Aiming Point Guidance Algorithm Based on Proportional Navigation Guidance Scheme

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Abstract: The proposed missile guidance algorithm is developed based on proportional navigation guidance scheme and the computation of aiming point. This research calculates the line-of-sight rate and the position of aiming point according to the current dynamics of missile and target, and applies particle swarm optimization to optimize and update the navigation constants of proportional navigation guidance continuously to figure out the missile control commands of lateral acceleration. Therefore, the missile will be guided to the aiming point as the computed target collision position. Simulation experiments prove the proposed guidance algorithm has the satisfied interception performance in a three dimensional engagement space with noise disturbance. The proposed method uses the shorter miss distance and less interception time compared with the proportional navigation guidance law and this could reduce the energy consumption as well. Besides, the outstanding guidance ability would be more obvious for intercepting the high agility aircraft. The proposed guidance algorithm is feasible to be applied to the real missile guidance system due to the advantages of simplicity and robustness.

Keywords: Missile; Guidance; Particle swarm optimization; Proportional navigation guidance.

1. INTRODUCTION

The famous proportional navigation guidance (PNG) law has been widely applied to the real missile system due to the simplicity and effectiveness. PNG performs well for intercepting the weak maneuvering target. However, the excess miss distance is often produced when PNG is applied to treat the high agility aircraft by using the big guidance commands at the terminal stage (Cho and Ryoo, 1999).

Missile guidance algorithms have been developed for several decades and contain many different types of development. However, these developed guidance algorithms can be basically divided into the following categories: First one develops the guidance algorithms based on the line-of-sight (LOS) throughout the engagement of target-missile. The principle for LOS guidance is to force a missile to fly as close as possible along the instantaneous LOS joining the ground tracker and the target (Lin and Hsu, 2002). Pursuit guidance (PG) law steers the velocity direction of missile to the target position all the time. Second one is proposed based on the bearing course guidance method which produces the heading angle to steer the missile on the collision course by decreasing the rotating rate of LOS such as the well-known proportional navigation guidance law (PNG), augmented PNG and modified PNG (Adler, 1956; Newman, 1996; Yuan, 2012). Third one guides the missile to the predicted engagement course. In this algorithm, the current motion state of missile and target are used to compute the predicted engagement course and update the guidance rules (Song and Tahk, 1998; Song and Tahk, 1999; Lin et al, 2010; Kim and Kim Y., 2004). Besides, artificial intelligence algorithms have been utilized to develop the guidance law for several decades. Fuzzy logic theory and neural network algorithm are widely applied to promote the guidance performance of missile control system. However, the input parameters and training samples of neural network deeply influence the guidance ability and the operation of fuzzy logic theory would increase the storage burden of computer (Steck and Balakrishnan, 1994; Song and Tahk, 2001; Song and Tahk, 2002; Mishra et al., 1994; Omar and Abido, 2010). Particle swarm optimization (PSO) has been used to design the missile guidance law in 2013 and the design of cost function would lead the missile moving towards the current target position just like the PG algorithm. The improved version applied the LOS rate to be the cost function to promote the guidance performance successfully (Kung and Chen, 2013; Chen et al., 2016).

It is very difficult to design a missile guidance law to intercept the maneuvering target and most of existing research papers in this field is restricted in a special study case (Razmjooei and Shafiei, 2016). Besides, these research papers of the missile guidance algorithms are hardly applied to the real-time target-interceptor game due to the problems of storage burden and computation speed in the guidance control systems. PNG has the advantages of simplicity and robustness that it has been widely applied to different missile guidance systems. However, the performance would be degraded for intercepting the high agility target. In this paper, an aiming point guidance algorithm has been developed based on PNG scheme and the application of PSO algorithm. The configuration of this paper is organized as follows: The dynamic mathematical equations of missile and target in the three dimensional (3-D) environment are described in section 2. Section 3 explains the operation steps of the proposed algorithm. Section 4 illustrates the performance of PNG and the proposed algorithm in different pursuit-evasion scenarios and the conclusion is in section 5.

2. DYNAMIC EQUATIONS OF TARGET AND MISSILE

The aerodynamic models of target and missile in the 3-D inertial coordinate are shown in Fig. 1. The missile model is built as a point-mass and the gravity centre is influenced by the aerodynamic effect. The skid-to-turn technique consists of the lateral acceleration control commands in pitch and yaw direction and that is used to guide the missile flight route. The following mathematical equations are used to describe the missile dynamics (Fumiaki, 1993):

$$\dot{x}_m = v_m \cos\gamma_m \cos\sigma_m \tag{1}$$

$$\dot{y}_m = v_m \cos\gamma_m \sin\sigma_m \tag{2}$$

$$\dot{z}_m = v_m \sin\gamma_m \tag{3}$$

$$\dot{v}_m = \frac{F_t - F_d}{m_m} - g\sin\gamma_m \tag{4}$$

$$\dot{\gamma}_m = \frac{a_p - g\cos\gamma_m}{v_m} \tag{5}$$

$$\dot{\sigma}_m = \frac{a_y}{v_m \cos\gamma_m} \tag{6}$$

$$\dot{a}_p = \frac{C_p - a_p}{\tau_m} \tag{7}$$

$$\dot{a}_y = \frac{C_y - a_y}{\tau_m} \tag{8}$$

$$F_d = \rho_1 v_m^2 + \rho_2 \frac{C_p^2 + C_y^2}{v_m^2} \tag{9}$$

where x_m, y_m, z_m denotes the missile position, v_m denotes the missile velocity, m_m denotes the mass, σ_m and γ_m are yaw angle and pitch angle respectively, F_t and F_d are thrust and drag force applied to the missile respectively. a_p and a_y are lateral acceleration along the direction of pitch and yaw that are used to change the flight route of missile, C_p and C_y are the control commands respectively. τ_m denotes the time delay constant. ρ_1, ρ_2 are drag coefficients. g is the gravity acceleration.

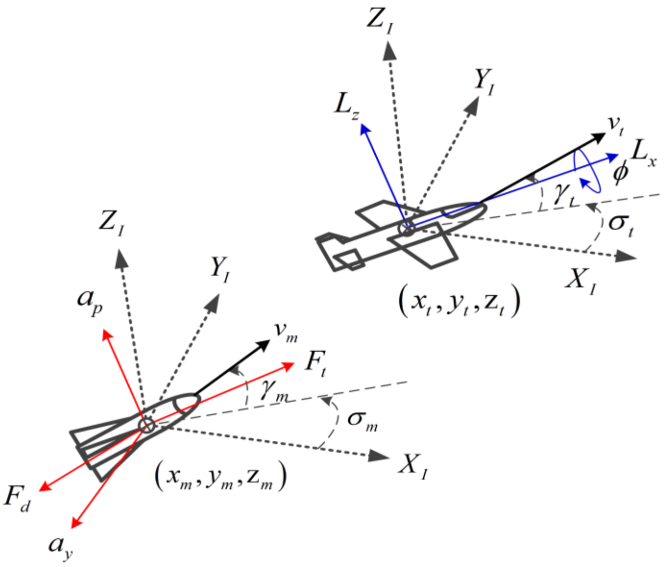

Fig. 1. Aerodynamic models of target and missile in the 3-D inertial coordinate.

In order to prove the interception performance of the proposed guidance algorithm, the target motion mathematical equations have to simulate the real target motion state as much as possible. In this paper, the target model is built as a point-mass and the flight route can be changed by three different control commands. The following mathematical equations are used to describe the target motion state:

$$\dot{x}_t = v_t \cos\gamma_t \cos\sigma_t \tag{10}$$

$$\dot{y}_t = v_t \cos\gamma_t \sin\sigma_t \tag{11}$$

$$\dot{z}_t = v_t \sin\gamma_t \tag{12}$$

$$\dot{v}_t = g\left(L_x - \sin\gamma_t\right) \tag{13}$$

$$\dot{\gamma}_t = \frac{g}{v_t}\left(L_z \cos\phi - \cos\gamma_t\right) \tag{14}$$

$$\dot{\sigma}_t = \frac{gL_z \sin\phi}{v_t \cos\gamma_t} \tag{15}$$

$$L_x = \frac{L_{xc}}{1 + s\tau_{tx}} \tag{16}$$

$$L_z = \frac{L_{zc}}{1 + s\tau_{tz}} \tag{17}$$

$$\phi = \frac{\omega_n^2}{s^2 + 2\omega_n \xi s + \omega_n^2} \times \phi_c \tag{18}$$

where x_t, y_t, z_t denotes the target position, v_t denotes the target velocity, σ_t and γ_t are yaw angle and pitch angle respectively. The target flight route can be changed by three different control commands L_x, L_z, ϕ . The three control commands produced by the pilots named L_{xc}, L_{zc}, ϕ_c could not coincide with L_x, L_z, ϕ because of the inertia influence. Therefore, the time delay constants τ_{tx}, τ_{tz}, damping ratio ξ and natural frequency ω_n are utilized in this target model (Sun *et al.*, 2008).

3. PROPOSED GUIDANCE ALGORITHM

3.1 PNG Algorithm and Computation of Aiming Point

PNG is a mature guidance technology and widely applied to different missile systems. PNG mainly utilizes LOS rate and the missile velocity to produce the guidance control commands of lateral acceleration in a 3-D space as follows:

$$C_p = K_p v_m \dot{\psi} + g\cos\gamma_m \tag{19}$$

$$C_y = K_y v_m \dot{\theta} \tag{20}$$

where K_p, K_y denote navigation constants, $\dot{\psi}, \dot{\theta}$ denote LOS rate shown in Fig. 2.

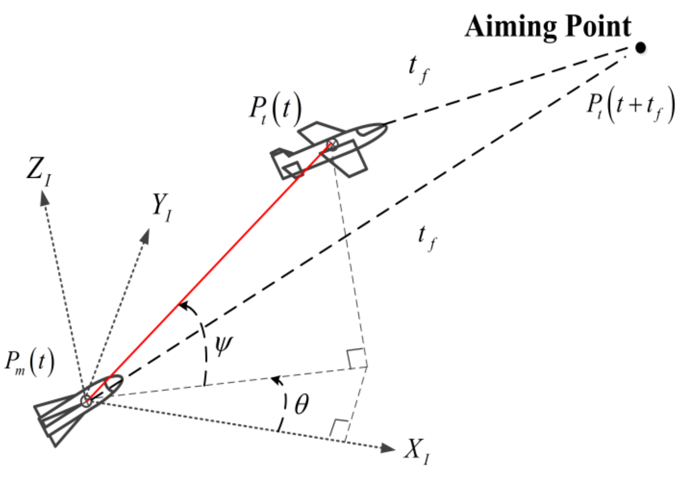

Fig. 2. Illustration of pursuit-evasion game.

In this paper, the computation of aiming point obeys the following assumptions:

1. The future position of the missile and the target will be the same after moving a period of time (t_f) shown in Fig. 2.
2. The target and the missile will move at constant velocity during the flight time (t_f) and straightly towards to the future position called aiming point $P_t(t+t_f)$ in this paper.
3. The flight time (t_f) can be computed according to the position of target $P_t(t+t_f)$ and missile $P_m(t)$ by Eq. (21):

$$t_f = \frac{P_t(t+t_f) - P_m(t)}{v_m} \tag{21}$$

4. Eq. (21) is an extremely nonlinear and complicated mathematical equation and Newton-Raphson method can be used to figure out the approximated numerical solution effectively.

3.2 Particle Swarm Optimization (PSO)

PSO algorithm develops based on the imitation of birds foraging behaviour and that is extensively applied to optimization research. PSO is an efficient optimization algorithm with fast computation speed. PSO utilizes a population of candidate solutions produced randomly to solve the problem. A particle denotes a solution for the optimum of problem and continuously searches for the local optimal solution in the problem space according to the definition of fitness function; meanwhile, these particles of local optimal solution would be compared as well for getting the global optimal solution during the evolutionary process (Eberhart, 1995; Kennedy, 1995). PSO consists of three operation steps mainly as follows:

1. Evaluate the fitness value of each particle.
2. Update the local optimum and global optimum during the iteration process.
3. Update the particle position and velocity.

$$\begin{aligned} V_i(k+1) &= wV_i(k) + c_1 r_1 \left(S_i(k) - X_i(k)\right) \\ &+ c_2 r_2 \left(G_g(k) - X_i(k)\right) \end{aligned} \tag{22}$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \tag{23}$$

where $1 \le i \le m$, m denotes the particle numbers, V_i denotes the particle velocity, X_i denotes the particle position, k denotes the iteration time, w denotes the inertia weight, r_1, r_2 are the random numbers in the interval (0, 1), c_1, c_2 are the positive constants named learning factors. S_i, G_g are the local optimum and global optimum respectively.

3.3 AIMING POINT GUIDANCE ALGORITHM BASED ON PROPORTIONAL NAVIGATION GUIDANCE SCHEME (APG-PNG)

The authors utilize the PNG scheme and the computation of aiming point to develop the aiming point missile guidance algorithm. This research calculates LOS rate and the position of aiming point according to the current dynamics of missile and target, and applies PSO to optimize and update the navigation constants of PNG continuously to figure out the missile control commands of lateral acceleration. The fitness function of PSO is defined as the relative distance between the position of aiming point and the future missile position at next time interval. During PSO evolution steps, the value of fitness function for each particle is computed. The missile will be steered towards the computed aiming point to intercept the target when the value of fitness function is the minimum. Fig. 3 is the flow chart of the proposed guidance algorithm and the detailed operation procedure has been explained as follows:

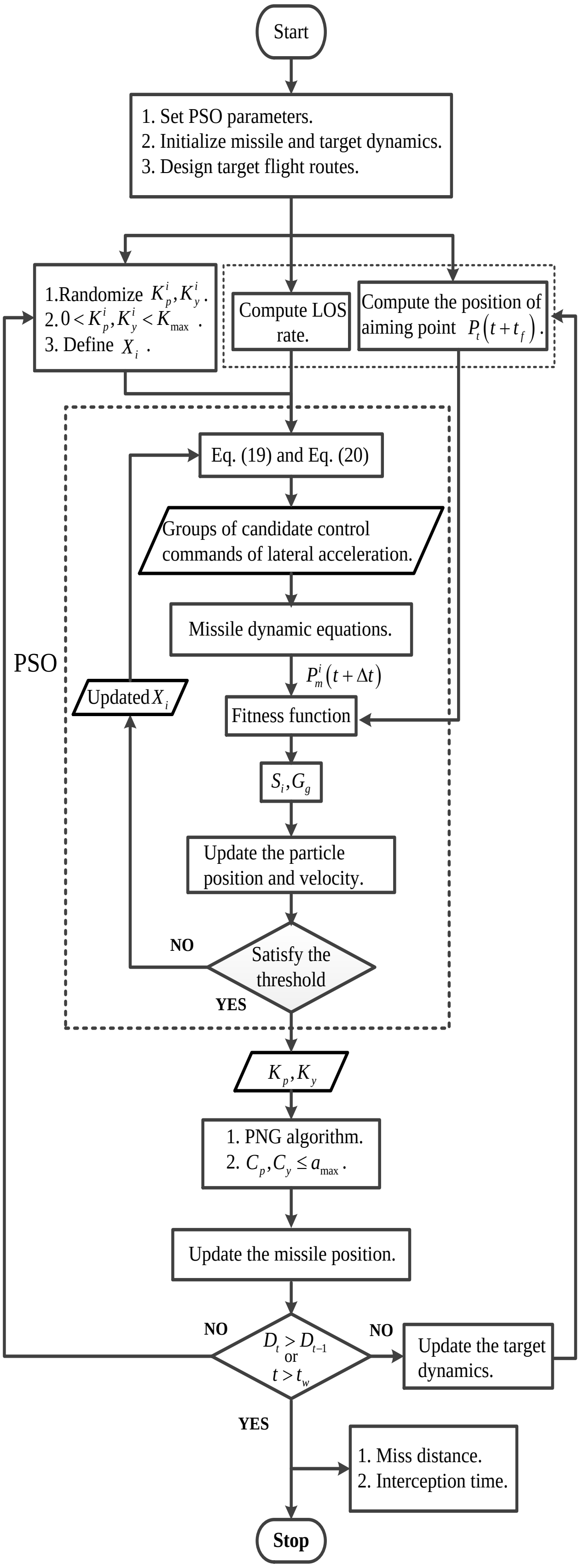

Fig. 3. Flow chart of the proposed guidance algorithm.

(1) Set PSO parameters including particle amounts, inertial weight, learning factors and iteration times. It needs to initialize the parameters of the dynamic equations of target and missile and input the target control commands to design the flight route, and then apply Runge Kutta method to execute the simulation experiments of pursuit-evasion game.

(2) Compute LOS rate and the position of aiming point $P_t(t+t_f)$ according to the current dynamics of missile and target. The navigation constants of PNG are designed as a two-dimension particle in PSO. The position of each particle is defined as $X_i = \left[K_p^i \quad K_y^i\right]$, $1 \le i \le m$, m denotes the particle numbers. The amount of solution for the optimum of problem is equal to particle numbers which are initialized randomly, and the value of PNG navigation constants is defined in the interval $0 < K_p^i, K_y^i < K_{\max}$.

(3) Apply LOS rate and K_p^i, K_y^i to the Eq. (19) and Eq. (20) for computing the groups of candidate control commands of lateral acceleration which are used in the missile dynamic equations to compute the future missile position at next time interval $P_m^i(t+\Delta t)$.

$$C_p^i = K_p^i v_m \dot{\psi} + g\cos\gamma_m \tag{24}$$

$$C_y^i = K_y^i v_m \dot{\theta} \tag{25}$$

(4) The fitness function of PSO is defined as the relative distance between $P_t(t+t_f)$ and $P_m^i(t+\Delta t)$.

$$\Phi_D = P_t(t+t_f) - P_m^i(t+\Delta t) \tag{26}$$

(5) Compute the fitness value of each particle and the local optimal solution is the minimal fitness value defined as $S_i = \min(\Phi_D)$ during the recursive steps. The global optimal solution is defined as G_g when this particle in the population has the minimum fitness value during the evolutionary process.

(6) Update each particle's position and velocity.

(7) Define the standard deviation as the threshold for the stop of evolutionary. Repeat the procedure from step 3 to step 6 until the threshold is satisfied. The optimal navigation constants (K_p, K_y) of PNG can be computed at this step.

(8) Apply K_p, K_y to figure out the optimal lateral acceleration control commands of the missile (C_p, C_y) which are smaller the maximum acceleration $a_{\max}$ based on the body structure and dynamic ability of the missile.

(9) Update the missile position.

(10) Repeat the procedure from step 2 to step 9 to figure out the miss distance and interception time. The calculation of APG-PNG algorithm will stop if $D_t > D_{t-1}$ or $t > t_w$. The relative distance (D_t) between the missile and the target and the missile thrust working time (t_w) are designed as the ending rule.

4. SIMULATION EXPERIMENTS

In the simulation experiments, the measurement data are combined with noise disturbance to verify the performance and feasibility of the proposed guidance algorithm. The missile would change the mass and the thrust over time shown in Fig. 4. The proposed research (APG-PNG) would be used to compare with PNG algorithm using different navigation constants for the performance certification.

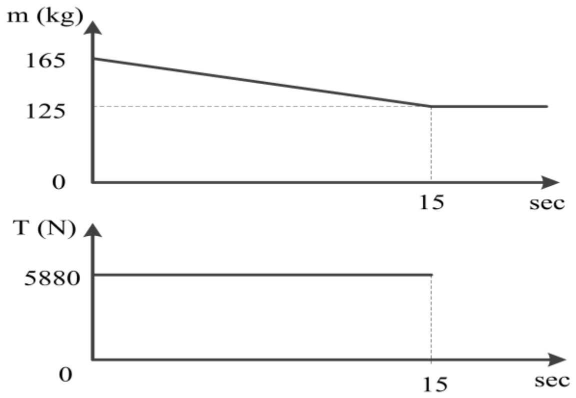

Fig. 4. Profiles of missile mass and thrust.

Table 1. Initial conditions of target and missile.

Item	X axis (m)	Y axis (m)	Z axis (m)	speed (m/sec)	Pitch angle (degree)	Yaw angle (degree)
Target	3000	3000	2000	300	0	0
Missile	1000	1000	1000	680	0	0

Note:

The missile maximum acceleration tolerance is designed as $a_{max} = 30g$ (g is the gravity acceleration).

The simulation platform applies the inertial coordinate to describe the 3-D engagement scenarios of target-interceptor. The initial conditions of simulation experiments are set as follows: Table 1 is the initial conditions of target and missile, time delay constants $\tau_{tx}, \tau_{tz}, \tau_m = 0.1$, natural frequency $\omega_n = 10$, damping ratio $\xi = 0.7$, drag coefficients $k_1 = 0.001$, $k_2 = 1$, sampling time is 0.02 second, the value of navigation constants of proposed guidance algorithm is defined in the interval (0, 6). PSO parameters are set as follows: particle numbers $m = 100$, inertial weight $w = 0.5$, learning factors $c_1, c_2 = 1$, maximum evolution times is 500, and the threshold value is 0.01. White Gaussian noise has been applied to the measurement data which contains the target position, velocity, pitch angle and yaw angle. Signal noise ratio is 50 (SNR=50). In the same scenario, the simulation results of experiment in each time would produce a little bit difference due to the noise disturbance. Therefore, Montel Carol method has been applied to the simulation experiments by 100 times.

Table 2 shows the guidance performance of PNG using different navigation constants (PNG-3~6) and APG-PNG in two different engagement scenarios of target-interceptor. In Scenario A, the target moves in a closely straight-line weak maneuvering shown in Fig. 5. APG-PNG has the shortest interception time. The miss distances of PNG-5 and APG-PNG are almost the same minimum. PNG-3 is the worst of all. In Scenario B, the target moves at acceleration initially and then turns with the big G-force shown in Fig. 6. APG-PNG has the best performance. The miss distance of PNG-5 is the maximum. PNG-3 has the longer interception time but the shorter miss distance compared with other PNG algorithms in this simulation experiment. Fig. 7 and Fig. 8 illustrate the history of missile control action in Scenario A and Scenario B. These figures show APG-PNG would change the missile motion state obviously at the initial pursuit stage. Besides, APG-PNG would greatly steer the missile at the initial pursuit stage because of the maneuvers of the target with big-G force and slightly revise the missile flight route at the middle stage compared with PNG-5 and PNG-3. Fig. 9 and Fig. 10 illustrate the history of guidance commands in Scenario A and Scenario B. These figures prove APG-PNG uses the big guidance commands to change the missile motion state at the initial pursuit stage and that PSO starts to work to optimize the navigation constants of PNG. The guidance commands of APG-PNG at the middle pursuit stage are obviously smaller than PNG-5 and PNG-3. The curve of guidance commands would produce huge oscillation due to the measurement data accompanied with noise disturbance when the missile gradually moves close to the target at the terminal stage. As a result, the guidance technique of APG-PNG is to compute the effective collision course that would lead to the big curved flight route of missile at the initial pursuit stage and then APG-PNG will steer the missile in an efficient way during the pursuit process.

In order to prove the effectiveness of the proposed guidance algorithm, the authors design the Scenario C in which the target would move with S-turn to evade the missile attack. Table 3 explains APG-PNG and PNG-6 has the same shortest interception time but APG-PNG has the minimum miss distance. The guidance ability of PNG-3 is the worst. Fig. 11 show the flight routes of APG-PNG and PNG-6 are closely similar. However, APG-PNG could steer the flight route of missile to the effective collision course compared with PNG-6 at the initial pursuit stage shown in Fig. 12. Fig. 13 explains APG-PNG uses PSO to optimize the navigation constants of PNG which leads to the bigger missile control commands of lateral acceleration at the initial pursuit stage. APG-PNG would continuously update the navigation constants of PNG and guide the missile to the computed target collision position according to the target motion state. Therefore, the proposed guidance algorithm is feasible to be applied to the missile guidance system because of simplicity and effectiveness and has the satisfied guidance performance.

Table 2. Guidance performance of PNG-3~6 and APG-PNG in Scenario A and Scenario B.

Scenario	Guidance algorithm	Navigation constants	Miss distance (m)	Interception time (sec)
A	PNG-3	3	**9.35**	**5.80**
A	PNG-4	4	7.11	5.74
A	PNG-5	5	**6.25**	5.72
A	PNG-6	6	8.63	**5.72**
A	APG-PNG	$0<K_p^i, K_y^i<6$	**6.68**	**5.70**
B	PNG-3	3	**7.82**	**5.28**
B	PNG-4	4	8.93	5.24
B	PNG-5	5	**10.90**	5.24
B	PNG-6	6	8.56	**5.22**
B	APG-PNG	$0<K_p^i, K_y^i<6$	**7.18**	**5.22**

Table 3. Guidance performance of PNG-3~6 and APG-PNG in Scenario C.

Scenario	Guidance algorithm	Navigation constants	Miss distance (m)	Interception time (sec)
C	PNG-3	3	**9.88**	**5.48**
C	PNG-4	4	8.97	5.44
C	PNG-5	5	9.55	5.42
C	PNG-6	6	**8.95**	**5.40**
C	APG-PNG	$0<K_p^i, K_y^i<6$	**7.59**	**5.40**

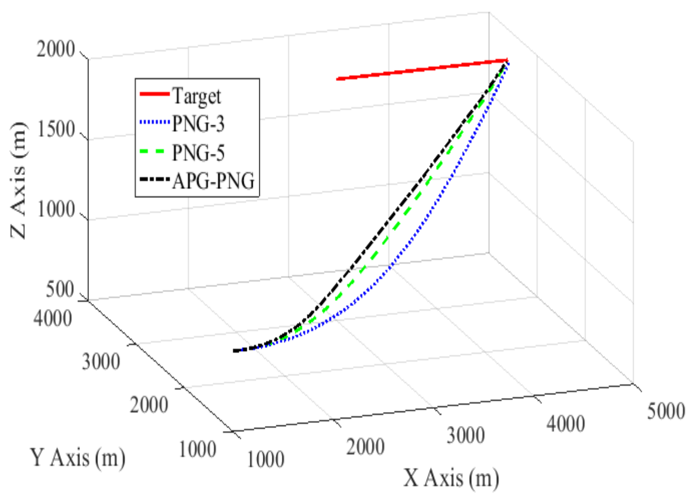

Fig. 5. Engagement of target-interceptor in Scenario A.

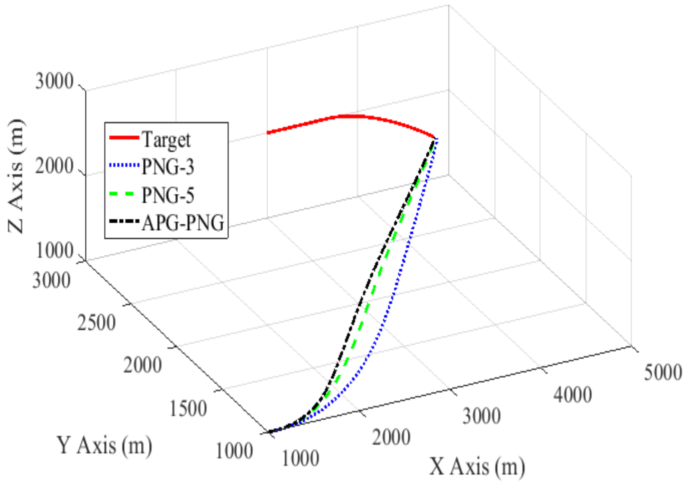

Fig. 6. Engagement of target-interceptor in Scenario B.

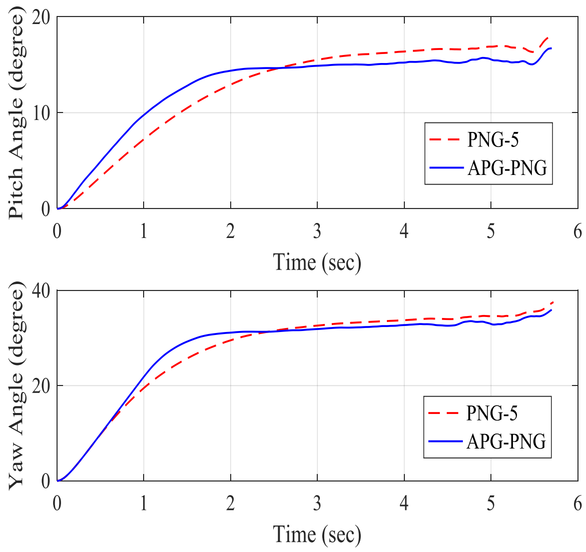

Fig. 7. History of missile control action in Scenario A.

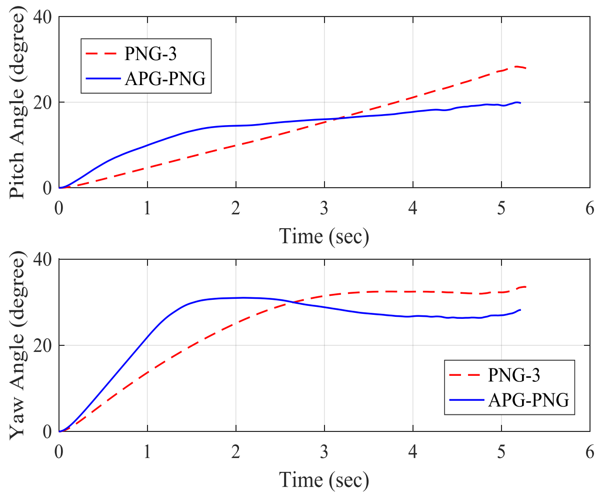

Fig. 8. History of missile control action in Scenario B.

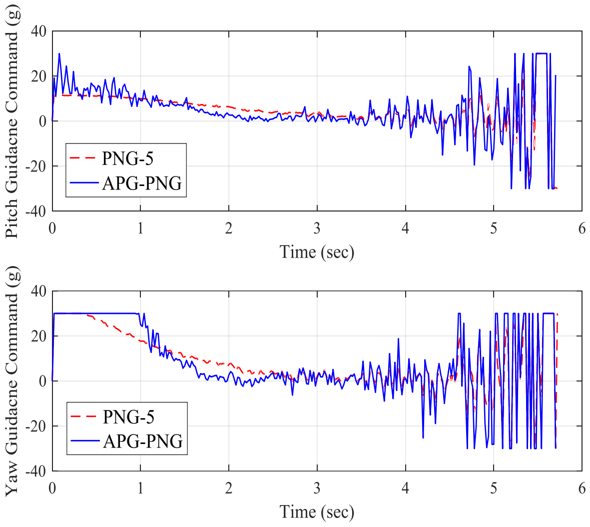

Fig. 9. History of guidance commands in Scenario A.

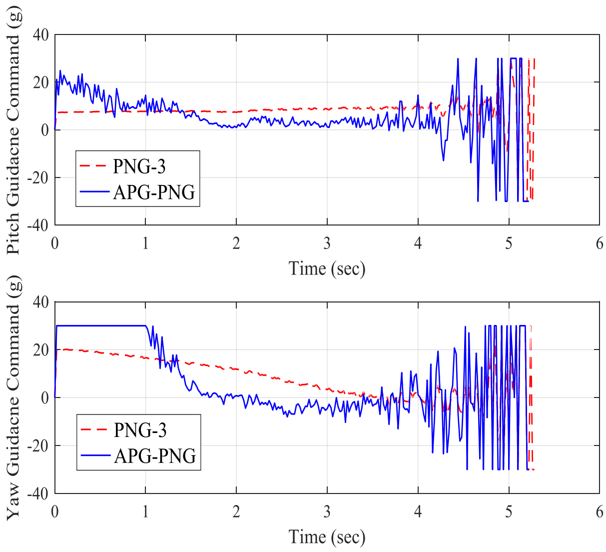

Fig. 10. History of guidance commands in Scenario B.

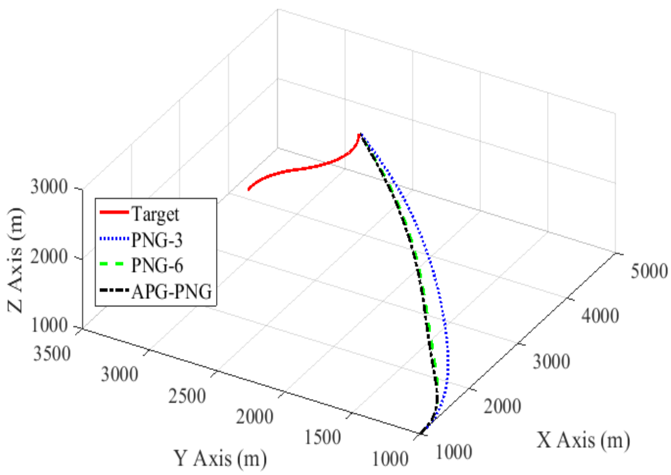

Fig. 11. Engagement of target-interceptor in Scenario C.

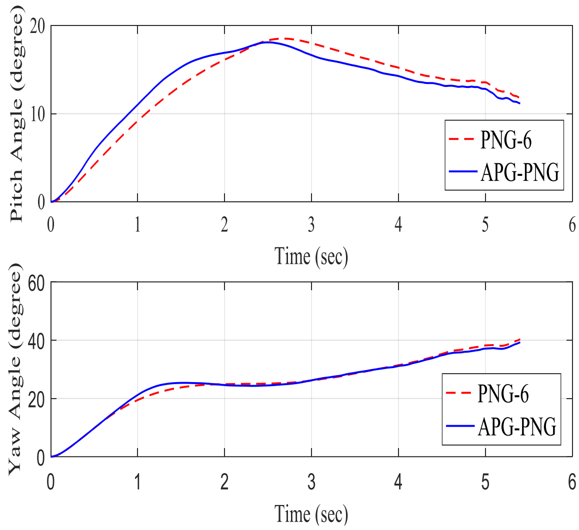

Fig. 12. History of missile control action in Scenario C.

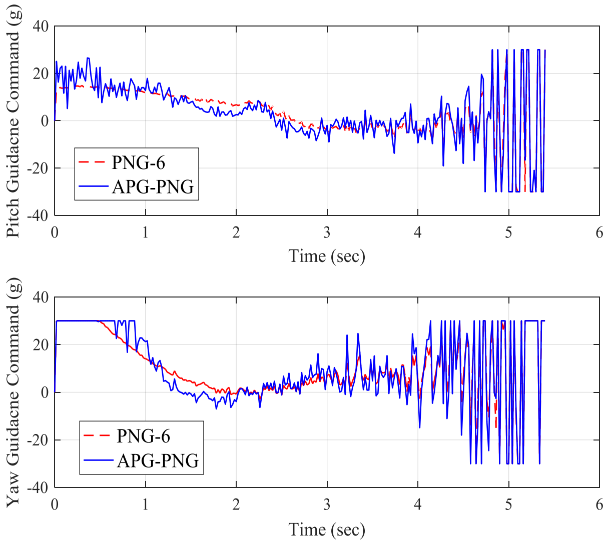

Fig. 13. History of missile control action in Scenario C.

5. CONCLUSIONS

It is very difficult to develop the real-time missile guidance law applied to the missile guidance system in the army. Most of missile guidance researches are not suitable for the real application due to the theory complexity, storage burden of computer and restriction for the special study case, etc. PNG algorithm has been widely applied to the missile guidance system because of simplicity and robustness but the guidance performance would be unsatisfied to the high agility maneuvering target.

In this paper, the computation of aiming point, PSO algorithm and PNG guidance scheme are used to develop a real-time dynamic missile guidance algorithm. The simulation experiments prove the proposed guidance algorithm can guide the missile to the effective target collision course. The missile motion state changes a lot at the initial pursuit stage and slightly revise the missile flight route at the middle stage. The performance of proposed guidance algorithm is much better than PNG even if the simulation platform has been set up in a 3-D engagement space with noise disturbance. This research can be applied to the real missile guidance system because of simplicity and robustness just like PNG algorithm.

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