CEAI, Vol.23, No.1, pp. 72-81, 2021 Printed in Romania

Aiming Point Guidance Algorithm Based on Proportional Navigation Guidance Scheme

Y.-W. Chen*, K.-Y. Chen, Y.-L. Fang*****

**Department of Mechanical Engineering, Air Force Institute of Technology, Taiwan R.O.C. (e-mail: chenyiwei530@yahoo.com.tw).*
***National Chung-Shan Institute of Science and Technology, Taiwan R.O.C. (e-mail: KueiYi.Chen@gmail.com.)*
****Department of Aeronautics and Astronautics, Air Force Academy, Taiwan R.O.C. (e-mail: fangiack@gmail.com).*

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. The outstanding guidance ability would be more obvious for intercepting the high agility aircraft. Furthermore, a novel artificial intelligence missile guidance algorithm is reproduced to execute the simulation experiments to compare the guidance technique with the proposed method. 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. The interception performance of PNG might be degraded and ineffective to deal with a powerful maneuvering target. (Li et al., 2015).

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; Choi and Kim, 2016; Jeon and Lee, 2010; Yuan et al., 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 (Tahk et al., 2002; 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 (Song and Tahk, 2001; Song and Tahk, 2002; Lin et al., 2003; Omar and Abido, 2010; Wang and Hung, 2013; Wang and Chen, 2014; Choi et al., 2006; Lin et al., 2009; Hossain et al., 2013). Particle swarm optimization (PSO) has been used to design the missile guidance law in 2013 and the design of fitness 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 fitness function to promote the guidance performance successfully (Kung and Chen, 2013; Lee et al., 2016; 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, computation of aiming point 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.

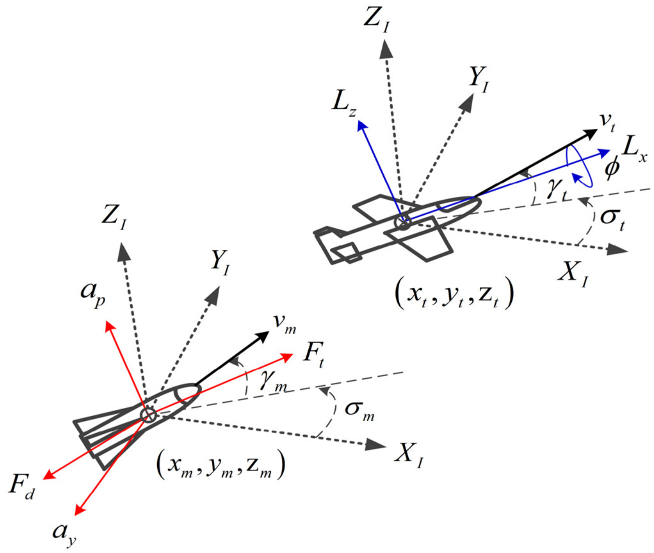

Fig. 1. Aerodynamic models of target and missile in the 3-D inertial coordinate.

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:

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

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

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

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

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

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

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

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

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

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.

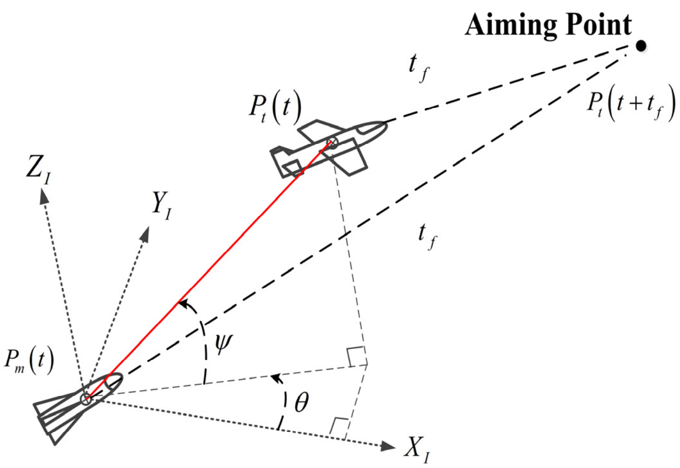

Fig. 2. Illustration of pursuit-evasion game.

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.

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

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

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:

(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 $P_t\left(t+t_f\right)$ 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 Eq. (7) and Eq. (8) of the missile dynamic equations to compute the future missile position $P_m^i\left(t+\Delta t\right)$ at next time interval.

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

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

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

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

(5) Compute the fitness value of each particle and the local optimal solution is the minimal fitness value defined as $S_i=\min\left(\Phi_D\right)$ 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 less than or equal to the maximum acceleration $a_{\max}$ based on the body structure and dynamic ability of the missile.

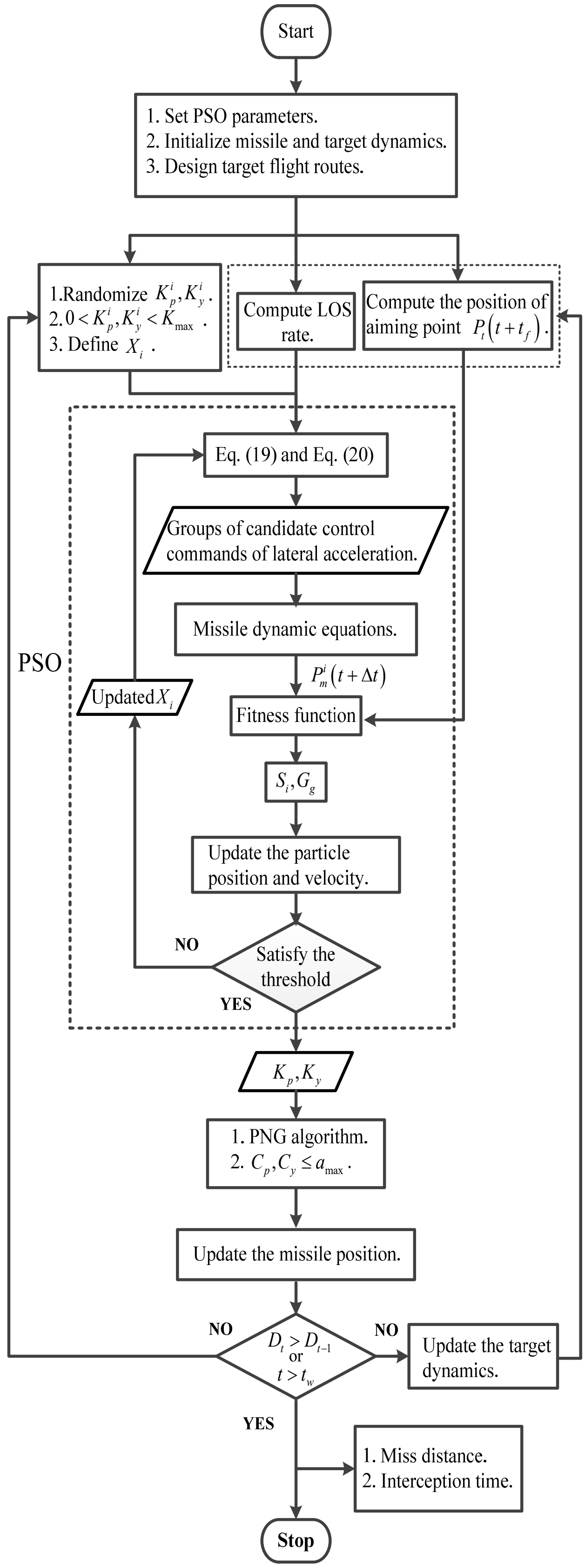

Fig. 3. Flow chart of the proposed guidance algorithm.

(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. Furthermore, a novel artificial intelligence missile guidance algorithm using PSO and LOS rate evaluation (MPSOG) is reproduced to execute the simulation experiments to compare the guidance performance with APG-PNG (Lee et al., 2016; Chen et al., 2016).

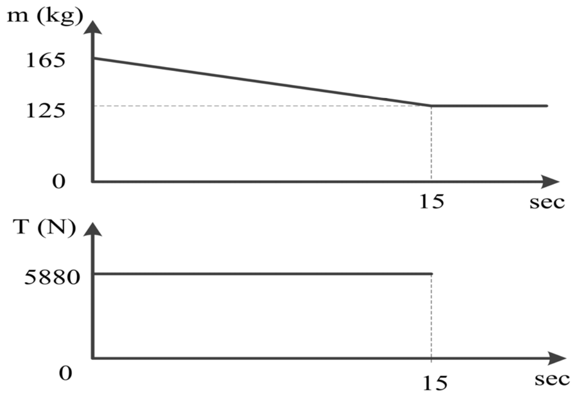

Fig. 4. Profiles of missile mass and thrust.

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 $\omega_n = 10$ (Hz), 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, Monte Carlo method has been applied to the simulation experiments by 100 times.

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).

In this section, the comparison of guidance performance for PNG and APG-PNG are proposed firstly and then MPSOG and APG-PNG would be discussed in detail. The guidance performance of PNG using different navigation constants (PNG-3~6) and APG-PNG in two different engagement scenarios of target-interceptor are shown in Table 2.

Table 2. Guidance performance of PNG-3~6, MPSOG 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**
A	MPSOG	–	**7.33**	**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**
B	MPSOG	–	**7.41**	**5.22**

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 shows 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.

Table 3. Guidance performance of PNG-3~6, MPSOG 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
C	MPSOG	–	8.23	5.38

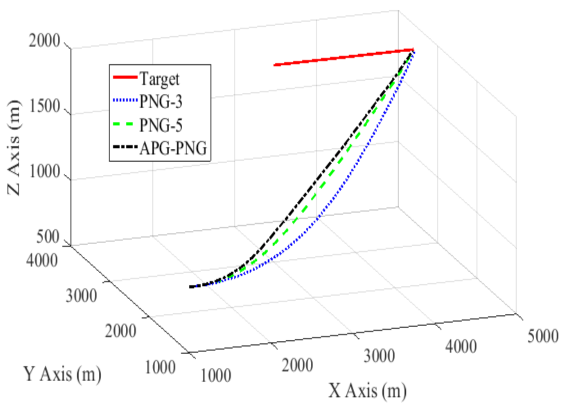

Fig. 5. Engagement of target-interceptor for PNG-3, PNG-5, and APG-PNG in Scenario A.

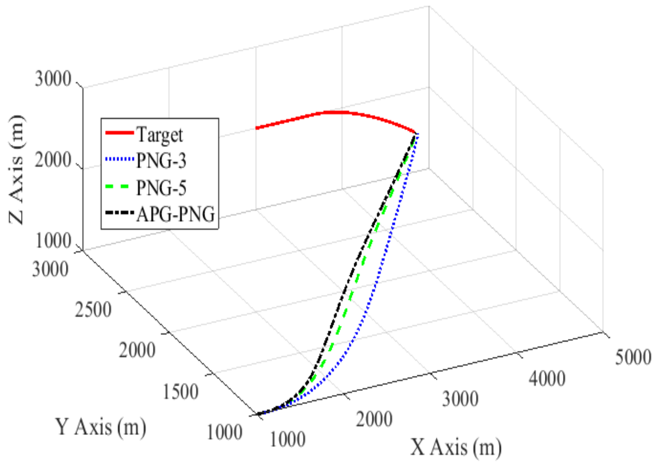

Fig. 6. Engagement of target-interceptor for PNG-3, PNG-5, and APG-PNG in Scenario B.

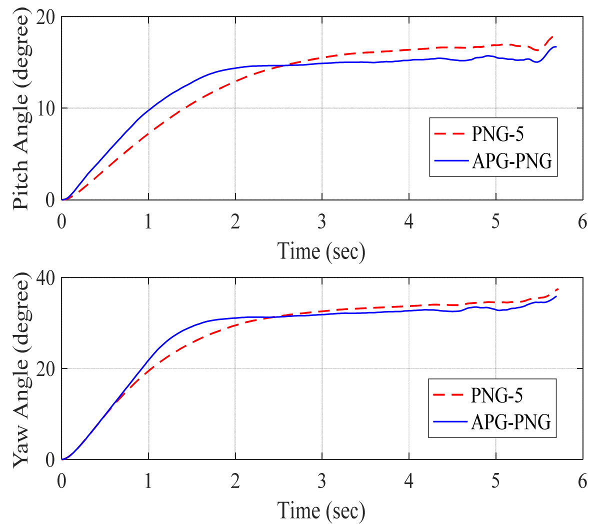

Fig. 7. History of missile control action for PNG-5 and APG-PNG in Scenario A.

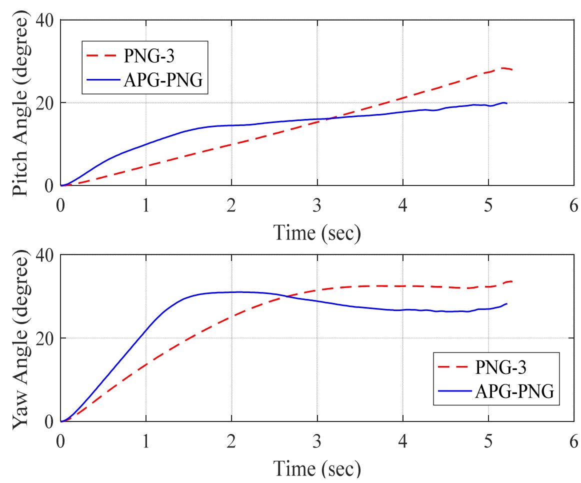

Fig. 8. History of missile control action for PNG-3 and APG-PNG in Scenario B.

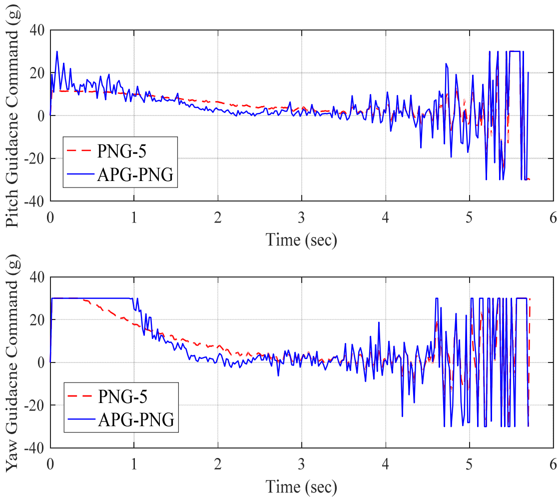

Fig. 9. History of guidance commands for PNG-5 and APG-PNG in Scenario A.

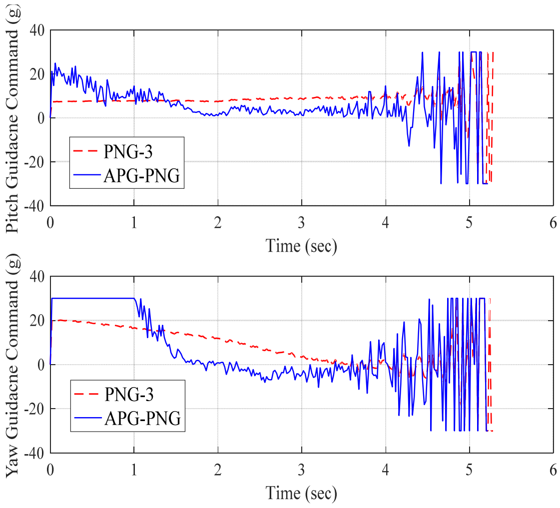

Fig. 10. History of guidance commands for PNG-3 and APG-PNG in Scenario B.

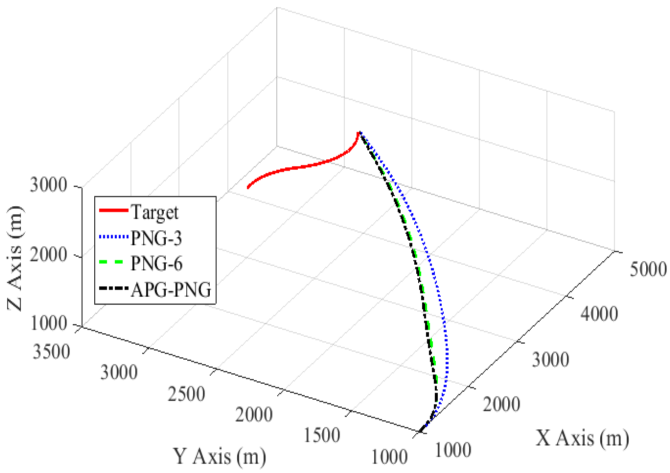

Fig. 11. Engagement of target-interceptor for PNG-3, PNG-6, and APG-PNG in Scenario C.

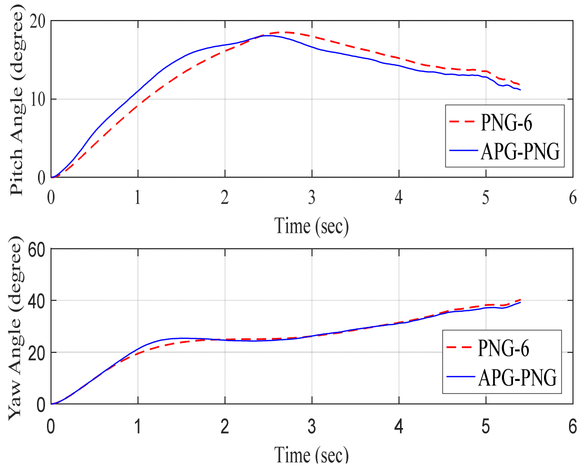

Fig. 12. History of missile control action for PNG-6 and APG-PNG in Scenario C.

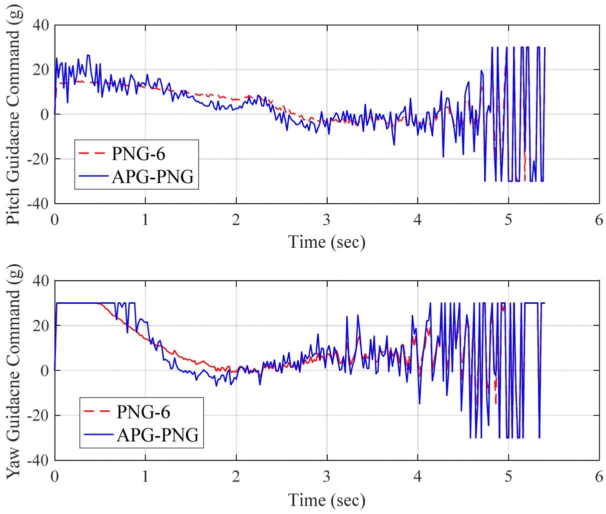

Fig. 13. History of guidance commands for PNG-6 and APG-PNG in Scenario C.

PSO has been used to design the missile guidance algorithm in 2013 and the improved version (MPSOG) in 2016 has been proven to perform effectively (Kung and Chen, 2013; Lee et al., 2016; Chen et al., 2016). In the core of MPSOG algorithm, PSO is directly applied to optimize and design the missile control commands of lateral acceleration and LOS rate is defined as the fitness function of PSO. The missile will be steered to intercept the target when the value of fitness function is the minimum. In this paper, MPSOG would be proposed to compare with APG-PNG. Fig. 14-16 show the flight route of MPSOG and APG-PNG are nearly overlapping in three different engagement scenarios. These figures illustrate the guidance ability of APG-PNG is closed to MPSOG. However, the guidance performance of APG-PNG is slightly better than MPSOG according to the miss distance shown in Table 2 and Table 3, and the interception time may explain why the two different guidance algorithms have the similar flight routes. Fig. 17-19 show the history of guidance commands for MPSOG in three different engagement scenarios. The curve of guidance commands of MPSOG produces huge oscillation during the whole pursuit process and that this phenomenon explains the missile frequently changes the motion state to the bound of missile maximum acceleration. The above reason may not only degrade the guidance performance of MPSOG but influence the body structure of missile. The oscillation behaviours primarily come from the parameters of missile guidance commands designed by PSO and the definition of fitness function in addition to the measurement data accompanied with noise disturbance. APG-PNG is steadier than MPSOG in terms of the control of missile guidance commands and that has the better guidance performance.

Most of research papers for missile guidance algorithms are hardly applied to the complicated real-time engagement of target-interceptor due to the complex theory and restriction in a special study case. Artificial intelligence has been utilized to design the missile guidance algorithm but the excess storage burden of computer and complicated definition of parameters such as the training of neural network, application of fuzzy theory and the confusing coding of genetic algorithm are not suitable to design the complicated real-time missile guidance algorithm. This is why PNG algorithm is still working in different missile guidance systems due to the advantages of simplicity and robustness, even though the guidance ability of PNG is not satisfied to treat the high agility aircraft. In this paper, the proposed APG-PNG computes the aiming point and applies PSO to continuously optimize and update the navigation constants of PNG-based scheme for the promotion of guidance performance during the pursuit process. PSO is a simple and efficient optimization method with the capability of fast computation speed. The missile would be steered towards the effective collision course because of the application of aiming point and the proposed method is developed based on PNG scheme. Simulation experiments have proven the outstanding guidance ability of APG-PNG. This study takes advantage of PSO, aiming point and PNG to design the aiming point guidance algorithm which is feasible to be applied to the missile guidance system because of simplicity and effectiveness.

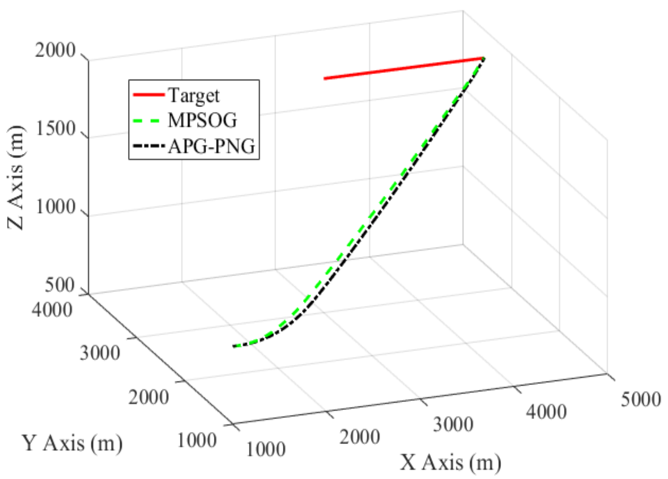

Fig. 14. Engagement of target-interceptor for MPSOG and APG-PNG in Scenario A.

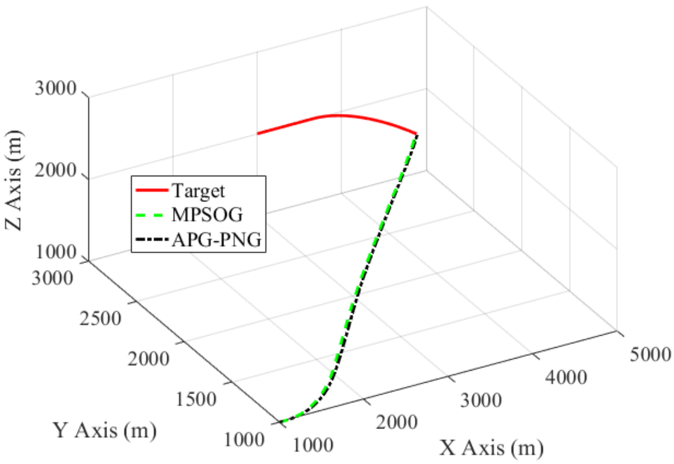

Fig. 15. Engagement of target-interceptor for MPSOG and APG-PNG in Scenario B.

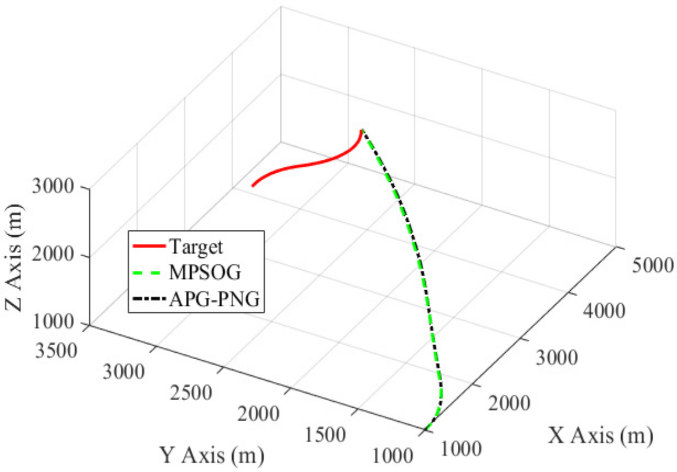

Fig. 16. Engagement of target-interceptor for MPSOG and APG-PNG in Scenario C.

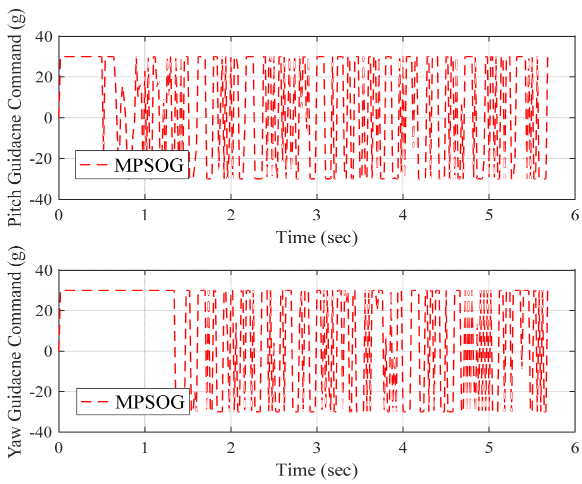

Fig. 17. History of guidance commands for MPSOG in Scenario A.

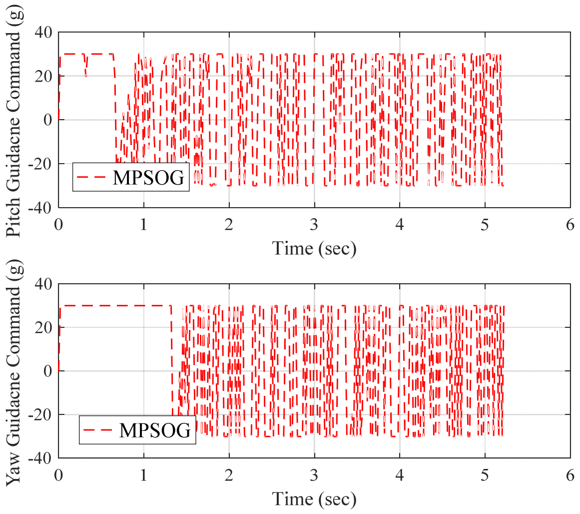

Fig. 18. History of guidance commands for MPSOG in Scenario B.

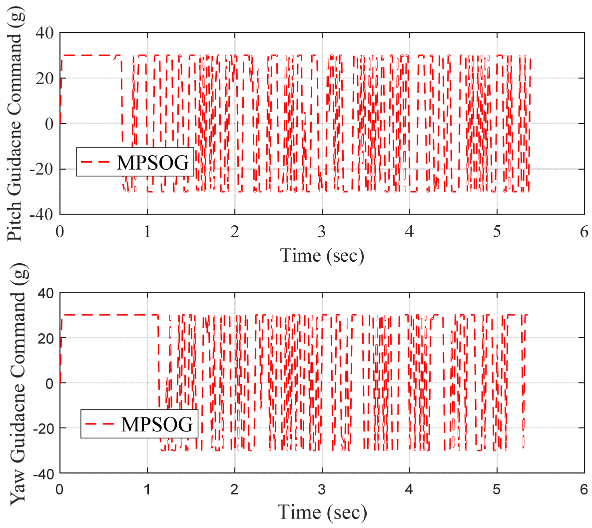

Fig. 19. History of guidance commands for MPSOG in Scenario C.

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. The guidance performance of this method is better than another developed artificial intelligence missile guidance algorithm as well. This research can be applied to the real missile guidance system because of simplicity and robustness just like PNG algorithm.

REFERENCES

Adler, F.P. (1956). Missile guidance by three-dimensional proportional navigation. *Journal of Applied Physics*. 27 (5), 500-507.

Chen, K.Y., Lee, Y.L., Liao, S.J., and Kung, C.C. (2016). The design of particle swarm optimization guidance using a line-of-sight evaluation method. *Computers and Electrical Engineering*. 54, 159-169.

Choi, H.L., Tahk, M.J., and Bang, H. (2006). Neural network guidance based on pursuit-evasion games with enhanced performance. *Control Engineering Practice*. 14, 735-742.

Choi, N. and Kim, Y. (2016). Optimality of augmented ideal proportional navigation for maneuvering target interception. *IEEE Transactions on Aerospace and Electronic Systems*. 52 (2), 945-954.

Eberhart, R.C. and Kennedy, J. (1995). A new optimizer using particle swarm theory. Proc. Sixth International Symposium on Micro Machine and Human Science. Nagoya, Japan, Oct. 4-6. 39-43.

Fumiaki, I. (1993). Some aspects of a realistic three-dimensional pursuit-evasion game. *Journal of Guidance, Control, and Dynamics*. 16 (2), 289-293.

Hossain, M.A., Madkour, A.A.M., Dahal, K.P., and Zhang, L. (2013). A real-time dynamic optimal guidance scheme using a general regression neural network. *Engineering Applications of Artificial Intelligence*. 26, 1230-1236.

Jeon, I.S. and Lee, J.I. (2010). Optimality of proportional navigation based on nonlinear formulation. IEEE Transactions on Aerospace and Electronic Systems. 46 (4), 2051-2055.

Kennedy, J. and Eberhart, R.C. (1995). Particle swarm optimization. Proc. IEEE International Conference on Neural Networks. Perth, WA, Nov. 27-Dec. 1. 1942-1948.

Kim, K.S. and Kim, Y. (2004). Design of generalized conceptual guidance law using aim angle. *Control Engineering Practice*. 12, pp. 291-298.

Kung, C.C. and Chen, K.Y. (2013). Missile guidance algorithm design using particle swarm optimization. *Transactions of the Canadian Society for Mechanical Engineering*. 37 (3), 971-979.

Lee, Y.L., Chen, K.Y., Chen, Y.W., Chen, Y.B., and Liao, S.J. (2016). The design of a modified PSO guidance law using predictor and LOS rate evaluation. MATEC Web of Conferences. 71, 1-3.

Lin, C.M. and Hsu, C.F. (2002). Guidance law design by adaptive fuzzy sliding-mode control. *Journal of Guidance, Control, and Dynamics*. 25 (2), 248-256.

Lin, C.M., Hsu, C.F., and Mon, Y.J. (2003). Self-Organizing fuzzy learning CLOS guidance law design. *IEEE Transactions on Aerospace and Electronic Systems*. 39 (4), 1144-1151.

Lin, Y.P., Tsao, L.P., and Lin, C.L. (2010). Development of three-dimensional aiming point guidance law. *International Journal of System Science*. 41 (11), 1353-1362.

Li, Z., Xia, Y. Su, C.Y., Deng. J., Fu, J., and He, W. (2015). Missile guidance law based on robust model predictive control using neural-network optimization. IEEE Transactions on Neural Network and Learning Systems. 26 (8), 1803-1809.

Lin, C.L., Lin, Y.P., and Chen, K.M. (2009). On the design of fuzzified trajectory shaping guidance law. *ISA Transactions.* 48, 148-155.

Omar, H.M. and Abido, M.A. (2010). Designing integrated guidance law for aerodynamic missiles by hybrid multi-objective evolutionary algorithm and Tabu search. *Aerospace Science and Technology*. 14 (5), 356-363.

Razmjooei, H. and Shafiei, M.H. (2016). A New Approach to Design a Robust Partial Control Law for the Missile Guidance Problem. *Journal of Control Engineering and Applied Informatics*. 18 (1), 3-10.

Song, E.J. and Tahk, M.J. (2001). Real-time neural-network midcourse guidance. *Control Engineering Practice*. 9 (10), 1145-1154.

Song, E.J. and Tahk, M.J. (2002). Three-dimensional midcourse guidance using neural networks for interception of ballistic targets. *IEEE Transactions on Aerospace and Electronic Systems*. 38 (2), 404-414.

Sun, T.Y., Tsai, S.J., and Huo, C.L. (2008). Intelligent maneuvering decision system for computer generated forces using predictive fuzzy inference system. *Journal of Computers*. 3 (11), 58-66.

Tahk, M.J., Ryoo, C.K., and Cho, H. (2002). Recursive time-to-go estimation for homing guidance missiles. *IEEE Transactions on Aerospace and Electronic Systems*. 38 (1), 13-24.

Wang, C.H. and Hung, K.N. (2013). Intelligent adaptive law for missile guidance using fuzzy neural networks. *International Journal of Fuzzy Systems*. 15 (2), 182-191.

Wang. C.H. and Chen, C.Y. (2014). Intelligent missile guidance by using adaptive recurrent neural networks. Proceedings of the 11th IEEE International Conference on Networking, Sensing and Control. 559-564.

Yuan, P.J., Chen, M.G., and Chern, J.S. (2012). Extended proportional navigation. AIAA Guidance, Navigation and Control Conference, AIAA-2000-4161.