International Journal of Advanced Science and Computer Applications (2025); 4(2):
DOI: 10.47679/ijasca.v4i2.71
https://ijasca.org/index.php/ijasca

RESEARCH ARTICLE

UAV Formation Control Using Enhanced Behavior Mechanism And Artificial Potential Field

Luke Deng; Jie Ya; Mingyang Zhao; Jianheng Pan; Xiaoting Bu

Abstract

Inspired by formation flight of pigeon flock, this paper proposes a enhanced method of autonomous formation control of multiple Unmanned Aerial Vehicles (UAVs) that can maintain high symmetry based on pigeon flock behavior mechanism. Addressing the instability of formation in the original method, the follow improvements have been made. Firstly, improve leadership of top three UAVs, Secondly, modify artificial potential field strategies for top two followers. Finally, through a series of simulation experiments, it is verified that the UAVs can form the expected formation under the autonomous formation control, and can maintain the formation under the complex motion of leader UAV..

Keyword: Unmanned Aerial Vehicles, formation control, leadership hierarchy, artificial potential field

Introduction

Recently, unmanned systems have been applied in many fields with the developing of artificial intelligence technologies [1]. Multiple unmanned aerial vehicles (UAVs) system is a important part of unmanned system [2]. The autonomous formation technology of UAVs is a frontier field in recent years. This technology allows multiple UAVs form a formation to complete complex tasks, such as agriculture, engineering construction, geological exploration and transportation [3, 4]. It is of great significance to study the autonomous formation control of unmanned aerial vehicles [5].

In 1998, Desai et al. proposed the Leader-Follower control method [6]. Many scientists use this method to study UAVs formation. Kartal et al. use back-stepping control to achieve Leader-Follower control [7]. No et at. design a hiearachal scheme with multi leaders [8]. Lin proposes formation control design method based on differential game theory [9]. Hafez et al. propose a tactic switch method of two control strategies based on decentralized approach [10].

UAVs have hierarchy when flying in formation, and they are similar to the biology in this world. Máté Nagy and Zsuzsa Akos found that not only the head pigeon, other followers in the pigeon flock also have hierarchy [11, 12]. The head pigeon is in the absolute leading position, subordinate pigeons are affected by superior pigeons. The subordinate behavior of pigeons is not only affected by the head pigeon, but also by other superior pigeons, and the influence from the neighboring superior is more direct and rapid.

Duan and Qiao propose a new swarm intelligence optimizer, Pigeon-Inspired Optimization [13]. The map and compass operator and landmark operator are propose to simulate the process of pigeons flying to the destination. Feng et al. use Adaptive Learning-based Pigeon-Inspired Optimization (ALPIO) algorithm to design the resilience of UAVs formation to achieve rapid and accurate reconfiguration [14].

Qiu et al. establish hierarchy model of UAVs based on the behavior of pigeon flocks, and proposed a method of autonomous formation control for multiple UAVs [15]. With this autonomous formation control method, Qiu and Duan propose the close formation control [2].

In the autonomous formation control method proposed by Qiu [15], the formation is determined by first three pigeons. The first pigeon is the leader. The second pigeon is only affected by the force of the first pigeon, but the third pigeon is subjected to the force of the first and the second pigeons. The number and direction of forces on the second pigeon and the third pigeon are different, so the resultant of forces on them is not symmetrical about the speed direction of the first pigeon, it is difficult to guarantee the formation.

The main contribution of this paper is to propose an improved autonomous formation control method based on the formation method proposed by Qiu. This method avoid the follower being far away from the desired position due to the different number and direction of force. This method can ensure that the UAVs keep symmetry under complex motion conditions.

The rest of the paper is organized as follows. Section 2 models the hierarchy of pigeon flock and complete formation based on the velocity direction of the first pigeon. Section 3 establishes the UAV model and designs the formation control. Our concluding remarks are contained in Section 4.

Model of the pigeon behavior mechanism

Model of hierarchies in pigeons based on graph theory

Intelligent Game and Decision Lab (IGDL) Beijing, China

*) corresponding author

Email: dengprolk@163.com

Received 25 May 2025 | Received in revised form 27 Juli 2025 | Accepted 21 August 2025
Available online 25 September 2025

Consider a directed graph $G=(V,E)$ describing the hierarchical structure of pigeon flock, where the set of vertex $V=\{v_1,v_2,\mathrm{K}\ ,v_n\}$ represents pigeons, the set of edges $E=\{e_1,e_2,\mathrm{K}\ ,e_m\}$ represents the leadership of the superior over the subordinate.The identifier N_i represents the number of pigeons.

$$N_i=\{j,k,\Lambda\ \}\subseteq\{1,2,\Lambda\ ,\mathrm{n}\} \quad (1)$$

where, *j*, *k* are the leader number of *i*th pigeon, *n* is the number of pigeon in pigeon flock.

The rank of each pigeon and the leader of the superior pigeon are artificially specified. Following the hierarchical network of the actual pigeon flock, the simplified directed graph of pigeon hierarchical is shown in Fig. 1.

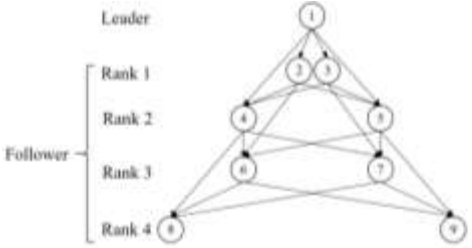


Fig 1. **Digraph of hierarchies in pigeons**

In Fig. 1, the circle represents the pigeon, that is, the vertex set in the directed graph. The arrow represents the leadership between pigeons, that is, the edge set. Each rank has two followers. In addition to the followers at Rank1, each follower has three superior pigeons. The head pigeon do not have any superiors. The Rank1 follower is leaded by the head pigeon.

The leader number N_i of ith is expressed as:

$$N_i=\begin{cases}\varnothing, & i=1,\\ 1, & i=2,\\ 1, & i=3,\\ 1,2,3 & i=4,\\ i-4,i-2,i-1 & i=2k,k=\{3,4,\Lambda\ \},\\ i-4,i-3,i-2 & i=2k+1,k=\{2,3,\Lambda\ \}.\end{cases} \quad (2)$$

Setting the formation and leadership can enhance the effect of gathering, anti-collision and stability at the specified distance. Fig. 2 shows the leading role of the head pigeon to the Rank1 follower. The head pigeon is flying in the expected velocity, and the Rank1 followers are distributed on both sides behind the head pigeon according to the velocity direction and expected distance of the head pigeon. Two followers can't interact on each other. It can effectively avoid the problem that the force difference between second follower and third follower in Rank1 follower. The formation is easier to maintain.

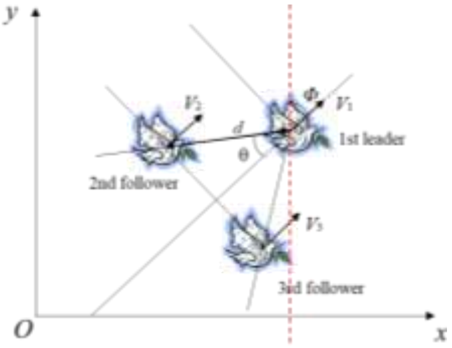


Fig 2. **Determination procedure for pigeon formation**

In Fig. 2, V_i (i=1, 2, 3) represents the velocity of pigeon, P_i (i=1, 2, 3) represents the position of pigeon, θ represents the angle between the direction of V_1 and the edge (P_1,P_2), d represents the expected distance from leader to follower. θ and d can determine the position the first three pigeons and the formation of pigeon flock.

The second pigeon and the third pigeon are only affected by the 1st pigeon, so they can't confirm their location. d, ϕ (yaw angle) and location of 1st pigeon are used to calculate their own expected location.

$$\begin{cases} x_0^2 = x^1 + d\left(\sin\left(\phi+\theta\right)\right) \\ y_0^2 = y^1 + d\left(\cos\left(\phi+\theta\right)\right) \\ z_0^2 = z^1 \\ x_0^3 = x^1 + d\left(\sin\left(\phi-\theta\right)\right) \\ y_0^3 = y^1 + d\left(\cos\left(\phi-\theta\right)\right) \\ z_0^3 = z^1 \end{cases} \quad (3)$$

where, x_0^i and y_0^i represent the expected horizontal location of ith pigeon, z_0^i represents expected height of ith pigeon, x^1 and y^1 represent the real horizontal location of first pigeon, z^1 represent the real height of first pigeon.

Model of leadership in pigeons based on potential field method

Identify applicable sponsor/s here. If no sponsors, delete this text box (*sponsors*).

The leadership between the superior and the subordinate in the pigeon flock enables the subordinate to try to keep close to the superior, avoid collision with the superior, and try to match its velocity. Because of the hierarchical structure in pigeon flock, subordinate pigeons always try to keep the expected distance and the same velocity of superior pigeons.

Considers that pigeons are all regarded as particles fly unobstructed in the three-dimensional Euclid space [16], the dynamics model of each pigeon is as follows:

$$\begin{cases} \dot{X}^i = V^i. \\ m^i\dot{V}^i = l^i - k^iV^i, i = 1,\ldots,n, \end{cases} \quad (4)$$

where, $X^i \in \mathrm{R}^3$ is the position vector of ith pigeon, $V^i \in \mathrm{R}^3$ is the velocity vector of ith pigeon, $m^i>0$ is the mass of ith pigeon, $l^i \in \mathrm{R}^3$ is the control input, $-k^iV^i$ is the velocity damping term, $k^i>0$ is the velocity attenuation gain, $X^{ij}=X^i-X^j$ is the relative position vector between ith and jth pigeon.

The control l^i of ith pigeon can be expressed as:

$$l^i = \alpha^i + \beta^i + \lambda^i + k^iV^i \quad (5)$$

where, α^i is the control component of the artificial potential field in pigeon flock, which is used to maintain the distance of each pigeon. It is derived from the potential function P_{att} and P^{ij}, β^i is the control component of ith pigeon's difference between the velocity of ith pigeon and the velocity of its superiors, λ^i is the control component of ith pigeon's difference between real velocity and expected velocity.

Reference [15] uses the potential field function as formula (6). As mentioned in the introduction, using this method will result in different forces on 2nd UAV and 3rd UAV, and the different distances between 1st UAV and 2nd UAV, 1st UAB and 3rd UAV. Formation cannot maintain symmetry about the speed direction of 1st UAV. When the formation is unstable, the distance between the follower and leader will be affected, which also lead to a decrease in the robustness of the communication system.

$$P^{ij}\left(\left\|X^{ij}\right\|\right) = \ln\left\|X^{ij}\right\|^2 + \frac{d_{ij}^2}{\left\|X^{ij}\right\|^2} \quad (6)$$

where, d_{ij} is the expected distance between ith pigeon and jth pigeon.

To solve this problem, both of 2nd UAV and 3rd UAV have the same leader, 1st UAV. Set the expected target point for 2nd UAV and 3rd UAV based on d.

When using the above method, X^{ij} is the distance between ith UAV and the expected target point, where $X^{ij} \geq 0$, so the original method cannot be used. This article use the potential field formula as shown in the following equation.

$$P_{att}\left(\left\|X^{ij}\right\|\right) = \frac{1}{2}\zeta\left\|X^{ij}\right\|^2 \quad (7)$$

where, ζ is the coefficient of potential.

After determine the positions of ith UAV (i=1,2,3), the formation is symmetrical about the speed direction of 1st UAV. On this basis, the remaining UAVs use the original potential field method to solve the control variables.

The identifier l_1^i, l_2^i, l_3^i are the control input of u(surge), v(sway), w(heave), respectively. l_1^i, l_2^i, l_3^i (i = 4, 5, ...) can be expressed as [17]:

$$l_1^i = (-K_p \sum \nabla_{\left\|X_1^{i,j}\right\|} P^{ij} - K_v \sum(u^i - u^j) - m(u^i - u^1))k_1 + k^i u^i \quad (8)$$

$$l_2^i = (-K_p \sum \nabla_{\left\|X_2^{i,j}\right\|} P^{ij} - K_v \sum(v^i - v^j) - m(v^i - v^1))k_1 + k^i v^i \quad (9)$$

$$l_3^i = (-K_h \sum(X_3^i - X_3^j) - K_v \sum(w^i - w^j) - m(w^i - w^1))k_2 + k^i w^i \quad (10)$$

where, K_v is the velocity feedback gain factor, K_p is the artificial potential field gain factor, K_h is the height feedback gain factor, both of which are greater than 0, k^1 is the horizontal adjustment factor, k^2 is the vertical adjustment factor, u^i, v^i, w^i are velocity of surge, sway, heave of ith UAV, respectively, u^j, v^j, w^j are velocity of surge, sway, heave of jth leader UAV, respectively.

Because of the leader of 3rd UAV and potential field function of 2nd and 3rd UAVs have changed, the control input in [17] is modified.

While $i = 2, 3$, l_1^i, l_2^i, l_3^i can be expressed as:

$$l_1^i = -(K_p \nabla_{\|X_1^{i,1}\|} P_{att} + (K_v + m)(u^i - u^1)) + k^i u^i \tag{11}$$

$$l_2^i = -(K_p \nabla_{\|X_2^{i,1}\|} P_{att} + (K_v + m)(v^i - v^1)) + k^i v^i \tag{12}$$

$$l_3^i = -(K_h \nabla_{\|X_3^{i,1}\|} P_{att} + (K_v + m)(w^i - w^1)) + k^i w^i \tag{13}$$

where, $X^{i,1}$ represents the distance between the current location and expected location of ith UAV.

UAV formation control based on the behavior mechanism in pigeon flocks

During the flying process, due to the limitation of communication distance and field of view, it is difficult for each pigeon to find and follow the head pigeon in real time. Therefore, it is necessary to refer to other pigeons within the range of communication or field of view. In autonomous formation flight, the subordinate UAV cannot guarantee that the head UAV is within the range of communication all the time, so it is necessary to establish a communication network between subordinate UAV and other UAV. The strict hierarchical structure between individual pigeons is established, and the pigeons need to complete actions according to the behavior of their superiors.

UAV model

Different from the traditional method using v, ψ, h, identifiers u, v, w are used to described the UAV model. Based on [18], horizontal velocity that in UAV model is decoupled into two velocity which has different direction by yaw angle. UAV model is expressed as:

$$\begin{cases} \dot{x}^i = u^i, \\ \dot{y}^i = v^i, \\ \dot{z}^i = w^i, \\ \dot{u}^i = \dfrac{1}{\tau_u}\left(l_1^i - u^i\right), \\ \dot{v}^i = \dfrac{1}{\tau_v}\left(l_2^i - v^i\right), \\ \dot{w}^i = \dfrac{1}{\tau_h}\left(l_3^i - w^i\right), \end{cases} \tag{14}$$

where, x^i, y^i, z^i are the coordinates of ith UAV, τ_u, τ_v, τ_w are the time constant.

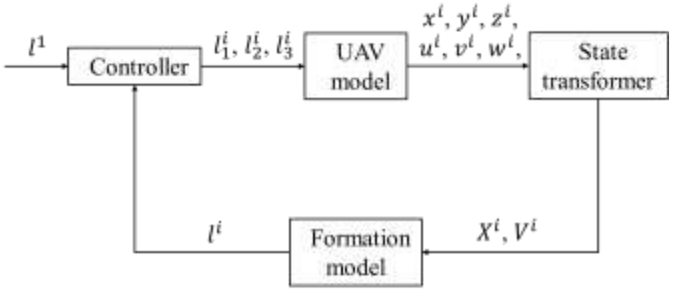
The practicability constraints of UAV are expressed as:

$$\begin{cases} u_{\min} \le u^i \le u_{\max}, \\ v_{\min} \le v^i \le v_{\max}, \\ w_{\min} \le w^i \le w_{\max}, \\ \dfrac{v^i}{u^i} \le \tan(\psi), \end{cases} \tag{15}$$

where, $u_{\min}$, $v_{\min}$, $w_{\min}$, $u_{\max}$, $v_{\max}$, $w_{\max}$, are the minimum velocity of surge, sway, heave and maximum velocity of surge, sway, heave respectively, ψ is the yaw angle.

UAV autonomous formation control system

UAV autonomous formation control system can be divided into four parts [17]: Controller, formation model and UAV model, and state transformer. The specific UAV autonomous formation control system framework is shown in Fig. 3.



Block diagram of UAV autonomous formation control system

In Fig. 3, Controller is used to convert the output l^i of the Formation model into the three control inputs.

State transformation formula is expressed as:

$$\begin{cases} X^i = \left(x^i, y^i, z^i\right) \\ V^i = \left(u^i, v^i, w^i\right) \end{cases} \quad (16)$$

The solutions can be found by the following steps:

Step 1. Set control input I^1 of head UAV, obtain the state by formula (14) and (15).
Step 2. Obtain superior UAV N^i of ith UAV by formula (2).
Step 3. Calculate the expected control input I^i by formula (8)-(13).
Step 4. Calculate the real-time state of follower N^i by formula (14).
Step 5. Get (X^i , V^i) of ith UAV by formula (16).
Step 6. Go to **Step 1**, until UAVs reach target point.

NUMERICAL SIMULATIONS

Assuming 5 UAVs (m^i = 1 kg) fly in 3d space, $\tau_u = 1$, $\tau_v = 1$, $\tau_h = 1$, $u_{\min} = 0$, $u_{\max} = 0.35$, $v_{\min} = 1$, $v_{\max} = 5$, $w_{\min} = -0.4$, $w_{\max} = 0.4$, d = 7.071 m, $\theta = 45°$.

The hierarchical structure of UAVs is shown in TABLE I. 1st UAV is leader (head UAV), rank 1 includes 2nd and 3rd UAVs, and their superior is 1st UAV. Rank 2 includes 4th and 5th UAVs, their superiors are 1st , 2nd and 3rd.

The parameters of hierarchies in UAVs

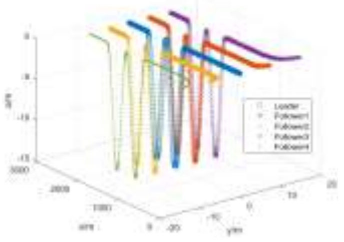
Category	Rank	Number	Superior Number
Leader	/	1	/
Follower	1	2	1
		3	1
	2	4	1, 2, 3
		5	1, 2, 3

Simulation lasts for 300 s, and the sampling time is 0.5s. Set the long aircraft flight to be divided into three stages. In the first stage, leader flies at a constant speed in a straight line, which lasts for 50s. The control input of leader $I^1 = [0, 0, 0]$. In the second stage, leader flies on a sine curve, which lasts for 100s. The control input of leader $I^1 = [0, 0, \sin(\pi t/50)]$, and t is simulate time. In the third stage, the control input of leader $I^1 = [0, 0, 0]$.

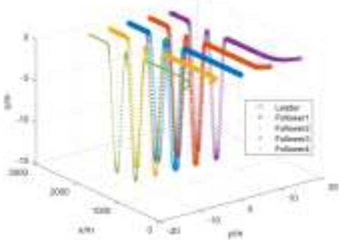
Initial states of UAVs

Variable	UAV number				
	1	2	3	4	5
x/m	0	0	0	0	0
y/m	0	7.5	-7.5	15	-15
z/m	0	0	0	0	0
u/(m/s)	3	0	0	0	0
v/(m/s)	0	0	0	0	0
w/(m/s)	0	0	0	0	0

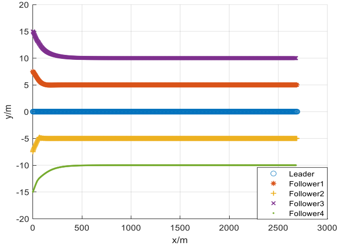
The other four followers complete the formation task according to the leader. UAVs gather to achieve and maintain a "V" formation. The expected position of UAV is shown in Fig. 4, he followers use the autonomous formation controller proposed in this paper for flight control. Other parameters are set as: $K_p = 30$, $K_v = 0.1$, $K_h = 0.5$, $k_1 = 1$, $k_2 = 1$.



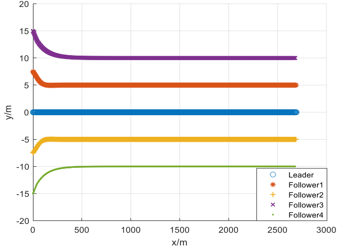
3D trajectories of UAVs (original)



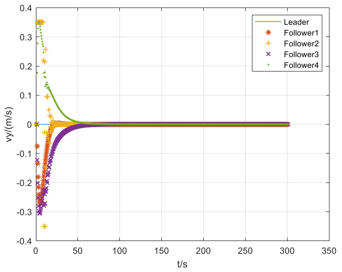
3D trajectories of UAVs (enhanced)



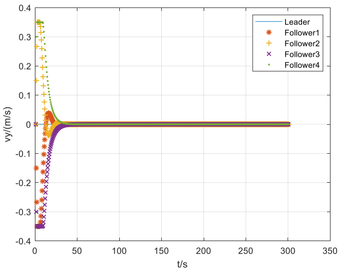
Horizontal tracjectories of UAVs (original)



Horizontal tracjectories of UAVs (enhanced)



velocity *v* curve of UAVs (original)



velocity *v* curve of UAVs (enhanced)

Simulation results of multiple UAVs autonomous formation

Fig. 4(a)-4(d) illustrate that UAVs form "V" formation at about 38 s and last 12 s in the first stage. From Fig. 4(e) and 4(f), the UAVs' velocity change more smoother using enhanced method. Fig. 4(c), 4(d) illustrate that the formation is still maintained under complex motion of head UAV.

(a) *t* = 62s (original)

(b) *t* = 62s (enhanced)

(c) *t* = 165.5s (original)

(d) *t* = 165.5s (enhanced)

(e) *t* = 200.5s (original)

(f) *t* = 200.5s (enhanced)

(g) *t* = 280.5s (original)

(h) *t* = 280.5s (enhanced)

Formation of multiple UAVs in different moment

In Fig. 5, *t*=62s is the moment in the stage of stable flight after UAVs assembly. When *t*=165s, leader start to perform sine motion. When *t*=200.5s, leader has made half sine motion. When *t*=280.5s, leader heads straight again. During simulation, UAVs' formation is more stable by using enhanced method. The route and formation displayed in Fig. 4 and 5 illustrate enhanced behavior mechanism and artificial potential field improve the robustness of the formation

References

[1] T. Zhang, Q. Li, C.-s. Zhang, H.-w. Liang, P. Li, T.-m. Wang, S. Li, Y.-l. Zhu, and C. Wu, "Current trends in the development of intelligent unmanned autonomous systems," Frontiers of Information Technology & Electronic Engineering, vol. 18, no. 1, pp. 68-85, 2017.

[2] H. Qiu, and H. Duan, "Multiple UAV distributed close formation control based on in-flight leadership hierarchies of pigeon flocks," Aerospace Science and Technology, vol. 70, pp. 471-486, 2017.

[3] L. He, J. Zhang, Y. Hou, X. Liang, and P. Bai, "Time-Varying Formation Control For Second-Order Discrete-Time Multi- Agent Systems With Switching Topologies and Nonuniform Communication Delays," IEEE Access, vol. 7, pp. 65379-65389, 2019.

[4] X. Ding, P. Guo, K. Xu, and Y. Yu, "A review of aerial manipulation of small-scale rotorcraft unmanned robotic systems," Chinese Journal of Aeronautics, vol. 32, no. 1, pp. 200-214, 2019.

[5] Y. Ding, X. Wang, Y. Cong, and H. Li, "Scalability Analysis of Algebraic Graph-Based Multi-UAVs Formation Control," IEEE Access, vol. 7, pp. 129719-129733, 2019.

[6] J. O. J.P. Desai, V. Kumar, "Controlling formations of multiple mobile robots," in 1998 IEEE International Conference on Robotics and Automation, Leuven, Belgium, 1998.

[7] Y. Kartal, K. Subbarao, N. R. Gans, A. Dogan, and F. Lewis, "Distributed backstepping based control of multiple UAV formation flight subject to time delays," Iet Control Theory and Applications, vol. 14, no. 12, pp. 1628-1638, Aug, 2020.

[8] T. S. No, Y. Kim, M.-J. Tahk, and G.-E. Jeon, "Cascade-type guidance law design for multiple-UAV formation keeping," Aerospace Science and Technology, vol. 15, no. 6, pp. 431-439, Sep, 2011.

[9] W. Lin, "Distributed UAV formation control using differential game approach," Aerospace Science and Technology, vol. 35, pp. 54-62, 2014.

[10] A. T. Hafez, M. Iskandarani, S. N. Givigi, S. Yousefi, and A. Beaulieu, "UAVs in Formation and Dynamic Encirclement via Model Predictive Control," 2014.

[11] M. Nagy, G. Vasarhelyi, B. Pettit, I. Roberts-Mariani, T. Vicsek, and D. Biro, "Context-dependent hierarchies in pigeons," Proc Natl Acad Sci U S A, vol. 110, no. 32, pp. 13049-54, Aug 6, 2013.

[12] M. Nagy, Z. Akos, D. Biro, and T. Vicsek, "Hierarchical group dynamics in pigeon flocks," Nature, vol. 464, no. 7290, pp. 890-3, Apr 8, 2010.

[13] H. Duan, and P. Qiao, "Pigeon-inspired optimization: a new swarm intelligence optimizer for air robot path planning," International Journal of Intelligent Computing and Cybernetics, vol. 7, no. 1, pp. 24-37, 2014.

[14] Q. Feng, X. Hai, B. Sun, Y. Ren, Z. Wang, D. Yang, Y. Hu, and R. Feng, "Resilience optimization for multi-UAV formation reconfiguration via enhanced pigeon-inspired optimization," Chinese Journal of Aeronautics, vol. 35, no. 1, pp. 110-123, 2022.

[15] H. Qiu, H. Duan, and Y. Fan, "Multiple unmanned aerial vehicle autonomous formation based on the behavior mechanism in pigeon flocks," Contro Theory & Applications vol. 32, no. 10, 2015.

[16] L. Wang, H. Shi, and T. Chu, "Flocking Control of Groups of Mobile Autonomous Agents Via Local Feedback," Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation Intelligent Control, 2005., pp. 441-446, 2005.

[17] Q. Hua-xin, D. Hai-bin, and F. Yan-ming, "Multiple unmanned aerial vehicle autonomous formation based on the behavior mechanism in pigeon flocks," Control Theory & Applications, vol. 32, 2015.

[18] W. Ren, "On Constrained Nonlinear Tracking Control of a Small Fixed-wing UAV," Journal of Intelligent and Robotic Systems, vol. 48, no. 4, pp. 525-537, 2007.

[19]