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Research Article

Novel Particle Swarm Optimization Guidance for Hypersonic Target Interception with Impact Angle Constraint

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Considering that the terminal impact angle constraint can improve the interception performance of hypersonic target, a novel particle swarm optimization guidance (NPSOG) algorithm is proposed to satisfy the impact angle constraint. Two-dimensional dynamics engagement mode for hypersonic target interception is formulated. The performance index is positively correlated with the line-of-sight (LOS), LOS rate, and the relative distance between missile and target. The weight coefficients among the three are adaptively adjusted by the fuzzy logic controller. The particle swarm optimization (PSO) algorithm is utilized to generate the guidance commands. Numerical examples are given to verify the performance of the proposed guidance law in various engagement scenarios, and the performance of the algorithm is validated comparing with several heuristic guidance methods and nonheuristic guidance methods.

1. Introduction

Recently, the engagement of hypersonic targets is among the new challenges. When the hypersonic target reenters the atmosphere and reaches the descent stage of the hypersonic flight trajectory, its speed is so fast, and the remaining time to defense system is so short that the interceptor no longer has an advantage in speed compared to the target [1, 2]. The maneuvering characteristics and structure of hypersonic targets put forward higher requirements for the guidance and control of missiles. The terminal impact angle constraint is one of the key requirements to ensure the interception effect [3, 4].

The impact angle constraint guidance based on classical guidance and state-of-the-art guidance theory has attracted wide attention from scholars at home and abroad. A trajectory shaping guidance based on the optimization theory is proposed in [5], and the impact angle can reach the preset angle at the moment of interception. In [6], a new homing guidance law is proposed to impact a target with a desired attitude angle. It is a variation of the conventional proportional navigation guidance (PNG) law which includes a supplementary time-varying bias. Based on sliding mode control theory, a variety of impact angle constrained sliding mode guidance laws are proposed in [7–9], which reduces the influence of uncertainty on guidance accuracy.

The above guidance methods considering impact angle constraint are based on classical control theory and modern control theory. It is worth noting that intelligent control theory is the third-generation control method after classic control theory and modern control theory. It can solve highly complex, nonlinear, and uncertain control problems [10, 11]. In a complex engagement environment, interception of hypersonic targets is a highly nonlinear control problem that contains many uncertainties. Therefore, the application of intelligent control theory to missile guidance and control has great research value. In addition, classical guidance theory and advanced guidance theory require specific formulas to calculate guidance commands, while intelligent algorithms do not require specific guidance command calculation formulas. Heuristic intelligent algorithms such as genetic algorithm [12], ant colony [13–15] algorithm, and particle swarm optimization (PSO) [16–19] algorithm have been utilized to calculate the guidance commands, which further improve the performance of both traditional and modern guidance laws.

A particle swarm optimization guidance (PSOG) method for the nonlinear and dynamic pursuit-evasion optimization problem is designed in [16], and the relative distance is taken to be objective function, which is solved by PSO algorithm. The improved particle swarm optimization guidance (IPSOG) is proposed in [17], and the objective function is changed from relative distance to line-of-sight rate, and the proposed IPSOG algorithm reduces the acceleration requirements of missile compared with PSOG. In [18], a combined PN-IPSOG guidance algorithm is presented, and PN guidance is adopted in the initial stage and then transferred to IPSOG, which can solve the shortcoming of IPSOG that the overload changes greatly in the initial stage. However, the PSOG, IPSOG, and PN-IPSOG mentioned in the literature cannot satisfy the terminal attack angle constraint, so it is difficult to guarantee the missile's interception effect on hypersonic targets.

To sum up, the above heuristic guidance algorithm used to intercept hypersonic targets may be ineffective because of not considering impact angle constraint. Consequently, a heuristic guidance algorithm named as novel particle swarm optimization guidance (NPSOG) for hypersonic targets interception with impact angle constraint. The objective function comprehensively considers the line-of-sight, the line-of-sight rate, and the relative distance between the missile and the target, and the weights between the three are adaptively adjusted by the fuzzy logic controller to reduce the missile's demand for overload. The guidance algorithm proposed in this paper can achieve the desired angle when the missile collides with the target, so as to improve the damage effect on the target. In addition, this method enriches the theory of heuristic guidance algorithm.

The rest of the paper is organized as follows. The two-dimensional kinematics model of the engagement is described in Section 2. The NPSOG algorithm is given in Section 3. The numerical simulation results are shown in Section 4. Eventually, the conclusion is summarized in Section 5.

2. Dynamic Engagement Model

The interception geometry in two-dimensional space is shown in Figure 1, and hypersonic target tends to strike in a top-down manner at the descent stage of the flight trajectory. I_{1-O-2} is the inertial reference frame. The relative distance and LOS angle are represented as R_{TM} and λ, V_M and V_T represent the velocity, n_c and n_T represent the acceleration, and β represents the flight path angle of target. The engagement geometry equations are written as follows [5]:

$$R_{\mathrm{TM1}} = R_{T1} - R_{M1}, \tag{1}$$

$$R_{\mathrm{TM2}} = R_{T2} - R_{M2}, \tag{2}$$

$$V_{\mathrm{TM1}} = V_{T1} - V_{M1}, \tag{3}$$

$$V_{\mathrm{TM2}} = V_{T2} - V_{M2}, \tag{4}$$

$$R_{\mathrm{TM}} = \left(R_{\mathrm{TM1}}^2 + R_{\mathrm{TM2}}^2\right)^{1/2}, \tag{5}$$

$$\lambda = \tan^{-1}\frac{R_{\mathrm{TM2}}}{R_{\mathrm{TM1}}}, \tag{6}$$

$$V_{T1} = V_T \cos\beta, \tag{7}$$

$$V_{T2} = V_T \sin\beta, \tag{8}$$

$$a_{M1} = -n_c \sin\lambda, \tag{9}$$

$$a_{M2} = n_c \cos\lambda, \tag{10}$$

where R_{T1}, R_{T2}, V_{T1}, and V_{T2} represent the components of the target position and velocity, respectively. R_{M1}, R_{M2}, V_{M1}, V_{M2}, a_{M1}, and a_{M2} represent the components of the missile position, velocity, and acceleration, respectively. The components of the relative distance are R_{TM1} and R_{TM2}. The relationship between the missile and target distance and velocity components can be described by the following differential equation:

$$\begin{aligned}\dot{R}_{T1} &= V_{T1},\\ \dot{R}_{T2} &= V_{T2},\\ \dot{R}_{M1} &= V_{M1},\\ \dot{R}_{M2} &= V_{M2}.\end{aligned} \tag{11}$$

The missile velocity differential equations are given by

$$\begin{aligned}\dot{V}_{M1} &= a_{M1},\\ \dot{V}_{M2} &= a_{M2}.\end{aligned} \tag{12}$$

During the engagement, the target maneuvers by applying lateral acceleration n_T, we can obtain that

$$\dot{\beta} = \frac{n_T}{V_T}. \tag{13}$$

Differentiating Equations (5) and (6) with respect to time produces closing velocity and line-of-sight rate

$$\begin{aligned}V_c &= -\dot{R}_{\mathrm{TM}} = -\frac{R_{\mathrm{TM1}}V_{\mathrm{TM1}} + R_{\mathrm{TM2}}V_{\mathrm{TM2}}}{R_{\mathrm{TM}}^2},\\ \dot{\lambda} &= \frac{R_{\mathrm{TM1}}V_{\mathrm{TM2}} - R_{\mathrm{TM2}}V_{\mathrm{TM1}}}{R_{\mathrm{TM}}^2}.\end{aligned} \tag{14}$$

The above (Equations (1)–(16)) are the dynamic model of missile-target engagement.

3. Novel Particle Swarm Optimization Guidance

3.1. Algorithm Design. As we all know, classic and advanced guidance and control methods require the construction of accurate mathematical models to calculate acceleration instructions. [16]. However, the NPSOG, a heuristic

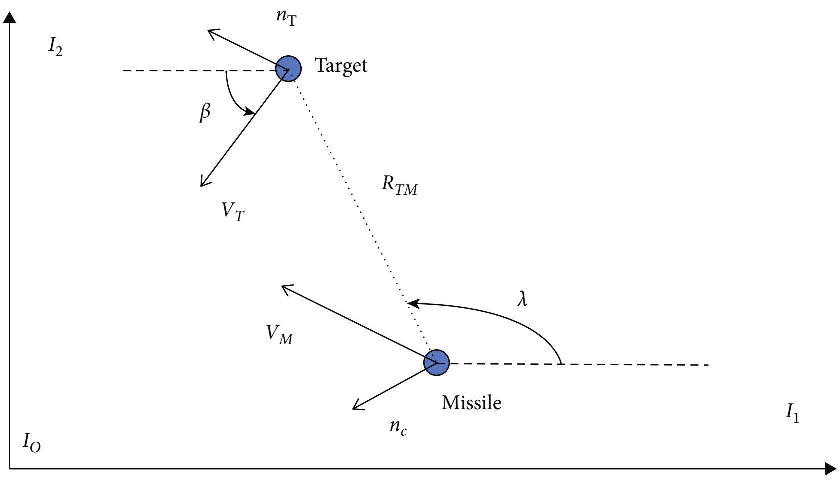


Figure 1: Missile-target engagement geometry.

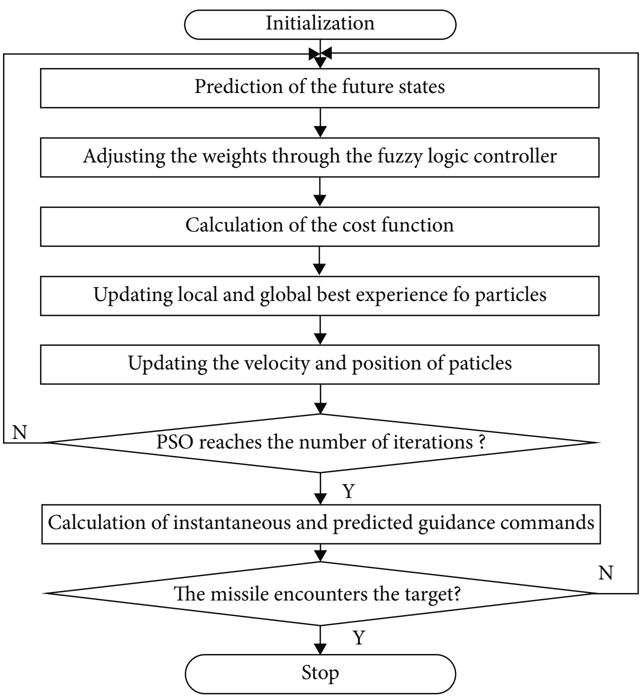


Figure 2: Flowchart of the NPSOG.

guidance method, uses PSO to derive the acceleration command by solving the objective function. The general structure of the NPSOG algorithm is shown in Figure 2, and more explanation is provided as follows:where λ_r is the preset line-of-sight. k_1, $k_{2,}$ and k_3 are the weight coefficients, and these three values are all positive numbers. The value of k_3 is 1, the value of k_1 is in the range of [3, 5], and the value of k_2 is in the range of [0.1, 4]. After k_1 and k_2 are determined, k_3 can be determined by fuzzy logic controller. In the following section, more details are provided. As can be seen from the above equation, the first term $J^1 = k_1|\lambda\text{-}\lambda_r|$ penalizes the deviation between the actual line-of-sight and the preset line-of-sight, and this item is used to satisfy the angle constraint. The second term $J^2 = k_2|\dot{\lambda}|$ penalizes the line-of-sight rate, which is to ensure that the trajectory of the missile and the target meets the collision triangle, thus reducing the overload requirement of missile. The third term $J^3 = k_3|\text{RTM}|$ penalizes the relative distance between missile and target, which is to keep the distance between the missile and the target decreasing.

Step 1. Initial parameter setting

The parameters of the NPSOG are set. These parameters are the initial state of the missile and the target, the prediction horizon, and the parameters of the PSO, including the initial particle $x_{i,j}$ and initial velocity $v_{i,j}$, the inertial weight w, the confidence factors c_1 and c_2, swarm size n $(1 \le i \le n)$, and iteration number j. It should be noted that the value of the particle $x_{i,j}$ is the acceleration command.

Step 2. Estimation of the future parameters

For different particles, using the engagement model prescribed in last section, line-of-sight, line-of-sight rate, and relative distance are calculated during the prediction horizon with Runge-Kuta method.

Step 3. Computation of the performance index

The performance index of the particle can be calculated as

$$J = k_1|\lambda - \lambda_r| + k_2\left|\dot{\lambda}\right| + k_3|\text{RTM}|, \tag{15}$$

Step 4. Updating optimal particles

The local optimal particles $P^i_{\text{best},j}$ and global optimal particle $G_{\text{best},j}$ are updated according to the performance index value of each particle, and the corresponding local performance index value and global performance index value are also updated.

Step 5. Computation of the velocity and location

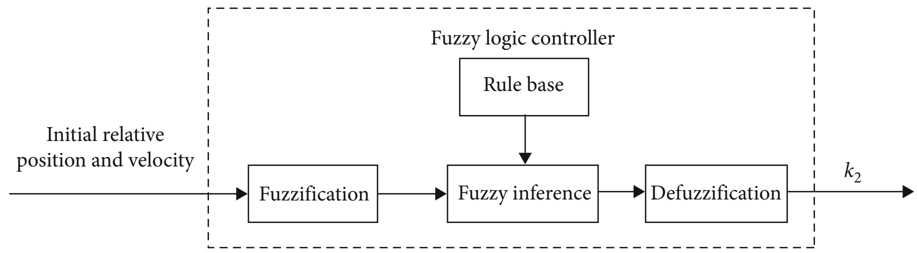


Figure 3: Fuzzy logic controller.

The velocity and location of particles are calculated as

$$\begin{aligned} V_{i,j+1} &= \omega V_{i,j} + c_1\left(P^i_{\text{best},j} - x_{i,j}\right) + c_2\left(G_{\text{best},j} - x_{i,j}\right), \\ x_{i,j+1} &= x_{i,j} + V_{i,j+1}. \end{aligned} \tag{16}$$

Step 6. End criteria

The best acceleration command can be got at each time step after n iterations. The engagement continues until the missile encounters the target.

In summary, the particle swarm algorithm is used to obtain the minimum value of the performance index. The value of the particles is the value of acceleration commands at the current moment t. For different acceleration commands, we can predict the values of line-of-sight, line-of-sight rate, and relative distance for next step $t + \Delta t$. Thus, the corresponding performance indexes of different particles can be calculated. With the continuous iteration of the particle swarm algorithm, we can get the optimal acceleration command a_t that minimizes the performance index, denoted as J_t. The value of the first term J_t^1 will also be relatively small. Then, the optimal acceleration command a_t is used for missile maneuvering. In the same way, we can obtain $a_{t+\Delta t}$, $J_{t+\Delta t}$, and $J^1_{t+\Delta t}$. It is worth noting that J_t^1 shows a decreasing trend and will eventually tend to 0, which will also be illustrated by simulation in Section 4. When J_t^1 tends to 0, the angle constraint is satisfied.

3.2. Adaptive Adjustment of the Weight Coefficients. As can be observed from Equation (15) that when k_1=0 and k_2=0, NPSOG is PSOG, when k_1=0 and k_3=0, it is IPSOG. The weight coefficients determine the guidance performance, such as the missile's flight trajectory, acceleration command, and miss distance in different engagement scenario. The optimal weight coefficients that can reduce the missile acceleration requirements and miss distance are determined by parameters such as the initial relative position and velocity. However, these quantities are difficult to describe with accurate mathematical models, so the weight coefficients in the objective function are obtained through the fuzzy logic controller. The structure of the fuzzy logic controller is shown in Figure 3. After a lot of experiments by the author, it is found that k_1 and k_3 can be set as constants, and k_2 can be adjusted to determine the performance of the NPSOB algorithm.

As shown in Figure 3, the input of the fuzzy controller is the initial relative position and velocity, and the output is the weight coefficient k_2. The design of NPSOG's fuzzy controller includes the following parts.

Table 1: Rule base as a 7×7 look-up table.

$V_c R_{\text{TM}}$	NB	NM	NS	ZE	PS	PM	PB
NB	PS	ZE	NS	NS	NM	NB	NB
NM	PS	PS	ZE	ZE	NS	NM	NB
NS	PM	PS	PS	ZE	NS	NS	BM
NE	PM	PS	PS	PS	ZE	NS	NS
PS	PB	PM	PS	PS	ZE	ZE	NS
PM	PB	PM	PM	PS	ZE	ZE	NS
PB	PB	PB	PM	PM	PS	ZE	ZE

Part 1. Physical set quantification

The physical set of relative position, relative velocity, and weight coefficient k_2 are [10000 m, 30000 m], [2500 m/s, 3500 m/s], and [0.1,4], respectively. Taking the seven fuzzy partitions in our research, its linguistic values can be represented as {NB,NM,NS,ZE,PS,PM,PB} [20].

Part 2. Rule base

The rule base is incorporated as a look up table in the form of a 7×7 matrix for faster computation. The rule base employed, after a large number of simulation experiments, is given in Table 1.

Part 3. Fuzzy inference

Mamdani method is adopted for fuzzy inference, which uses the maximum-minimum method. According to the input fuzzy quantity, the output fuzzy control quantity is derived based on fuzzy rules.

Part 4. Defuzzification

The result of fuzzy inference is a fuzzy set. It needs to be crisped back to deterministic control value before applied to missile. The method of centroid of area is adopted in this paper.

4. Simulation and Discussion

In this section, the effectiveness of NPSOG law proposed in this paper would be investigated through numerical simulation. The performance of the NPSOG is compared with PSOG and IPSOG against nonmaneuvering and maneuvering targets, including step-maneuvering and weave-maneuvering target.

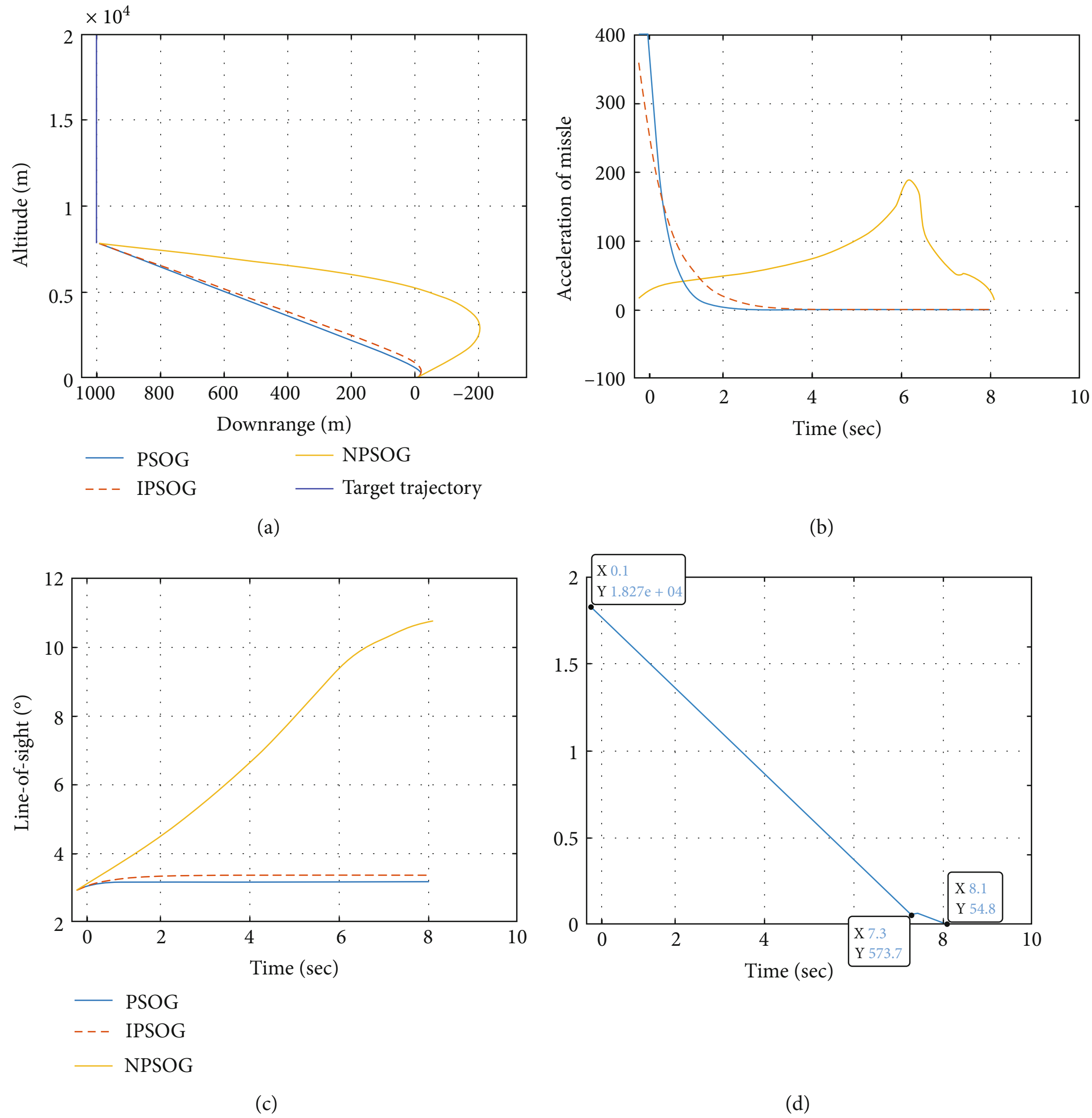


FIGURE 4: Simulation results of intercepting nonmaneuvering hypersonic targets.

4.1. Comparison with Heuristic Guidance Laws. The hypersonic target tends to strike in a top-down manner during the descent stage of the flight trajectory. When the target does not maneuver or performs a weave maneuver, the initial coordinates of the missile and the target are $(0, 0)$ and $(1\text{km}, 20\text{km})$, respectively. When the target performs a step maneuver, the initial coordinates of the missile and the target are $(0, 0)$ and $(3\text{km}, 20\text{km})$. The initial velocity of the interceptor and the target is 1000m/s and 1500m/s. Given the initial relative position and velocity, the weight coefficient can be obtained through the fuzzy logic controller, and the result is k_2=14.The step-maneuvering overload and weave-maneuvering overload of the target are $70\,\text{m/s}^2$ and $200\,\text{m/s}^2$, respectively. The frequency of the weave maneuver is 3rad/*s*. The initial heading angle of the missile is the initial line-of-sight angle, and the initial heading error is -20°. The preset impact angle is 10°. The acceleration command is bounded within $[-400\,\text{m/s}^2, 400\,\text{m/s}^2]$. The time step is 0.01 s, and the prediction horizon is 0.5 s. The Runge-Kutta method is used to integrate the differential equation to predict the future state. In addition, the parameters of PSO are given as i=100, j=100, w=0.5, c_1=1, and c_2=1. The initial particles are initialized randomly between -400 and 400, $V_{i,j}$ is initialized randomly between -10 and 10.

Case 1. Nonmaneuvering target

Simulation results are depicted in Figure 4. As can be seen from Figure 4(a), the flight trajectory of NPSOG is quite different from that of PSOG and IPSGO, but it can successfully intercept the hypersonic target. The acceleration requirements for three guidance laws are displayed in Figure 4(b). We can see that the acceleration requirements of NPSOG are less than the other algorithm in the initial stage; however, more commanded acceleration is required for NPSOG to reach the desired line-of-sight angle that can be observed from Figure 4(c). In addition, it can be seen from Figure 4(c) that when PSOG and IPSGO are used to

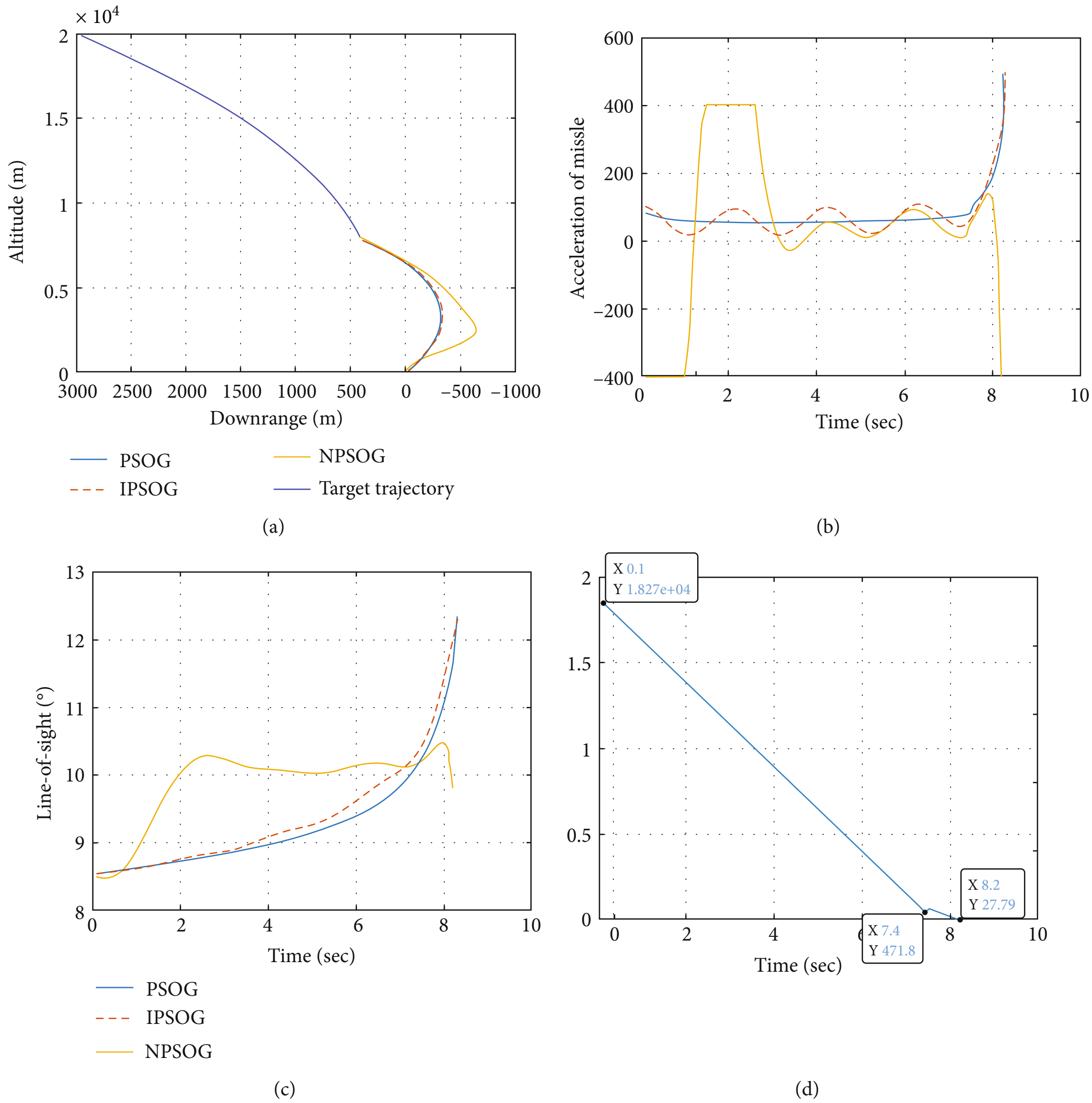


Figure 5: Simulation results of intercepting step-maneuvering hypersonic targets.

intercept the target, and the desired angle cannot be achieved, so it is difficult to improve the damage effect on the target. Figure 4(d) shows the curve of performance index. In the process of intercepting target, performance index decreases continuously and tends to 0, which also indicates that each item of performance index tends to 0. When $J^1 = k_1|\lambda\text{-}\lambda_r|$ tends to 0, it means that when the missile collides with the target, the angle constraint can be satisfied. $J^2 = k_2|\dot{\lambda}|$ tending to 0 indicates that the line-of-sight rate is small, which can reduce the overload requirement of missile. When $J^3 = k_3|\mathrm{RTM}|$ approaches 0, it indicates that the missile and the target are approaching, and the collision between the missile and the target can be finally achieved.

Case 2. Step-maneuvering target

In this scenario, the target makes a step maneuver. The engagement trajectory is presented in Figure 5(a), and interceptions are achieved successfully with PSOG, IPOSG, and NPSOG. We can see from Figure 5(b) that NPSOG requires more acceleration than PSOG and IPOSG to hit the maneuvering target. Figure 5(c) depicts that the NPSOG can reach the desired line-of-sight angle, while PSOG and IPSGO are not restricted by angle constraint. Figure 5(d) shows the curve of performance indexes. When intercepting the step maneuvering target, performance indexes still show a decreasing trend and tend to 0. Therefore, NPSOG can not only ensure that the missile successfully intercepts the target, but also meets the angle constraint condition to improve the damage effect on the target.

Case 3. Weave-maneuvering target

Here, a sinusoidal maneuver is executed by the target. Simulation results are shown in Figure 6. Again, we can see that the hypersonic target is intercepted by missile in Figure 6(a). Figure 6(b) shows that the acceleration

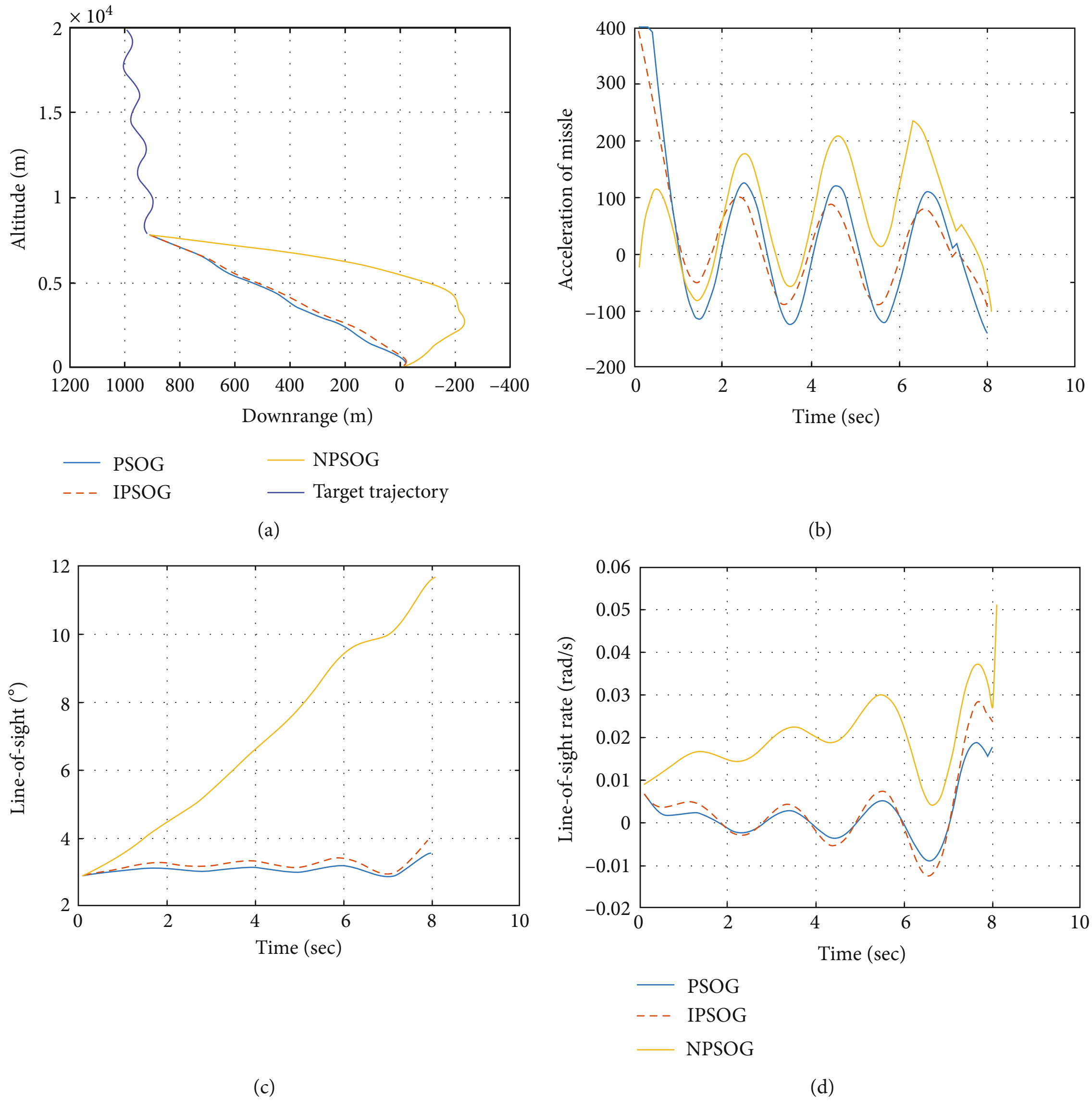


FIGURE 6: Simulation results of intercepting weave-maneuvering hypersonic targets.

requirements of NPSOG is small compared to the other algorithm in the initial stage, because the PSOG and INPSOG need more acceleration to reduce the influence of heading error, and then, the acceleration commands become stable, which is identical to the NPSOG. It can be observed from Figures 6(c) and 6(d) that the higher line-of-sight rate of NPSOG is the reason for line-of-sight angle to reach the desired line-of-sight angle.

When the target performs the sinusoidal maneuver, the value of the performance index J and the value of each item J^1, J^2, and J^3 are shown in Figure 7. Figure 7(a) shows the curve of performance index. Similar to Figure 4(d) and Figure 5(d), performance index shows a decreasing trend in the process of missile intercepting targets. It can be seen from Figure 7(b) that the deviation between the actual angle λ and the desired angle λ_r gradually decreases. When deviation tends to 0, it will perturb near 0. Since the perturbation is small, it can be considered that the angle constraint can be satisfied. Figure 7(c) shows the curve of the second term $J^2 = k_2|\dot{\lambda}|$. It can be seen from the figure that the disturbance of the line-of-sight rate is large in the late interception period. The reason is that when the distance between the missile and the target is close, the influence of the target's sinusoidal maneuver is more obvious. Figure 7(d) shows the curve of the third item $J^3 = k_3|\mathrm{RTM}|$. It can be seen from the figure that the distance between the missile and the target will eventually tend to 0; that is, the missile can successfully intercept the target.

4.2. Comparison with Nonheuristic Guidance Laws. In this section, the NPSOG is compared with several nonheuristic guidance laws with impact angle constraint, including the nonsingular terminal sliding mode control guidance (NTSMG) [21], the nonsingular fast terminal sliding mode

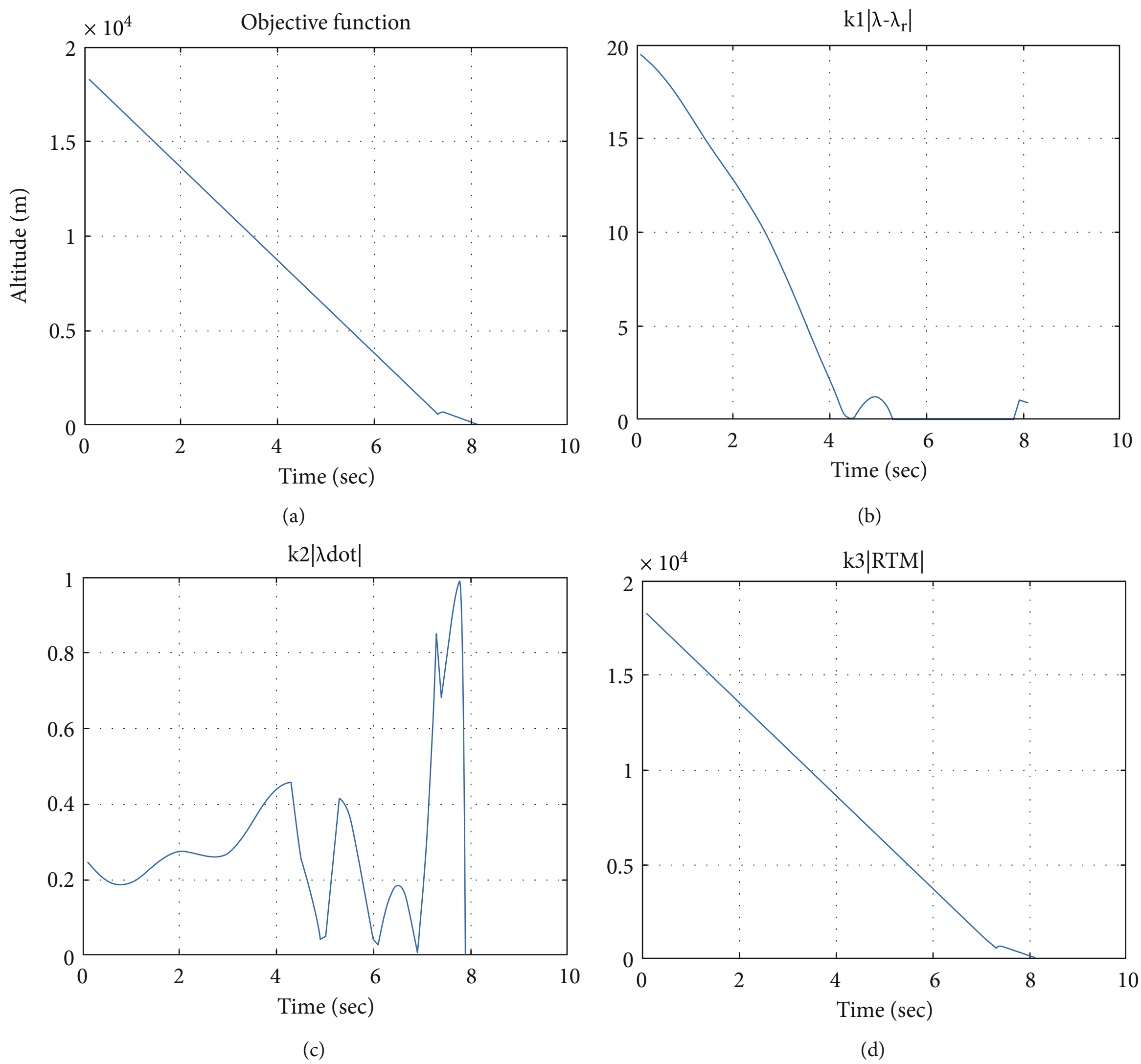


Figure 7: Performance index of intercepting weave-maneuvering hypersonic targets.

Table 2: The initial condition for the missile and target.

R_{M1}	0	λ	60°	R_{M1}	$2500\sqrt{3}$m	β	0°
R_{M2}	0	V_M	600m/s	R_{M2}	2500 m	V_T	300m/s

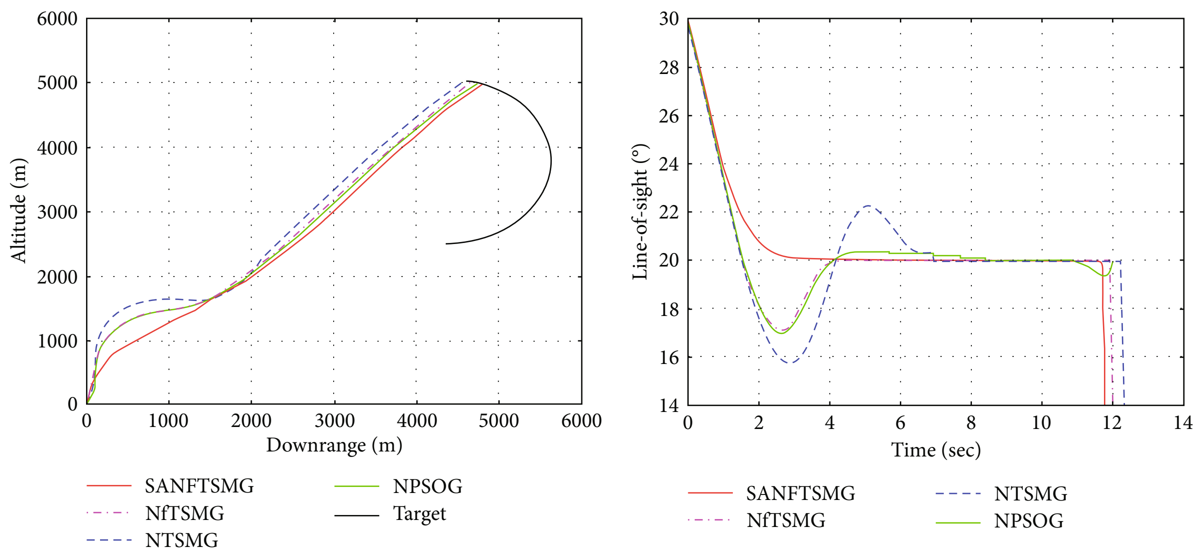
control guidance (NFTSMG) [22], and the smooth adaptive nonsingular fast terminal sliding mode guidance (SANFTSMG) law [23]. The parameters, required for the simulation, are selected according to [23] as given in Table 2. The simulation results are as follows.

Figures 8(a) and 9(a) show the engagement trajectories of the missile and the target. Figures 8(b) and 9(b) show the line-of-sight profile with different guidance laws. It can be seen from the simulation results that the missile can successfully intercept the target. The miss distance and interception time are shown in Table 3, and compared with other guidance methods, the NPSOG can also achieve a small miss distance, so as to ensure accurate interception of the target. From Figures 8(b) and 9(b), we can observe that these four kinds of guidance laws can all guarantee that the LOS angle converges to the neighborhood of the desired line-of-sight. When the missile adopts the NPSOG, although there is a small fluctuation of line-of-sight angle, it will gradually adjust to the desired value when it deviates from the desired value.

4.3. Computational Cost. The simulations of NPSOG are implemented in a MATLAB environment, and the main configuration of the computer is 2.1 GHz CPU and 16 GByte RAM. The computing time of each guidance command is approximately 0.006 seconds, while the sampling time of the problem is 0.01 s, so the real-time requirement is met. Moreover, it is evident that using C++ programming language will greatly improve the real-time performance of the algorithm.

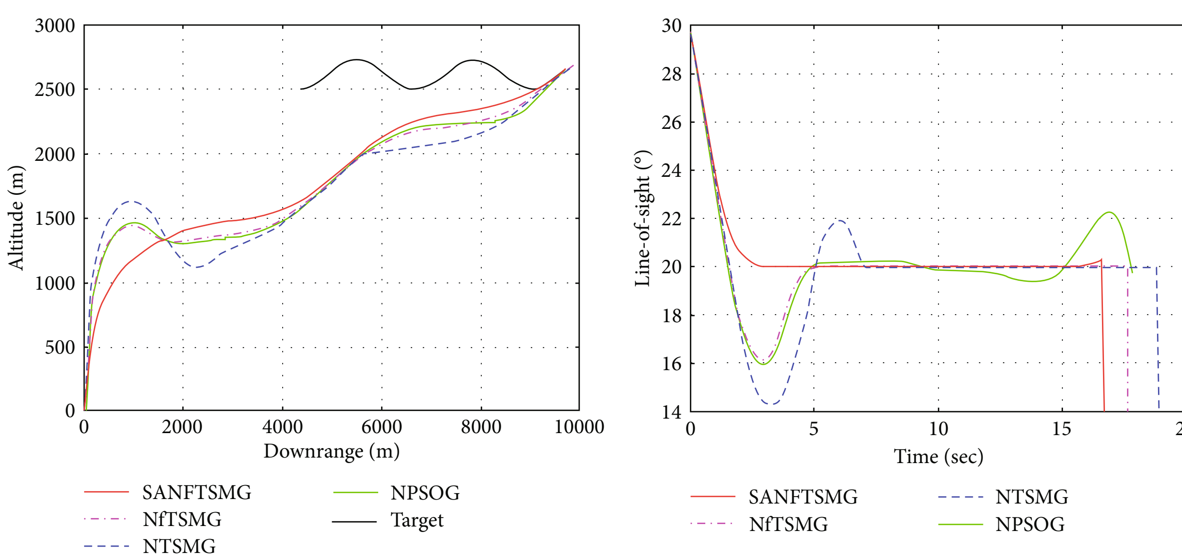
5. Conclusion

In this work, a heuristic guidance method, called NPSOG, is designed for hypersonic target interception. First, the



(a) (b)

Figure 8: Simulation results of intercepting step-maneuvering targets.



(a) (b)

Figure 9: Simulation results of intercepting weave-maneuvering targets.

Table 3: The miss distance and interception time with different guidance law.

	Step-maneuvering targets			Weave-maneuvering targets	
Guidance law	Interception time (s)	Miss distance (m)	Guidance law	Interception time (s)	Miss distance (m)
SANFTSMG	11.840	0.012	SANFTSMG	16.697	0.112
NFTSMG	12.105	0.013	NFTSMG	17.815	0.077
NTSMG	12.378	0.391	NTSMG	18.985	0.003
NPSOG	12.010	0.062	NPSOG	17.920	0.018

dynamics engagement model is established to predict the future state during prediction horizon. Then, the objective function is constructed by weighting line-of-sight, line-of-sight rate, and relative distance. The weight coefficients among the three are adaptively adjusted by the fuzzy logic controller. Moreover, The PSO algorithm is used to drive the optimal acceleration command. Finally, the performance of the NPSOG was compared with PSOG, IPSOG, SANFTSMG, NFTSMG, and NTSMG. Simulation results show that the NPSOG algorithm exhibits the robust pursuit capability to different escape strategies. Compared with other heuristic guidance methods, although the NPSOG needs more acceleration requirements than the PSOG and IPSOG, the extra control effort is used to achieve impact angle, so the NPSOG has a better performance than the other techniques for hypersonic target interception. Compared with other nonheuristic guidance methods, the NPSOG can also achieve smaller miss distance and desired line-of-sight angle. As a brief summary, the performance of NPSOG is superior to the heuristic guidance methods, and similar to the performance of the nonheuristic guidance methods mentioned in this paper.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Acknowledgments

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