Research Article

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

Fan He, Weiyi Chen, and Yang Bao

Department of Ordnance Engineering, Naval University of Engineering, Wuhan 430030, China
Naval Equipment Department, Beijing 100071, China

Correspondence should be addressed to Fan He; hefan9503@163.com

Received 12 December 2021; Revised 9 March 2022; Accepted 8 August 2022; Published 24 August 2022

Copyright © 2022 Fan He et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

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
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. $I_{1-2}$ is the inertial reference frame. The relative distance and LOS angle are represented as $R_{TM}$ and $\lambda$, $V_{TM}$ and $V_T$ represent the velocity, $n_1$ and $n_2$ represent the acceleration, and $\beta$ represents the flight path angle of target. The engagement geometry equations are written as follows [5]:

$$R_{TM1} = R_T - R_M,$$  
(1)

$$R_{TM2} = R'_T - R'_M,$$  
(2)

$$V_{TM1} = V_T - V_M,$$  
(3)

where $R_T$, $R'_T$, $V_T$, and $V_T'$ represent the components of the target position and velocity, respectively. $R_{TM1}$, $R_{TM2}$, $V_{TM1}$, $V_{TM2}$, $a_{M1}$, 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:

$$\dot{R}_{TM1} = V_{TM1},$$  

$$\dot{R}_{TM2} = V_{TM2},$$  

$$\dot{V}_{TM1} = a_{TM1},$$  

$$\dot{V}_{TM2} = a_{TM2}.$$  

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

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

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

$$V_c = -\dot{R}_{TM} = -\frac{R_{TM1} V_{TM1} + R_{TM2} V_{TM2}}{R_{TM}^2},$$  

$$\dot{\lambda} = \frac{R_{TM1} V_{TM2} - R_{TM2} V_{TM1}}{R_{TM}^3}.$$  

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
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 \( \lambda \) 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 \( J^1 = k_1|\lambda - \lambda_j| \) 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 \( J^3 = k_3|RTM| \) 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 \( n \) (\( 1 \leq i \leq n \)), 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-Kutta method.

**Step 3. Computation of the performance index**

The performance index of the particle can be calculated as

\[
J = k_1|\lambda - \lambda_j| + k_2|\dot{\lambda}| + k_3|RTM|, \tag{15}
\]

**Step 4. Updating optimal particles**

The local optimal particles \( p_{best,j} \) and global optimal particle \( G_{best} \) 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**
The velocity and location of particles are calculated as

$$V_{i,j+1} = \omega V_{i,j} + c_1 \left( p_{\text{best},j} - x_{i,j} \right) + c_2 \left( G_{\text{best},j} - x_{i,j} \right),$$
$$x_{i,j+1} = x_{i,j} + V_{i,j+1}. \quad (16)$$

**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 $a$ that minimizes the performance index, denoted as $J^*$. The value of the first term $J^1$ will also be relatively small. Then, the optimal acceleration command $a$ is used for missile maneuvering. In the same way, we can obtain $a_{t+\Delta t}^1$, $J^2_{t+\Delta t}$, and $J^3_{t+\Delta t}$. It is worth noting that $J^1_t$ shows a decreasing trend and will eventually tend to 0, which will also be illustrated by simulation in Section 4. When $J^1_t$ 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 NPSOG 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.

**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 $7 \times 7$ 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 3: Fuzzy logic controller.](image_url)
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 1000\(\text{m/s}\) and 1500\(\text{m/s}\). 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 \(3\text{rad/s}\). The initial heading angle of the missile is the initial line-of-sight angle, and the initial heading error is \(-20^\circ\). The preset impact angle is \(10^\circ\). The acceleration command is bounded within \([-400\text{m/s}^2, 400\text{m/s}^2]\). The time step is 0.01\(\text{s}\), and the prediction horizon is 0.5\(\text{s}\). 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, \(V_{ij}\) 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
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 $J^1 = k_1 |\lambda - \lambda_c|$ 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 $J^3 = k_3 |\text{RTM}|$ 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 IPSOG 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 5: Simulation results of intercepting step-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 $J_1, J_2, J_3$ 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 $\lambda$ and the desired angle $\lambda_d$ 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 $J_2 = k_j |\dot{\lambda}|$. 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 $J_3 = k_3 |\text{RTM}|$. 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
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
The 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
The authors gratefully acknowledge the financial support of the Department of Ordnance Engineering at Naval University of Engineering.

References
[1] Y. Si, S.-M. Song, and X. Wei, "An adaptive reaching law based three-dimensional guidance laws for intercepting hypersonic vehicle," *International Journal of Innovative Computing, Information and Control*, vol. 12, no. 4, 2017.

[2] Y. Z. Elhalwagy and M. Tarbouchi, "Integration of a fuzzy guidance-control system for a command interceptor against hypersonic target," *IIECON’01. 27th Annual Conference of the IEEE Industrial Electronics Society (Cat. No.37243)*, vol. 3, pp. 2050–2055, 2001.

[3] K.-B. Li, X.-P. Liao, Y.-G. Liang, C.-Y. Li, and L. Chen, "Guidance strategy with impact angle constraints based on pure proportional navigation," *Acta Aeronauticaet Astronautica Sinica*, vol. 41, 2020.

[4] L. Yan, J.-G. Zhao, H.-R. Shen, and Y. Li, "Three-dimensional united biased proportional navigation law for interception of maneuvering targets with angular constraint," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 229, no. 6, pp. 1013–1024, 2015.

[5] Z. Paul, *Tactical and Strategic Missile Guidance*, six ed, American Institute of Aeronautics and Astronautics, Reston, VA, 2012.

[6] K. Byung Soo, L. Jang Gu, and H. Hyung Seok, "Biased PNG law for impact with angular constraint," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 34, no. 1, pp. 277–288, 1998.

[7] X. Wang, C. P. Tan, and D. Zhou, "Observer-based PIGC for missiles with impact angle constraint," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 5, pp. 2226–2240, 2019.

[8] S. He, D. Lin, and J. Wang, "Integral global sliding mode guidance for impact angle control," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 4, pp. 1843–1849, 2019.

[9] Q. Ye, C. Liu, and J. Sun, "A backstepping-based guidance law for an exoatmospheric missile with impact angle constraint," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 2, pp. 547–561, 2019.

[10] M. J. Blondin, J. Sanchis Sáez, and P. M. Pardalos, "Control engineering from classical to intelligent control theory—an overview," in *Computational Intelligence and Optimization Methods for Control Engineering*, M. J. Blondin, P. M. Pardalos, and J. Sanchis Sáez, Eds., pp. 1–30, Springer International Publishing, Cham, 2019.

[11] S. Tariq, "Intelligent control: an overview of techniques," in *Perspectives in Control Engineering Technologies, Applications, and New Directions*, pp. 104–133, IEEE, 2001.

[12] M. B. Anderson, J. E. Burkhalert, and R. M. Jenkins, "Design of a guided missile interceptor using a genetic algorithm," *Journal of Spacecraft and Rockets*, vol. 38, no. 1, pp. 28–35, 2001.

[13] H. Nobahari and S. Nasrollahi, "A non-linear estimation and model predictive control algorithm based on ant colony optimization," *Transactions of the Institute of Measurement and Control*, vol. 41, no. 4, pp. 1123–1138, 2019.

[14] H. Nobahari and S. Nasrollahi, "A terminal guidance algorithm based on ant colony optimization," *Computers and Electrical Engineering*, vol. 77, pp. 128–146, 2019.

[15] H. Nobahari and S. Nasrollahi, "A nonlinear estimation and control algorithm based on ant colony optimization," 2016 *IEEE Congress on Evolutionary Computation (CEC)*, pp. 5120–5127, 2016.

[16] C.-C. Kung and K.-Y. Chen, "Missile guidance algorithm design using particle swarm optimization," *Transactions of the Canadian Society for Mechanical Engineering*, vol. 37, no. 3, pp. 971–979, 2013.

[17] K.-Y. Chen, Y.-L. Lee, S.-J. Liao, and C.-C. Kung, "The design of particle swarm optimization guidance using a line-of-sight evaluation method," *Computers and Electrical Engineering*, vol. 54, pp. 159–169, 2016.

[18] Y.-L. Lee, K.-Y. Chen, and S.-J. Liao, "Using proportional navigation and a particle swarm optimization algorithm to design a dual mode guidance," *Computers and Electrical Engineering*, vol. 54, pp. 137–146, 2016.

[19] H. Nobahari and S. Nasrollahi, "A nonlinear robust model predictive differential game guidance algorithm based on the particle swarm optimization," *Journal of the Franklin Institute*, vol. 357, no. 15, pp. 11042–11071, 2020.

[20] V. Rajasekhar and A. G. Sreenatha, "Fuzzy logic implementation of proportional navigation guidance," *Acta Astronautica*, vol. 46, no. 1, pp. 17–24, 2000.

[21] J. Song, S. Song, and H. Zhou, "Adaptive nonsingular fast terminal sliding mode guidance law with impact angle constraints," *International Journal of Control, Automation and Systems*, vol. 14, no. 1, pp. 99–114, 2016.

[22] S. He and D. Lin, "Adaptive nonsingular sliding mode based guidance law with terminal angular constraint," *International Journal of Aeronautical and Space Sciences*, vol. 15, no. 2, pp. 146–152, 2014.

[23] B. Zhao and J. Zhou, "Smooth adaptive finite time guidance law with impact angle constraints," *International Journal of Aerospace Engineering*, vol. 2016, 19 pages, 2016.