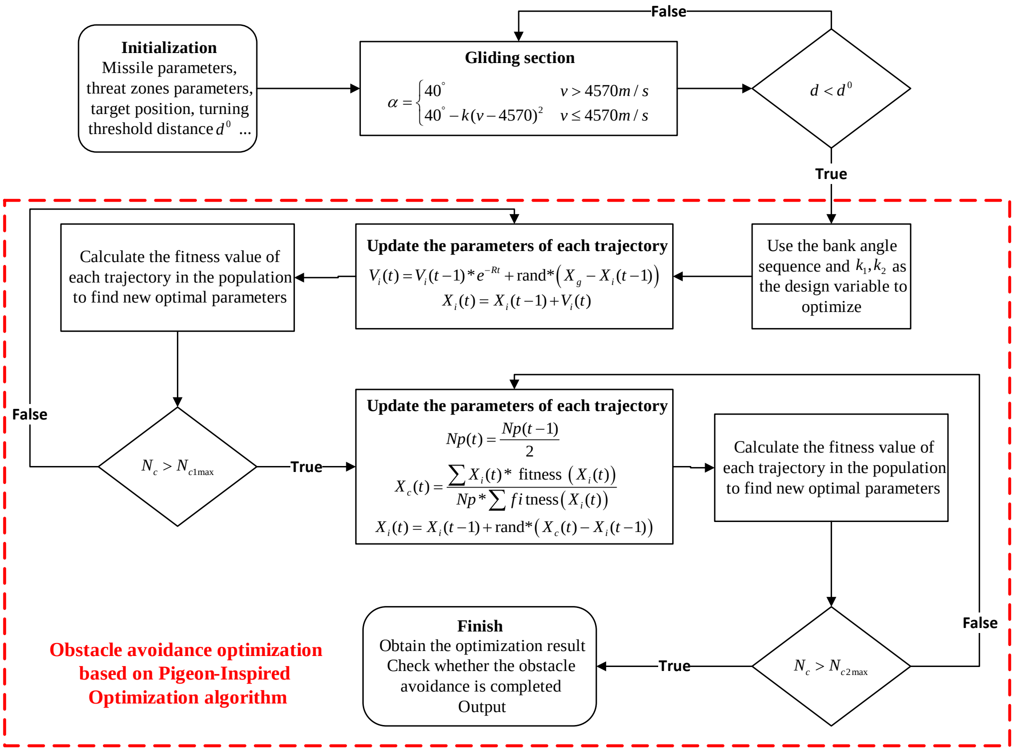

Fig. 2. Algorithm flow char

In the optimization of the obstacle avoidance model, first set the number of optimization parameters Dim as the number of design variables, which corresponds to the dimension of the speed vector of the pigeons; the vector composed of the rate of change of each parameter corresponds to the speed of the pigeon; and set the population size PN used to determine the number of candidate trajectories in each round of the optimization process. After two rounds of iteration of the compass operator and the landmark operator, each parameter will iterate to the value that minimizes the objective function $\mathrm{f(x)} = \Gamma + \sum_{i=1}^{N} 1/\mathrm{d}_i^2$, that is, reach the target position of the pigeon flock.

Compass operator. We use X_i and V_i to represent the value and rate of change of the i-th trajectory design variable, corresponding to the position and speed of the i-th pigeon. The design variables are respectively calculated by formula (10) and formula (11):

$$V_i(t) = V_i(t-1)*e^{-Rt} + \text{rand}*\left(X_g - X_i(t-1)\right) \tag{10}$$

$$X_i(t) = X_i(t-1) + V_i(t) \tag{11}$$

where R is the map factor, $Rand$ is a random number, and t is the number of iterations. The parameters of the i-th trajectory are determined by the trajectory parameters of the previous generation and the current speed. Each trajectory will be adjusted according to the optimal trajectory in the previous generation according to equation (10).

Landmark Operator. The landmark model is established based on pigeons using landmarks to navigate. In the landmark model, N_p is used to record the number of half of the trajectories in each generation, and $X_c(t)$ is the center position of all the trajectories of the t-th generation. If each trajectory changes in the direction of the optimal trajectory, there will be the following formula:

$$Np(t) = \frac{Np(t-1)}{2} \tag{12}$$

$$X_c(t) = \frac{\sum X_i(t) * \text{ fitness } \left(X_i(t)\right)}{Np * \sum fi\text{tness}\left(X_i(t)\right)} \tag{13}$$

$$X_i(t) = X_i(t-1) + \text{rand}*\left(X_c(t) - X_i(t-1)\right) \tag{14}$$

where fitness(x) is the fitness value of each trajectory.

4.3 The overall flow of the algorithm

In summary, the pigeon swarm algorithm is used to solve the missile obstacle avoidance optimization model. The specific process is shown in **Fig. 2**.

5 NUMERICAL EXAMPLES

In order to reveal the effectiveness and the veracity of the proposed method, two numerical examples are presented in this section.

5.1 Example. 1

Example. 1: First, set the missile mass to 1800kg, the initial velocity and altitude are 24Ma and 120000km, respectively, the missile launches from the $(0°, 0°)$ with the initial azimuth angle $A_0 = 90°$. Then set the target point to $(80°, 10°)$. Furthermore, set up 6 threat zones ($N = 6$), which are shown in **Table 1**. The trajectory and command sequences are shown in **Fig. 3** and **Fig. 4**. The deflection angle gain $k_1 = 0.001$ and the flight path angle gain $k_2 = 0.002$. The simulation lasts for 302s, and the number of ballistic iterations is only about 60 times.

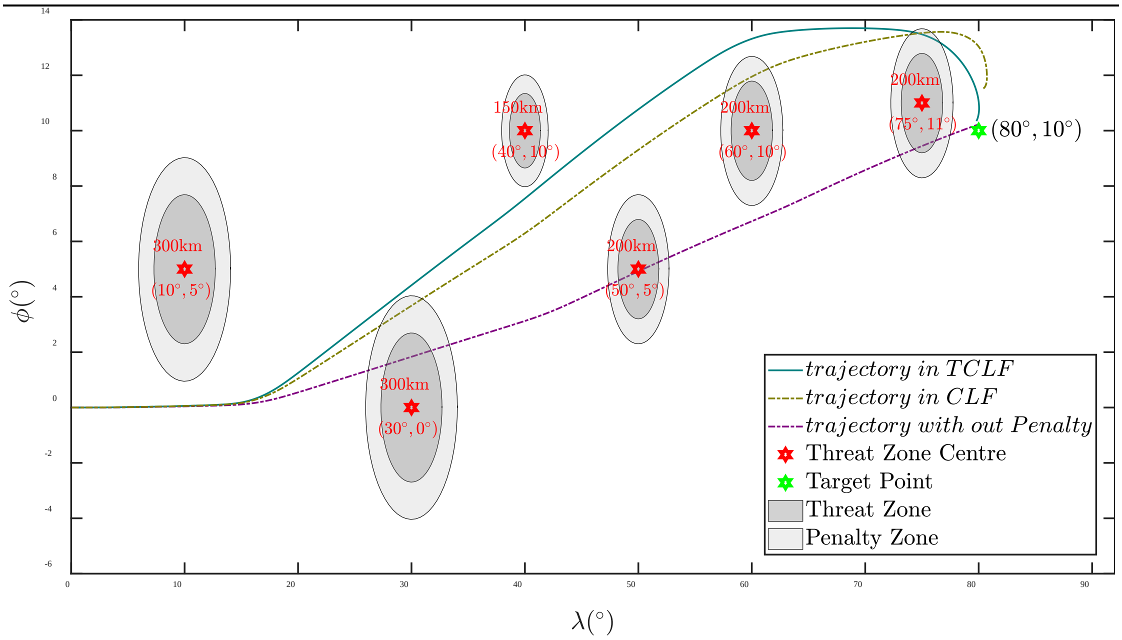

Fig. 3. Example.1:Trajectory in 6 threat zones

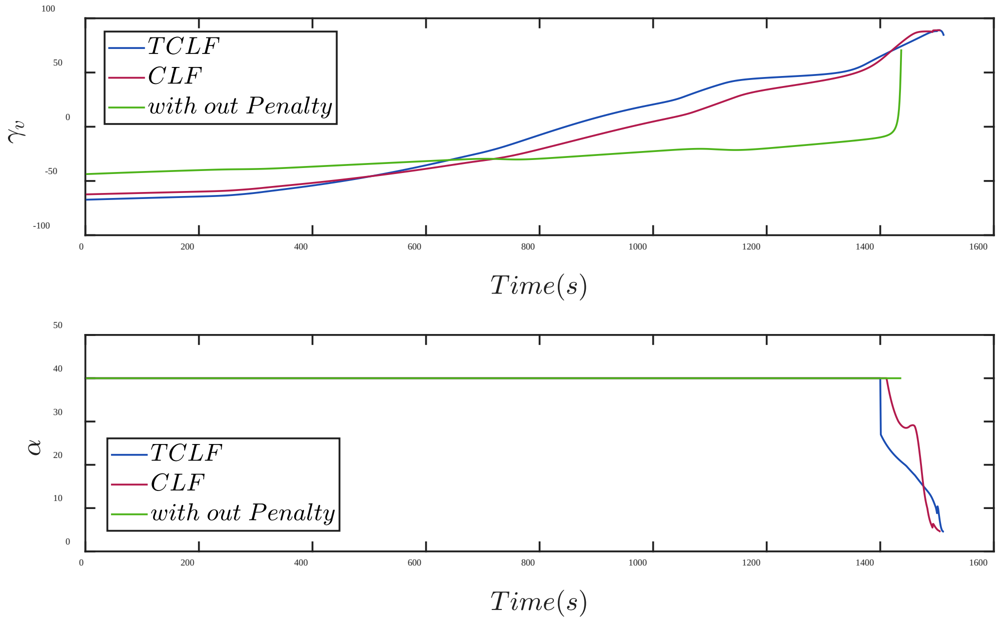

Fig. 4. Example.1: Guidance signals

Table 1. Example.1:Threat zones parameters

Center	Radius(km)	Center	Radius(km)
(10°,5°)	300	(60°,10°)	200
(30°,0°)	300	(40°,10°)	150

(50°,5°)	200	(75°,11°)	200

5.2 Example. 2

Example. 2: First, only the initial launch azimuth is changed to $A_0 = 45°$, compared with **Example. 1**. Then set the target point to $(80°, 0°)$. Furthermore, set up 5 threat zones ($N = 5$), which are shown in **Table 2**. The simulation results are shown in **Fig. 5** and **Fig. 6**. The deflection angle gain $k_1 = 0.0025$ and the flight path angle gain $k_2 = 0.0058$. The simulation lasts for 353s, and the number of ballistic iterations is only about 70 times.

Table 2. Example.2:Threat zones parameters

Center	Radius(km)	Center	Radius(km)
(10°,5°)	200	(45°,3°)	200
(20°,15°)	250	(70°,3°)	200
(30°,6°)	300		

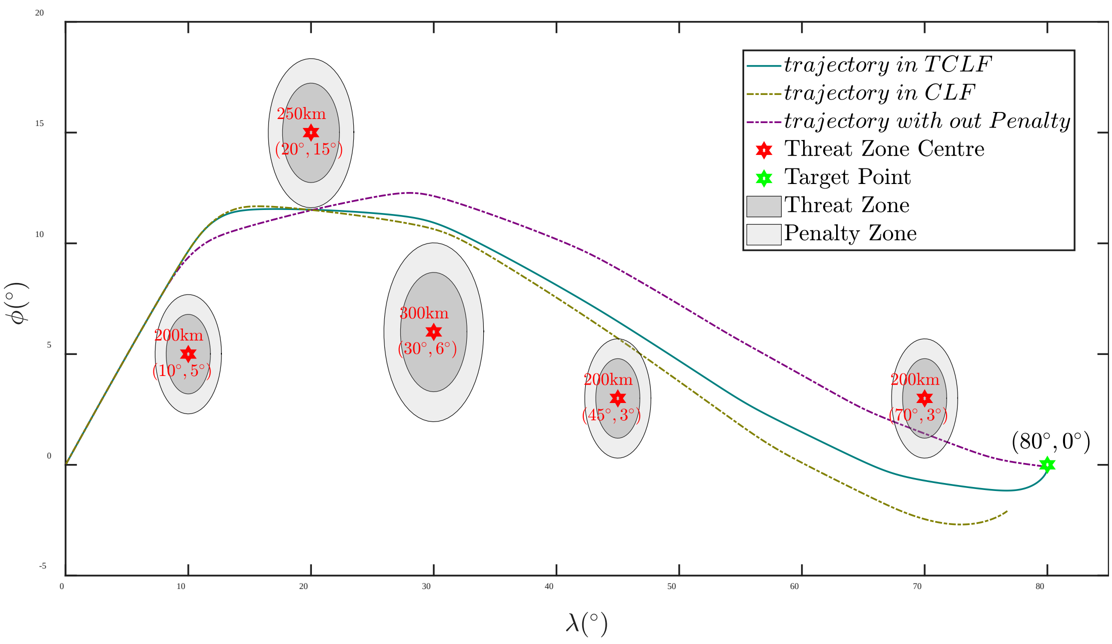

Fig. 5. Example.2:Trajectory in 5 threat zones

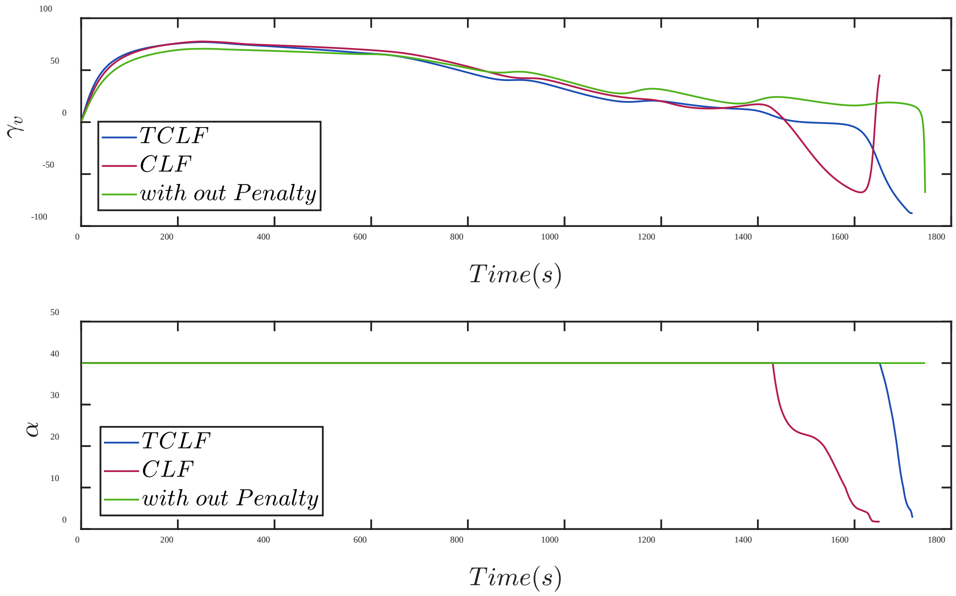

Fig. 6. Example.2: Guidance signals

6 Conclution

In order to solve the problem of missile autonomous obstacle avoidance in the case of multiple obstacle zones, this paper proposes a penalty function design method based on the TCLF, and the pigeon swarm algorithm is used for optimization. The method has good versatility and high efficiency, which is proved by numerical simulation. As shown in the simulation results in **Section 5**, this method can adapt to different launch situations and threat zone settings, such as target locations and initial launch direction. At the same time, it has a high operating efficiency, and the ballistic trajectory has a satisfactory convergence effect after about 60 iterations. However, in Example. 1, the trajectory entered the penalty zone, due to the presence of a threat zone close to the target location, and the missile's maneuverability decreased at the end of the phase. The quantitative index of maneuverability consumption can be considered to be introduced to reduce the early energy consumption of the missile, thereby improving the terminal maneuverability.

References

1. Zhu Da-qi, Yan Ming-chong. Survey on Technology of Mobile Robot Path Planning[J]. Control and Decision, 25(7): 961-967 (2010).
2. Song B, Wang Z, Sheng L. A New Genetic Algorithm Approach to Smooth Path Planning for Mobile Robots[J]. Assembly Automation, 36(2): 138-145（2016）.
3. Chen Shi, Liu Chun-wu, Huang Zhi-ping, et al. Global Path Planning for AUV Based on Sparse A* Search Algorithm[J]. Torpedo Technology, 20(4): 271-275 (2012).
4. Cao J. Robot Global Path Planning Based on an Improved Ant Colony Algorithm[J]. Journal of Computer & Comm- unications, 4(2): 11-19 (2015).

5. Bharadwaj H, Vinodh K E. Comparative Study of Neural Networks in Path Planning for Catering Robots[J]. Pr- ocedia Computer Science, 133: 417-423 (2018)
6. Luo Qiang, Wang Hai-bao, Cui Xiao-jin. Improved Artificial Potential Field Method for Autonomous Mobile Robot Path Planning[J]. Control Engineering of China, 29(6): 1091-1098 (2019).
7. Fiorini P, Shiller Z. Motion Planning in Dynamic Environments Using the Relative Velocity Paradigm[C]//IEEE International Conference on Robotics & Automation. At- lanta, USA: IEEE: 560-565 (1993).
8. Zhang Chun-gang, Xi Yu-geng. Rolling Path Planning and Safety Analysis of Mobile Robot in Dynamic Uncertain Environment[J]. Control Theory & Applications, 2003, 20(1): 37-44 (2003).
9. Campbell S, Naeem W, Irwin G W. A Review on Improving the Autonomy of Unmanned Surface Vehicles through Intelligent Collision Avoidance Manoeuvres[J]. Annual Reviews in Control, 2012, 36(2): 267-283.
10. Li Shi-yong, Yang Dan. Route Planning of Cruise Missile Based on Improved Ant Colony Algorithm [J].Journal of Astronautics, (04):903-907 (2007).
11. Huang Jun, Yu Lei, Chen Zhong-qi, Ren Bo, Zhang Bin. Rea-l time path planning for optic-guided cruise missiles [J].Systems Engineering And ELectronics,32(04):799-802 (2010).
12. Chen Ke-jun, Liu Lu-hua, Meng Yun-he. Launch Vehicle Flight Dynamics and Guidance[M]. National Dfense Industry Press, 2014.
13. Schierman J , Hull J . In-Flight Entry Trajectory Optimization for Reusable Launch Vehicles[C]// Aiaa Guidance, Navigation, & Control Conference & Exhibit (2013).