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Formation control of unmanned aerial vehicle swarms: A comprehensive review

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Abstract

The unmanned aerial vehicle formation plays a crucial role in numerous applications, such as reconnaissance, agricultural plant protection, and electric power inspection. This paper provides a comprehensive review and analysis of the unmanned aerial vehicle swarm communication networks and formation control strategies. First, the most commonly used unmanned aerial vehicles are introduced and compared. Next, the entire process of the formation task, from the formation assignment to the formation transformation, is detailed described. At last, the widely adopted communication networks are analyzed, and the existing formation control strategies of the UAV swarm are compared, which shows that the distributed formation control is superior to the centralized method and is the future development trend.

KEYWORDS

communication network, comprehensive review, formation control, unmanned aerial vehicle swarm

1 | INTRODUCTION

In recent years, unmanned aerial vehicles (UAVs) have attracted numerous research interests due to their advantages of simple structure, low cost, rapid maneuvering, and high concealment [1–3]. They can excellently complete boring and high-risk tasks in the harsh working environment [4], which can not only reduce casualties but also reduce the equipment cost. However, a single UAV is difficult to complete the current increasingly complicated mission requirements, such as large-area searching, because of its limited flight time and small sensing range [5, 6]. To remedy these deficiencies, the concept of UAV swarms is proposed [7, 8], where multiple UAVs form a group to collaboratively complete one large-scale and complicated task that is difficult for one UAV [9, 10]. In particular, the entire task can be divided into some simple and small assignments, and each UAV carries different sensors and other equipment to perform its assigned task, so that the overall task can be completed in a short time, thus significantly improving the efficiency of the task completion [11, 12]. Through mutual cooperation among UAVs, the UAV swarm demonstrates superior coordination, intelligence, and autonomy [13].

Because of the above advantages, the UAV swarm has gained widespread applications in many military and civil tasks stretching from reconnaissance to environmental monitoring [14, 15], as illustrated in Figure 1.

- **Reconnaissance.** There is an increasingly crucial demand to realize the real-time and accurate intelligence gathering on the battlefield, which could effectively contribute to the victory of the war [16, 17]. Therefore, the UAV swarm is commonly used for cooperative reconnaissance due to its advantages of strong autonomy and flexible maneuverability [18]. They can quickly and accurately detect the environmental information and then perform the identification and location of the target. Moreover, the UAV swarm has

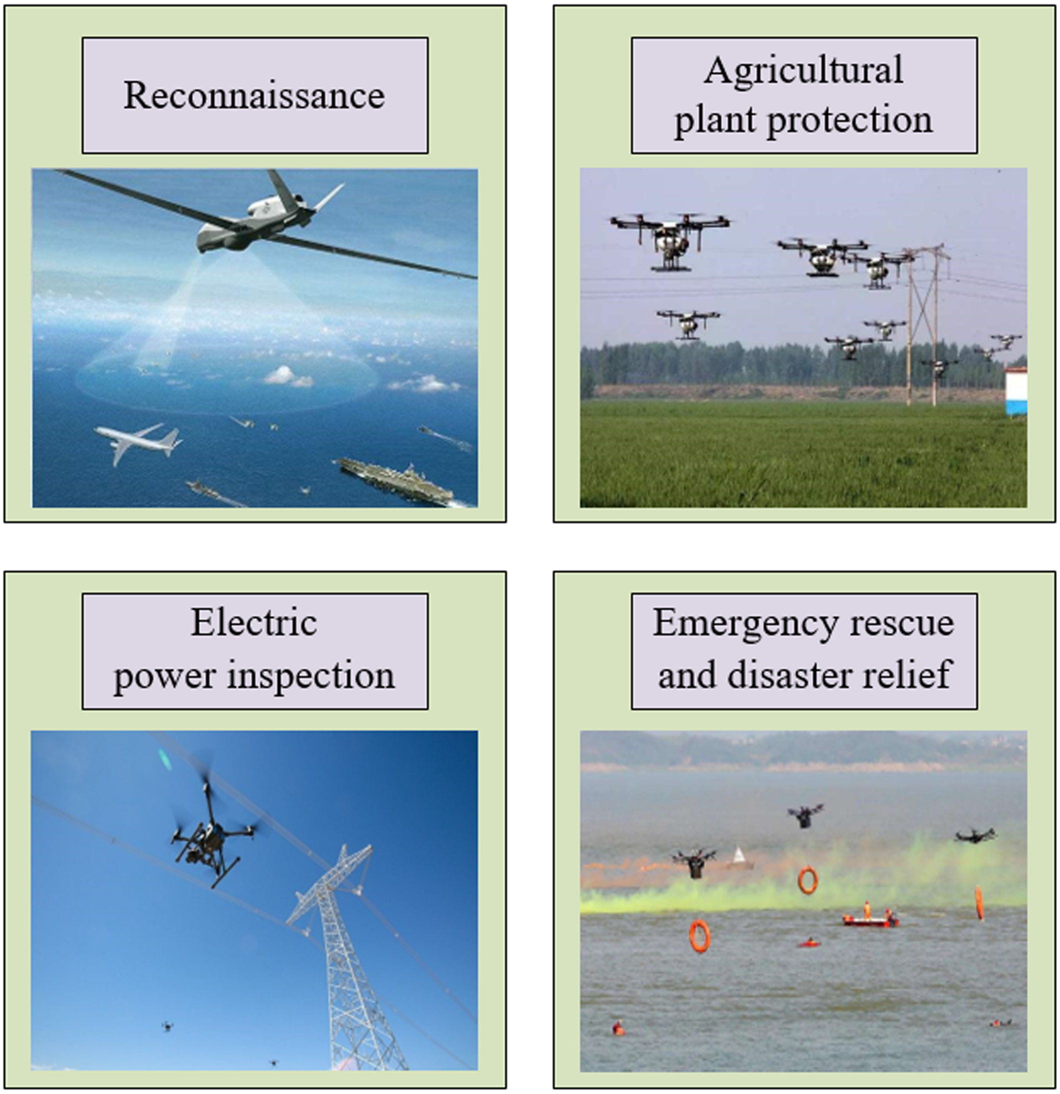

FIGURE 1 Applications of UAV swarms

the capabilities of long-term and large-scale reconnaissance, which can be used to achieve all-round surveillance of the battlefield [19].

- **Agricultural plant protection.** UAVs equipped with specific spraying devices are controlled to quantitatively and accurately spray pesticides on crops, which can not only provide higher efficiency than the traditional manual operation but also overcome the problem that the ground spraying equipment is restricted by the terrain [20]. Overall, the agricultural plant protection UAVs have the advantages of simple operation, fast speed, high efficiency, low cost, and uniform spraying [21, 22]. The amount and time of the spraying can be effectively optimized through controlling the UAV swarm to prevent respraying and missed spraying. Moreover, UAV swarms can also be utilized in seed sowing, precision plant irrigation, pest monitoring, and other agricultural applications [23, 24].
- **Electric power inspection.** The UAV swarm can quickly and accurately inspect the actual operating conditions of power lines, lightning protection, and grounding devices under complex working conditions [25]. Through the wireless communication system, the inspection results can be sent to the technicians in time, which can contribute to rapid data analysis and accurate fault diagnosis of the electric power devices [26]. Compared with manual inspection, the use of UAV swarms can improve the inspection efficiency and guarantee the safety of inspection operators [27, 28]. Due to the above advantages, that the UAVs are applied to the daily electric power inspection is the potential development trend in the future.
- **Emergency rescue and disaster relief.** Most disasters, such as earthquakes, floods, and fires, have the characteristics of suddenness and destructiveness, which may cause communication and road

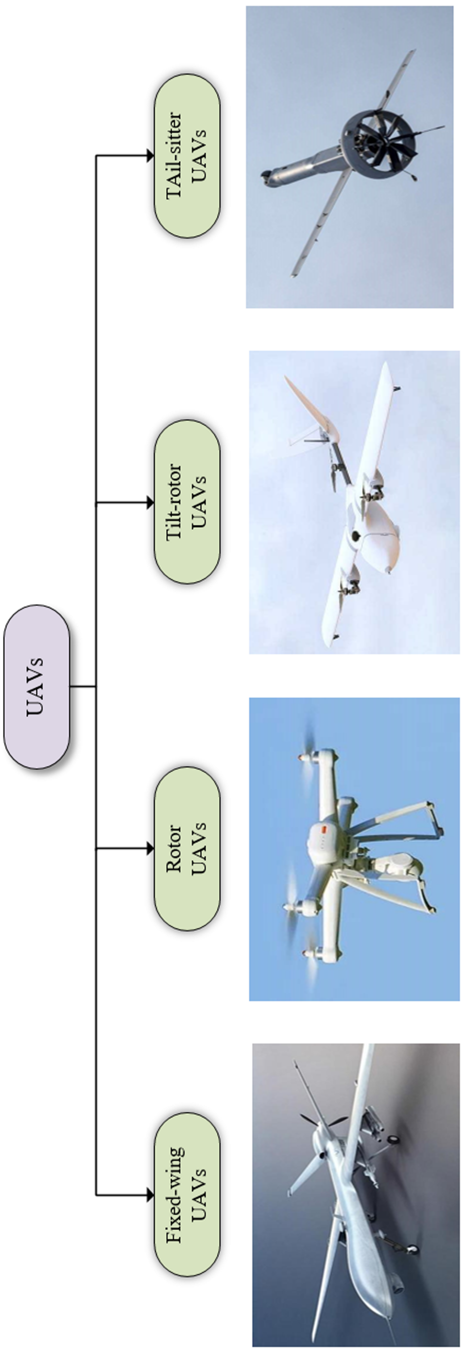

FIGURE 2 Classification of UAVs

interruptions in the damaged region [29, 30]. This brings great difficulties to the accurate acquisition of the disaster information in time, thus increasing the difficulty of rescue. Therefore, it is of great necessity to use the UAV swarm to search for the injured and provide the rescuers with their accurate information [31]. With the participation of the UAV swarm, the accuracy and speed of rescue can be significantly improved. Moreover, the UAV swarm can delivery medical and daily necessities to the people in the disaster area, which can significantly improve the living standards of the victims and reduce casualties.

The main research contents of UAV swarm control include communication networking, collaborative task assignment, trajectory planning, and autonomous formation control. Among them, formation control has received extensive attention because of its potential applications in broad fields. It is inspired by the animals' self-organizing behavior in nature, such as the flocking of birds and the schooling of fish. Formation control focuses on making the UAV swarm move in a specific formation through controlling their relative positions and velocities, which can not only reduce the UAVs' energy consumption for propulsion but also expand their sensing range [32]. It enhances the reconfiguration ability and structure flexibility of the UAV swarm, thus improving the robustness and efficiency of task completion. During the formation, UAVs are required to autonomously fly between different locations to avoid collision between obstacles and UAV members [33]. Moreover, the collision avoidance between UAVs in the swarm also needs to be taken into consideration. When some UAV members fail or are damaged, the swarm can effectively reconstruct the formation based on the remaining UAVs.

Extensive formation control strategies are proposed for UAV swarms, and most of them focus on control algorithms design for formation generation, formation maintenance, formation transformation, and obstacle avoidance. In this paper, a systematic analysis and comparison is provided for the existing UAV swarm communication networks and formation control methods. First, the most commonly used UAVs are introduced and compared. Then, the formation task is described, which includes the assignment of feasible formation, generation, and maintenance of formation, collision avoidance, and switching between formations. Next, the communication network, such as star topology network, ad hoc network, and mesh network, is analyzed. At last, the existing formation control strategies of the UAV swarm are compared, and the challenges and prospects of the formation control is provided.

The rest of this paper is organized in the following manner. The classification of the UAVs is provided in Section 2, and the formation task statement is given in Section 3. The communication network and formation control for the UAV swarm are reviewed in Sections 4, and 5, respectively. Section 6 illustrates the challenges and prospects of the UAV formation, and Section 7 concludes this paper.

2 | CLASSIFICATION OF UAVS

With the rapid development of UAV-related technologies, a wide variety of UAVs have been proposed. According to the structure, UAVs can be classified into fixed-wing UAVs [30], rotor UAVs [34], tilt-rotor UAVs [35], tail-sitter UAVs [36], and so forth, as shown in Figure 2.

2.1 | Fixed-wing UAV

The fixed-wing UAV is a type of aircraft that relies on propellers or turbine engines to provide forward power and force relative movement between the wings and the air to generate lift [37, 38]. Due to its unique aerodynamic advantages, fixed-wing UAVs have payloads, fast flight speed, low-energy consumption, and long endurance. They are suitable for large-scale and long-distance missions, which play an increasingly crucial role in the military and civil fields [39]. However, the flight of the fixed-wing UAV depends on the forward speed, which makes it unable to hover. Moreover, the fixed-wing UAV needs a runway for take-off and landing. It is difficult to be satisfied in many task environments [40, 41].

2.2 | Rotor UAV

The rotor UAV is one of the most popular drone types, mainly including quadrotor UAVs [42, 43], hexarotor UAVs, and octorotor UAVs [44–47]. The rotor UAV flies based on the lift generated by multiple rotors. By controlling the motor speed to adjust its attitude and speed, the rotor UAV can fly to its desired position smoothly. The rotor UAV has the advantages of simple and flexible structure, capable of vertical take-off and landing, and simple operation. It can hover and fly at a small speed, which is usually utilized for small-scale tasks such as electric power inspection [48]. However, since the lift generated by the propeller must be greater than its own gravity, its energy consumption is high, and it limits the fuel carrying capacity, which results in the short flight time. Moreover, the use of rotating wings also limits the flying speed of the UAV due to the shock wave at the leading edge of the wingtip and the stall of the trailing blade near the fuselage.

2.3 | Other UAVs

Tilt-rotor UAVs and tail-sitter UAVs are also commonly used drones, especially in military applications [49, 50]. The tilt-rotor UAV is a mixed version of the fixed-wing and rotor UAVs, where a set of rotor tilting system that can rotate between the horizontal and vertical positions are installed on the tips or middle of the two wings in the fixed-wing UAV [51]. When the UAV takes off or lands, the rotor axis is perpendicular to the ground, which makes the tilt-rotor UAV have the capabilities of vertical take-off and landing like the rotor UAVs. When the tilt-rotor UAV flies in the air, the rotor shaft is tilted at a certain angle to form a structure similar to the fixed-wing UAVs, then it has a high-speed cruise capability. However, the complicated structure of the tilt-rotor UAV makes it have a higher potential failure rate [52]. Moreover, when the rotor gradually tilts from the vertical direction to the horizontal direction, the UAV is easy to stall since the upward lift is changed to the forward pull force, easily leading to a flight accident.

TABLE 1 Comparison of UAVs

Types	Advantages	Disadvantages	Suitable applications
Fixed-wing UAVs	1. Large payload 2. Fast flight speed 3. Low-energy consumption 4. Long endurance	1. Unable hover 2. Relying on runway	Large-scale and long-distance missions, such as remote sensing mapping
Rotor UAVs	1. Simple and flexible structure 2. Capable of vertical take-off and landing 3. Simple operation	1. High-energy consumption 2. Short flight time 3. Limited flying speed	Small-scale tasks, such as electric power inspection
Tilt-rotor UAVs	1. Capable of vertical take-off and landing 2. High flight speed 3. Long-distance cruise	1. Complicated structure 2. High cost 3. Great probability of flight accident	Civil fields such as forest fire prevention and military fields such as marine surveillance
Tail-sitter UAVs	1. Capable of vertical take-off and landing 2. High-speed 3. Long-distance cruise	1. Strong dynamic coupling 2. Poor wind-resistance performance	Military missions such as rescue, search, reconnaissance, aerial mapping and transportation

For the tail-sitter UAV, it also combines the advantages of fixed-wing and rotor UAV. It takes off, lands, and hovers in the vertical state of the fuselage. After the fuselage is tilted to the horizontal direction, its flight mode is consistent with that of the fixed-wing UAV [53]. Through this operation, it can not only get rid of the dependence on the long runway in the take-off environment but also have the capabilities of the high-speed and long-distance cruise. It becomes a new trend in the development of shipborne drones. However, it still exists problems such as strong dynamic coupling, which makes its control algorithm design quite difficult [54].

2.4 | Comparisons

From the above analysis, it observes that the fixed-wing and rotor UAVs are the two basic and most commonly used aircrafts. On the one hand, the fixed-wing UAV has been proven to be a reliable, long flight time, and high cruise efficiency aircraft, but it cannot hover or flight at a low speed. On the other hand, the rotor UAV has the operational flexibility, where it can vertically take off, hover and land. However, it usually has certain limitations when flying forward, such as lower flight speed and poor endurance. Other types of UAVs, such as the tilt-rotor UAV and the tail-sitter UAV, are the modified versions to take the advantages of both fixed-wing and rotor UAVs. However, they all have their own problems and deficiencies. The detailed comparison of the existing commonly used UAVs is illustrated in Table 1.

3 | FORMATION TASK STATEMENT

During the execution of the task, the UAVs in the swarm usually need to follow a scheduled trajectory while maintaining a required formation shape [55, 56]. The target of formation control is to design control algorithms to make the UAV swarm achieve typical formation generation [57], maintenance [58], and switching with utilizing the detected environmental information and interactive information between UAVs [59]. The main contents of formation control include: assignment of feasible formation, generation and maintenance of formation [60, 61], collision avoidance [62], and switching between formations [63].

3.1 | Assignment of feasible formation

In practice, the UAV swarm can take different formation shapes in the mission to accomplish complicated tasks such as coordinated reconnaissance, defense, and offense. As illustrated in Figure 3, the most commonly used formation shapes are straight line, diamond, wedge, snake, and

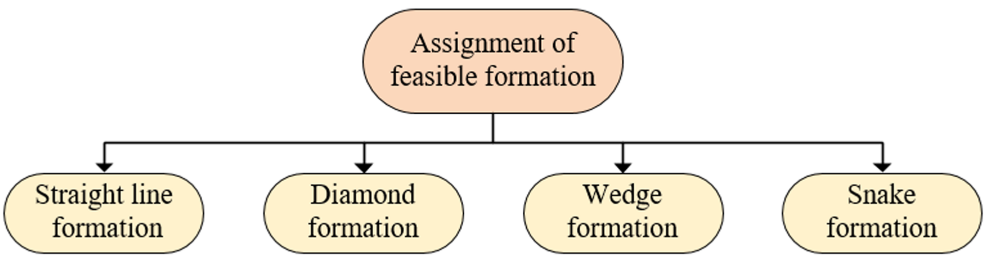

FIGURE 3 Feasible formation shapes

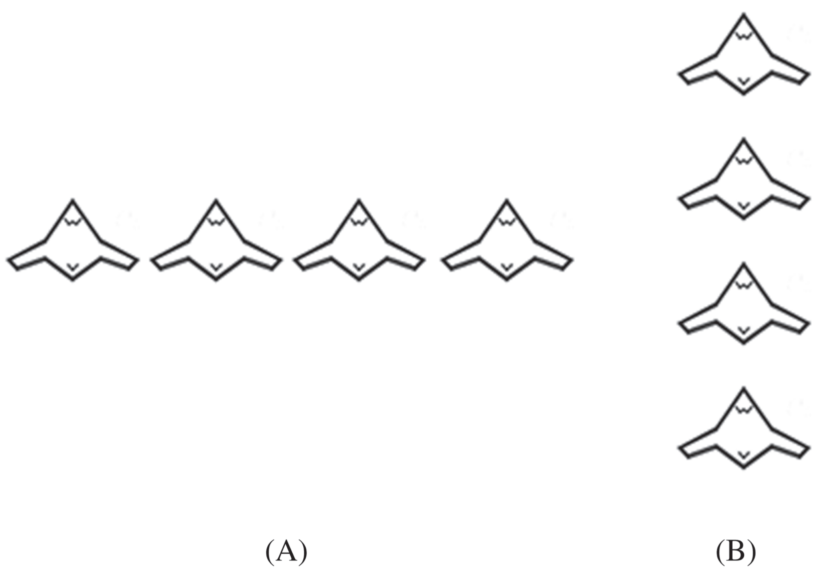

FIGURE 4 Two types of straight line formation: (A) lateral formation and (B) vertical formation

so on. Each formation shape has its unique characteristics and is suitable for some specific tasks. Reasonable and effective formation shape design can reduce the fuel consumption, extend the flight distance of UAVs, and increase the formation flexibility, which greatly improves the safety and mission completion rate of the UAV swarm [64, 65].

The detailed description of the commonly used formation shapes is as follows:

- **Straight line.** As shown in Figure 4, the formation shape with a straight line can be divided into two types: lateral and vertical. In the straight line formation, all UAVs in the swarm are at the identical height and have the same adjacent distance. The lateral formation is usually utilized to search for targets in a large area, since it can bring a large search horizon. It can effectively shorten the search time and improve the search efficiency. The vertical formation is commonly applied to the mission scenarios with airdrops and threat avoidance.
- **Diamond.** In Figure 5, all UAVs are distributed in a diamond shape at the same height, namely, diamond formation. The main purpose of this formation is to protect important targets, where the targets are in the middle of the diamond [66]. When the formation encounters a powerful enemy, the UAVs will protect the important targets and quickly evacuate the battlefield in a diamond shape. Besides, the UAVs could attract the firepower of the incoming enemies if necessary, which can ensure the safety of the important targets to the greatest extent [67].
- **Wedge.** The UAVs are distributed in a wedge shape and diagonally behind the two sides of the drone leader, as shown in Figure 6. According to the analysis based on numerous tests, the UAV followers can obtain the highest aerodynamic efficiency, when the relative distance between the followers and the leader is $d = [dx, dy, dz]^T = [2b, (b\pi)/4, 0]^T$, where b is the wingspan of the UAV leader. Through this formation, it can effectively reduce the fuel consumption of the UAV followers, thereby increasing their flight time. In practice, the wedge formation is often used for the UAV swarm to perform the tasks of patrolling and bombing.
- **Snake.** The serpentine shape is a special formation, where the UAV swarm imitates a snake to move forward. As illustrated in Figure 7, the UAVs follow the drone leader one by one in a serpentine curve. When the number of UAVs in the swarm increases, they join the rear of the formation according to the law of the curve. The serpentine formation is very flexible and is mainly used for long-distance formation trips.

FIGURE 6 Diagram of wedge formation

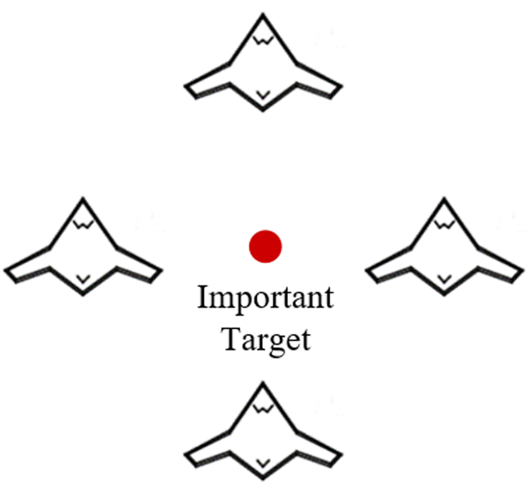

FIGURE 5 Diagram of diamond formation

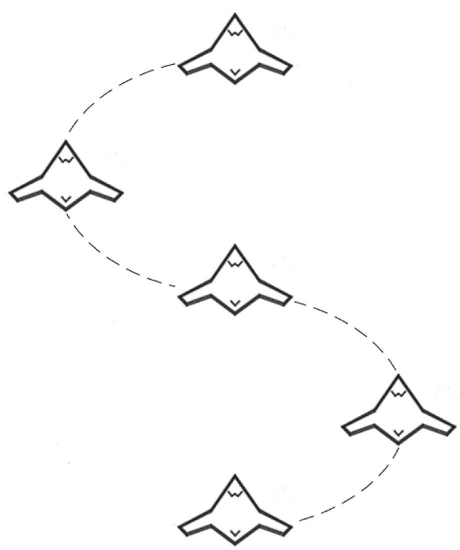

FIGURE 7 Diagram of snake formation

TABLE 2 Performance comparison of different formations

Feasible formations	Suitable applications	Energy efficiency	Flexibility	Safety
Straight line	Large-scale reconnaissance (lateral) Airdrops and threat avoidance (vertical)	3	3	3
Diamond	Protecting important targets	2	2	5
Wedge	Patrolling and bombing	5	3	2
Snake	Long-distance formation trip	3	5	2

Note: Scores of comparison: energy efficiency (1: low, 5: high), flexibility (1: low, 5: high), and safety (1: low, 5: high).

The performance comparison of the above-mentioned formations is illustrated in Table 2 in terms of suitable applications, energy efficiency, flexibility, and safety, where the scores ranging from 1 to 5 are used to quantify the corresponding performance of the last three factors. Note that all kinds of UAVs mentioned in Table 1 can perform these four types of formations. In practice, suitable formation shapes and UAV types are usually assigned according to the demands of the specific tasks with consideration of their advantages.

3.2 | Formation generation and maintenance

Formation generation is the basis for the UAV swarm to perform formation tasks [68], as shown in Figure 8. For any initial positions and velocities of the UAVs, the UAV swarm can form a formation in a specific shape that is suitable for the task requirement through controlling their relative positions and velocities based on the interactive communication information between UAVs or the communication between the UAVs and the ground station, where the UAV flight and environmental constraints should be satisfied. After the formation is generated, the UAV swarm should maintain that formation shape and keep moving to complete the mission with the same speed [69]. The related research focuses mainly include:

1) To make the UAV swarm complete the formation in a relatively short time.
2) To minimize the total energy consumption of all UAVs during the formation generation process.
3) To ensure that multiple drones will not collide with each other or with external obstacles.

The existing formation generation control methods can be divided into two categories: offline trajectory planning and real-time trajectory control [70, 71]. By utilizing the offline trajectory planning method, the real-time computing restrictions do not need to be satisfied, and an optimal trajectory can be assigned with consideration of complicated multi-objective optimization. It is easy to be implemented, and the communication between UAVs is not needed. However, once the offline trajectory planning is finished, the corresponding route is determined, which results in that the formation has low flexibility and poor disturbance rejection ability. The real-time trajectory control refers to a real-time adjustment of the speed and acceleration of the UAVs according to their current positions so that the UAV swarm can complete the formation task. It can provide better formation performance with higher robustness and smaller formation position error than the offline trajectory planning method. But it brings a large amount of computational burden to the UAVs' controllers. After the formation of the UAV swarm is completed, the relative position and speed of each UAV are kept within a certain small range. Then, the control goal of the formation changes to how to control the UAVs to maintain the required formation shape.

3.3 | Collision avoidance

In the task environment, there usually exist many uncertain moving or stationary obstacles, which may bring potential dangers to the UAV swarm [72, 73]. Hence, collision avoidance is one of the fundamental requirements of the UAV formation control, which is crucial to ensure the safety of the UAVs. To perform collision avoidance, the formation can be disbanded first, and then the formation should be resumed again after flying through the dangerous area [74, 75]. Under some environmental conditions, the UAV swarm can also maintain the formation and fly through the obstacle space. Therefore, how to achieve coordinated obstacle avoidance of multiple UAVs so that they can maintain their formation while avoiding obstacles remains to be studied. The characteristics of proximity interaction, group stability, and environmental adaptability during the flock flight process are similar to the autonomous, coordinated, and intelligent control requirements of the UAV formation [76]. In practice, the collision avoidance control process can be divided into environmental assessment, obstacle recognition, and implementation of obstacle avoidance (shown in Figure 9).

- **Environmental assessment:** The collision should be both avoided between the UAVs and between the UAVs and the obstacles [77]. During the flight of the UAV formation, the environment of the route is usually uncertain, which includes non-cooperative and cooperative obstacles. The non-cooperative obstacle means other

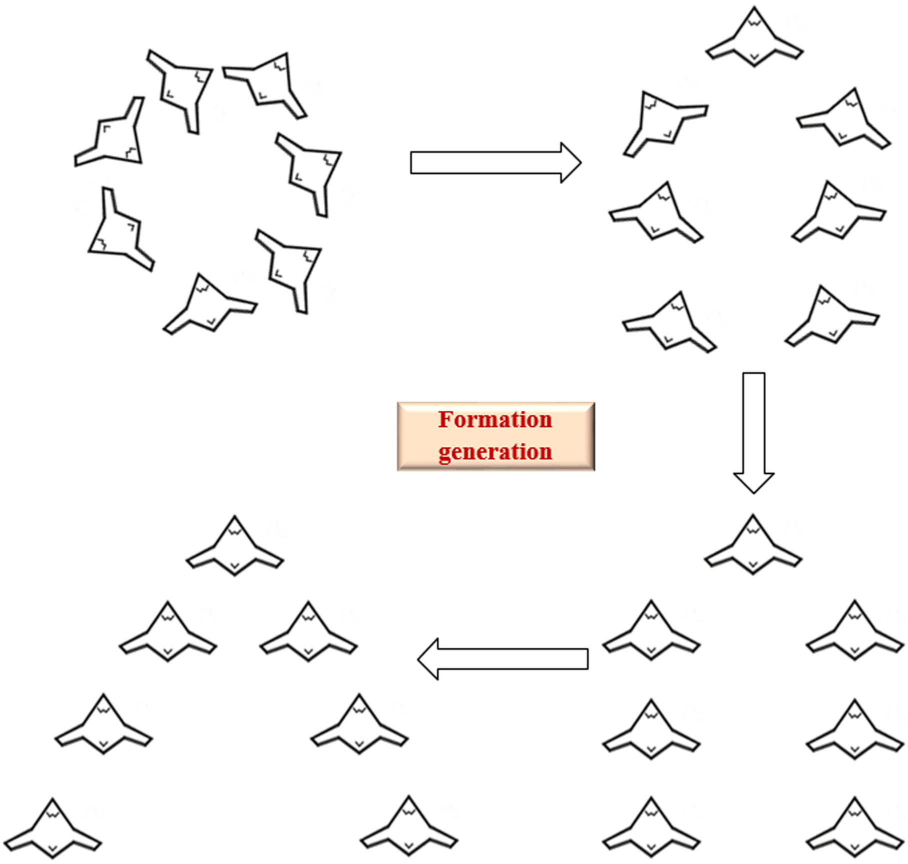

FIGURE 8 Formation generation process [Color figure can be viewed at wileyonlinelibrary.com]

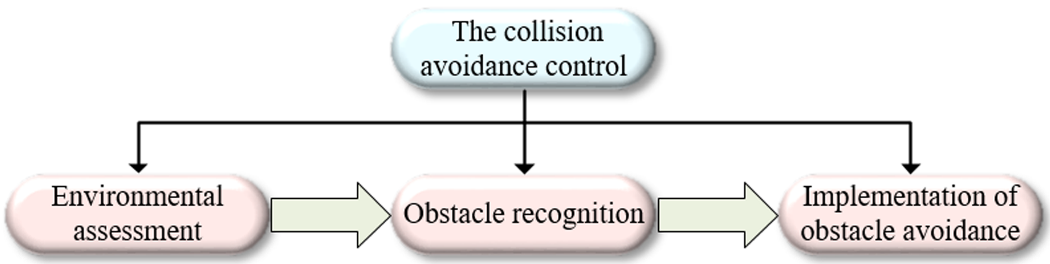

FIGURE 9 Collision avoidance control process

objects in the flight environment that may collide with the UAVs. It includes movable and stationary obstacles, where the UAVs of other teams or enemies are commonly encountered dynamic obstacles, and the stationary obstacles usually are mountains, buildings, and so on, as shown in Figure 10. Moreover, the UAVs are also moving obstacles to their surrounding UAVs in the formation, as illustrated in Figure 11. They can be treated as the cooperative obstacles for a certain UAV, since the UAVs can cooperate to avoid collision between them. The collision between UAVs will also bring huge losses and should be avoided [78].

In order to be able to better deal with the uncertain obstacles in the flight environment, perform coordinated tasks, and reasonably avoid obstacles in the formation flight, it is necessary to combine the airspace environment information, drone status information, and formation task information through mathematical modeling methods to establish the environmental assessment model to provide a better planning basis for collaborative planning tasks.

- **Obstacle recognition:** It is very important to quickly and accurately recognize obstacles for the formation, which is the basis of obstacle avoidance control. Usually, the UAV is equipped with radar, photoelectric, infrared, and other sensors to measure the environmental information of the route airspace [79]. Then, through matching the detected data with the specific information in the database, the obstacles can be identified. The distance between the obstacle and the UAV can be determined through measuring the flight time between the reflected and the original transmitted radar,

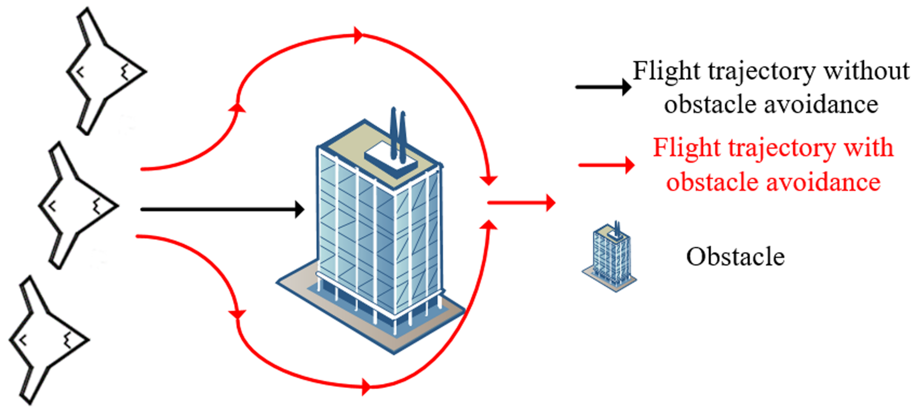

FIGURE 10 Potential collision between UAVs and obstacles

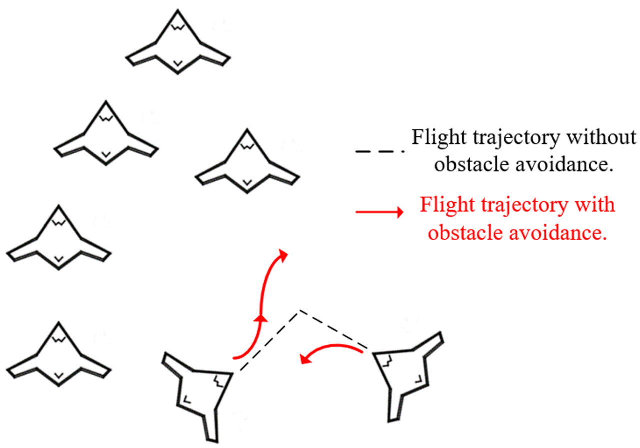

FIGURE 11 Potential collision between UAVs

photoelectric, or infrared signals [80]. The rapid detection and recognition of the obstacles and the distance between the obstacles and the UAVs by sensors equipped in the UAV, and even assisted positioning are the focus of research of obstacle recognition.

Low-cost ultrasonic and infrared range finders are utilized in Gageik et al. [72] as the distance measuring sensors. With data fusion, better performance of collision avoidance can be achieved. In Lyu et al. [81], a vision-only based sensor system is utilized for the collision avoidance of UAVs, and a two-dimension dynamic safety range is generated to capture the threat level of the non-cooperative obstacles.

- **Implementation of obstacle avoidance:** In the formation, it is necessary to consider avoiding collisions with neighboring UAVs and maintaining a predetermined distance to the greatest extent. Therefore, although the UAV detects the obstacle, the obstacle avoidance strategy is activated only when the obstacle is close to the UAV formation that could bring potential threatens the UAV. When the sensor equipped in the UAV detects that the distance between the UAV and the obstacle reaches to be less than a safety distance, it needs to perform obstacle avoidance operations immediately to ensure the safety of the UAV. As shown in Figure 12, the control input of UAV formation can be designed in the form of virtual repulsion force, where the formation repulsion force is calculated based on the distance between the UAVs and the obstacles. When the actual distance between the UAVs and the obstacles is larger than the preset safety distance, the repulsion force is set as zero, which indicates that obstacle avoidance behavior is not performed. Otherwise, the formation repulsion forces the UAV to move in the opposite direction, thereby avoiding collisions between the UAVs and the obstacles. Note that the repulsion force is not real and is only a virtual control variable for the UAV controller.

  The proportional navigation guidance law based method is proposed in Han et al. [82] for the optimal collision avoidance of the UAV swarm. A dual-mode control algorithm is designed in Wang et al. [62], which includes safe and danger modes. The safe mode and danger mode correspond to the situations with obstacle-free environment and potential obstacles in the path, respectively. In the danger mode, a modified Grossberg neural network based method is developed to avoid collision. The artificial potential field method is utilized in Zhang et al. [83] that can effectively enable the UAVs to avoid collision. In Lin and Saripalli [77], a sampling-based path planning method is proposed for collision between the UAV and the moving obstacles.

3.4 | Formation transformation

For the UAV swarm, a complicated mission often consists of several tasks in sequence. To more effectively deal with these tasks, reasonable formation shape switching is necessary during the missions with comprehensively consideration of the flight and environmental constraints. Especially, in the face of complex environments and sudden changes in the tasks, how to switch to the most suitable formation shape in the shortest time is a crucial and interesting topic. As shown in Figure 13, the UAV

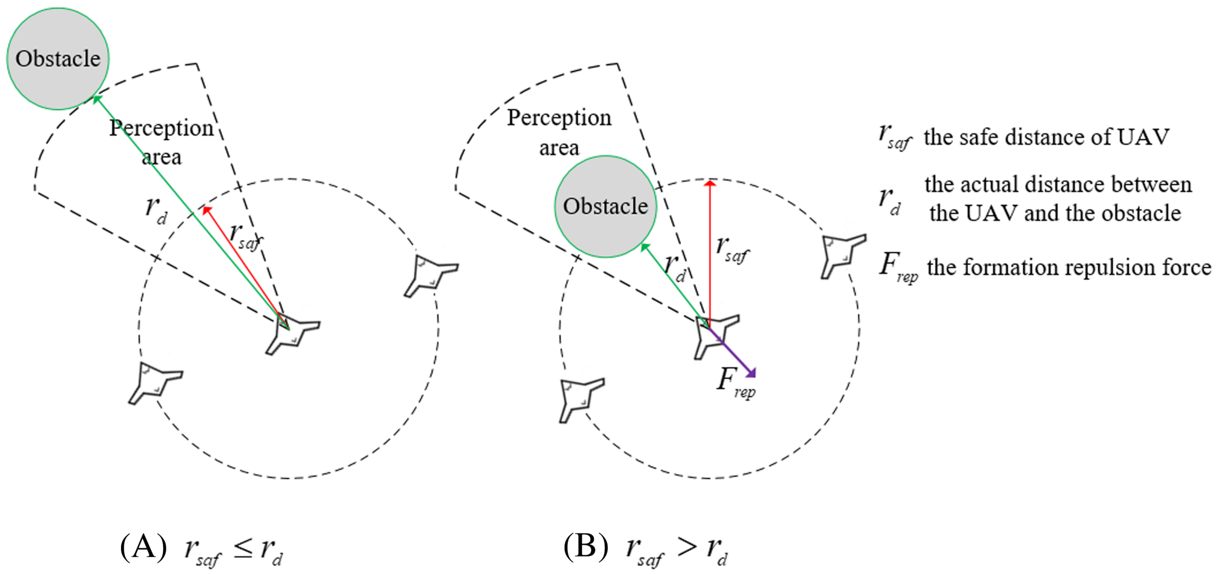

FIGURE 12 Control of executing obstacle avoidance

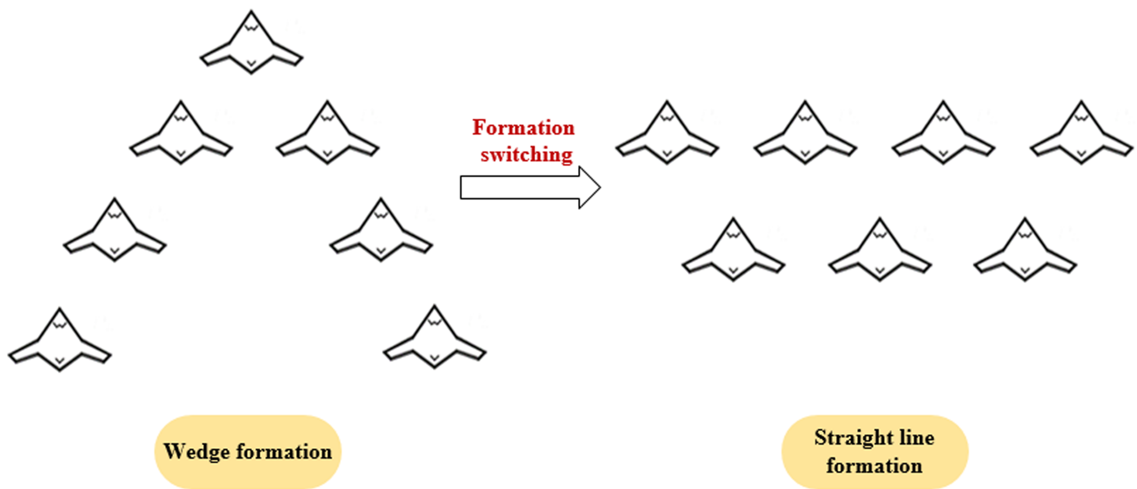

FIGURE 13 Switching from wedge formation to straight line formation

formation finds suspicious targets when patrolling so that its formation shape changes from the wedge formation to the straight line formation to search and track targets in a large area. When performing formation switching, the consumed switching time is one of the most important indicators to evaluate the performance of the formation switching technology.

Lin et al. in [84] propose a formation transformation strategy by controlling the formation spacing between UAVs, which can effectively realize the real-time transformation of formation. In Bayezit and Fidan [58], the formation reconfiguration of the UAV swarm is formulated as a constrained optimal control issue, and the hybrid particle swarm optimization and genetic strategy are designed to solve it to obtain the optimal trajectory of the formation transformation. A formation reconfiguration method based on segments is proposed in Giacomin and Hemerly [85] to achieve the formation transformation between longitudinal and circular formations. With utilizing a modified artificial physics strategy, a formation switching method is proposed in Lincheng et al. [86].

4 | COMMUNICATION NETWORKS OF UAV SWARMS

When the UAV swarm performs the formation mission, an effective and reliable communication network is indispensable, where the UAVs do not completely rely on the control of facilities such as ground stations or satellites. The communication network enables the connection and collaboration among UAVs possible [87, 88]. There are many kinds of communication networks that have been

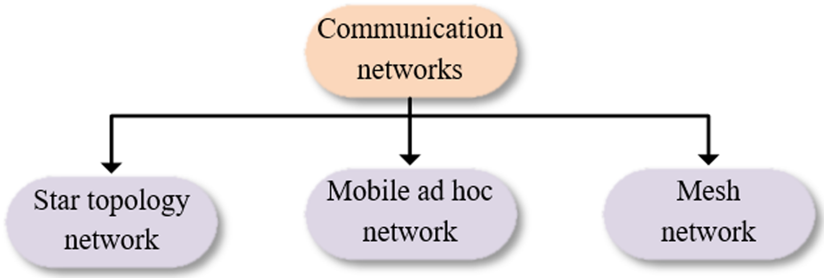

FIGURE 14 Classification of communication networks

developed for the UAV swarm, such as star topology network [89], mobile ad hoc network [90], and mesh network[91], as shown in Figure 14. Each network has its own advantages and disadvantages. Their detailed introduction is as in the following part.

4.1 | Star topology network

At present, most strategies use the ground station to directly control UAVs through the communication network of star topology, as illustrated in Figure 15. In the star topology, there exists a central UAV (also called a central node), and other UAVs in the formation are connected to the central in a point-to-point manner [92]. The central UAV receives the instructions from the ground station and transmits the corresponding information to the destination UAVs. Since other UAV is only connected to the central UAV, the access protocol is very simple, which makes this network easy to be implemented and managed [93]. Moreover, the failure of any other UAV except the central UAV does not affect the entire network. However, the central UAV implements a centralized communication control strategy, so the computational burden of the central UAV is quite complicated and much heavier than other UAVs [94]. Moreover, the communication between any two UAVs in the star network must pass through the central UAV. If the central UAV is crashed or damaged, the entire communication network will fail.

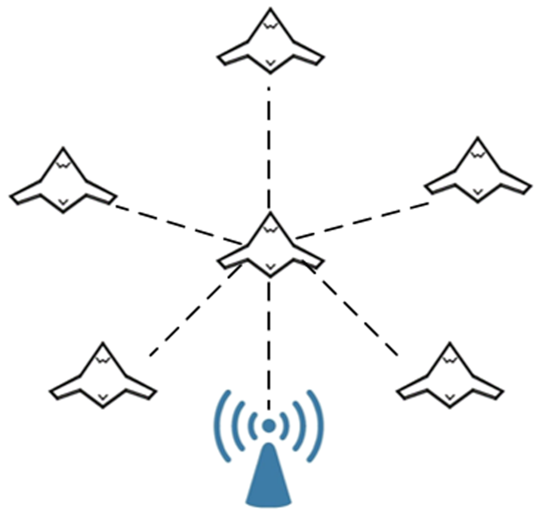

FIGURE 15 Diagram of star topology network

4.2 | Ad hoc network

The ad hoc network is a multi-hop self-organizing network composed of mobile nodes, also known as multi-hop network, infrastructureless network, or self-organizing network [95, 96]. The entire network has no fixed infrastructure, where each node is mobile and can dynamically maintain contact with other nodes. The ad hoc network has the characteristics of centerless and self-organization, which is especially suitable for coordinated operations of the UAV swarm. Not limited to the network structure centered on the control base station, its multi-hop communication mode breaks through the constraint that the UAV can only work within the communication range of the base station [97, 98]. In this kind of network, due to the limitation of the communication coverage range, two

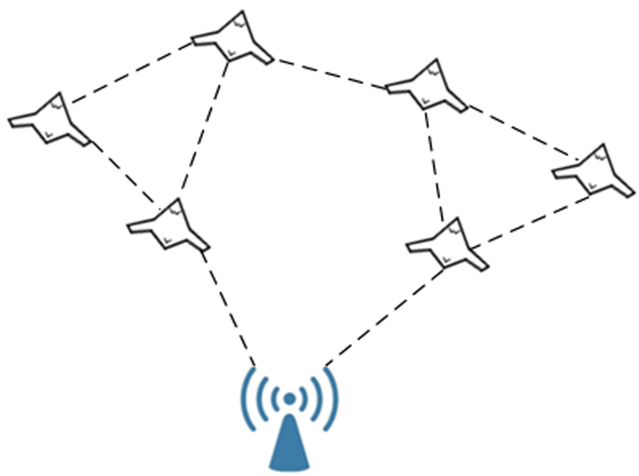

FIGURE 16 Diagram of mesh network

UAVs with a long distance do communicate directly but use other UAVs as the repeater to transfer messages, which can effectively expand the network coverage atmosphere. But its characteristics of multi-hop, self-organization, centerlessness, high moving speed, and rapid network topology change also bring new challenges and requirements to the design and implementation of UAV communication systems [99]. Overall, compared with the star topology network, it has the following advantages:

1) In the ad hoc networks, there is no strict control center; that is, it is a peer-to-peer network. All UAVs in the swarm have equal status. The failure of any UAV will not affect the operation of the entire network.
2) The ad hoc network equipment is deployed on the UAV, which does not need to rely on any preset network facilities. The network nodes coordinate their respective behaviors through layered protocols and distributed algorithms, and the UAVs can quickly and automatically form an independent network.
3) The ad hoc network is a dynamic network. The UAVs can join in and leave the formation (network) at any time. Although the topology of the network changes, the communication network still works with good performance.

With the maturity of military UAV technology and the increasing number of equipment, the ad hoc large-scale network can adapt to the changes of highly dynamic topology and maintain good communication performance capabilities and challenges [100]. Many distributed gateway-selection methods and cloud-based stability-control mechanisms are summarized in Wang et al. [101] to guarantee the stability of the ad hoc network.

4.3 | Mesh network

The mesh network is also a self-organizing network, where the network nodes are divided into several clusters. Each cluster is composed of the cluster head and the cluster members [92]. The cluster head is responsible for maintaining information transmission, data aggregation, and communication between clusters. The cluster members only need to complete the communication with the cluster heads. Clustering mainly includes two stages: cluster generation and cluster maintenance. At the initial stage of network establishment, all nodes are in an isolated state. Each node finds a suitable cluster head and joins the cluster according to the message of neighbor nodes. The mesh network topology is adopted within and between clusters corresponding to the above clustering scheme, as illustrated in Figure 16. Note that the mesh network is flexible and reliable and can provide high performance. In a mesh network, communication nodes are connected to each other, and a node can usually communicate directly with multiple nodes [101, 102]. In addition, the mesh network has a multi-hop feature, and a data packet of a node can be forwarded from the source node to the destination node through other intermediate nodes. The mesh network has the self-healing capability, that is, the ability to reconfig-

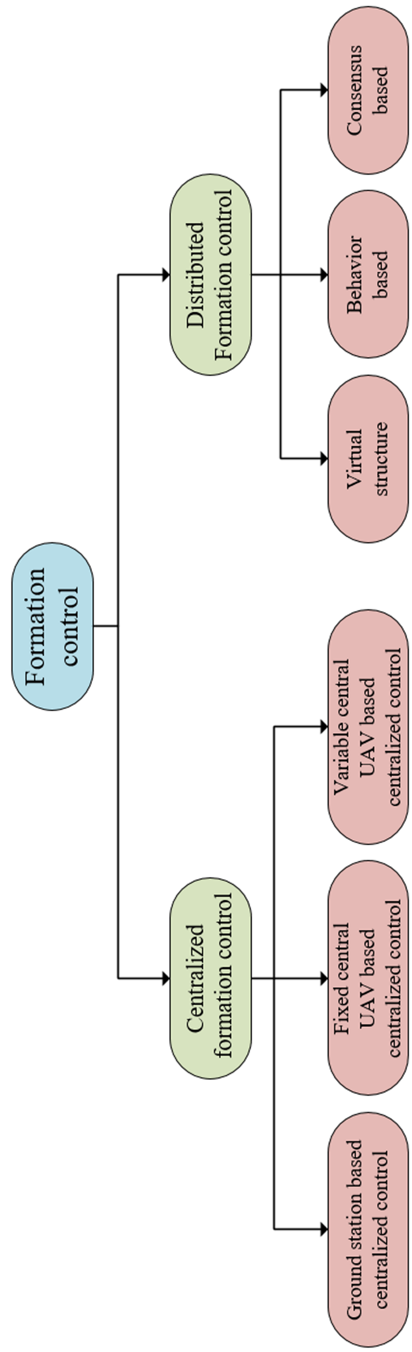

FIGURE 17 Classification of formation control

ure disconnected connections. In the mesh network, the UAVs in the formation are connected to each other, and a few UAVs are directly connected to the ground station. The mesh network is suitable for the UAV formation due to its features of flexible, reliable, and self-organizing networking [103]. Moreover, the mesh network has the advantage of easy implementation. Compared with the ad hoc network, the mesh network can form a large network that could accommodate more UAVs.

5 | FORMATION CONTROL OF UAV SWARMS

The formation of the UAV swarm requires the UAVs in different states to cooperate to move with a preset formation shape, which is a complicated task [104]. It relies on effective formation control strategies to enable the UAV swarm to autonomously form and maintain a formation to perform tasks and switch and reconstruct the formation due to specific tasks. According to whether there exists a control center in the UAV formation, the formation control methods can be divided into centralized based and distributed based, as shown in Figure 17 .

- In the centralized formation control strategies, there is a control center in the formation, and all UAVs send their status information to the control center for unified processing. Among them, the control center can be a drone, a ground station, and so on [80]. Moreover, the control center can be fixed or changed during the task.
- The distributed based formation control does not rely on the control center, and all UAVs have equal status in the formation. Each UAV has a certain degree of autonomous control and decision-making capabilities and can interact with other UAVs based on the connectivity of the topology network [105]. Under the distributed cooperative control, the formation of the UAV swarm can be realized.

5.1 | Centralized formation control

Under the centralized formation control (as shown in Figure 18), there is a control center in the formation, and the UAVs in the swarm receive the control commands from a powerful control center, which can be either a central UAV in the formation with strong computational capability or a ground control station [106]. All UAVs send their own status information or perceived information to the control center, and the control center transmits the control information to each UAV through data processing, task planning, and control decision making to ensure the UAV swarm to accomplish the specified formation tasks. The characteristics of centralized control are centralized organizational structure and global information processing.

Under the centralized control, the control center uses global information of the whole UAV swarm for analysis and decision making. Since it can obtain the global optimization solution, the centralized structure can well handle tasks with complex control requirements and provide high control performance. However, its most fatal weakness is that the control system relies on the control center. When the control center fails, all UAVs will be out of control, and the formation is hard to be maintained [107]. Hence, the centralized structure has poor resistance to destruction and poor robustness. Since all UAV shares information with the control center, it brings a large amount of computational burden to the control center, especially for the large-scale UAV swarm. Therefore, the centralized structure is suitable for the tasks with low real-time requirements and high control performance requirements.

According to different types of control center, the centralized formation control can be classified into ground station based, fixed central UAV based, and variable central UAV based.

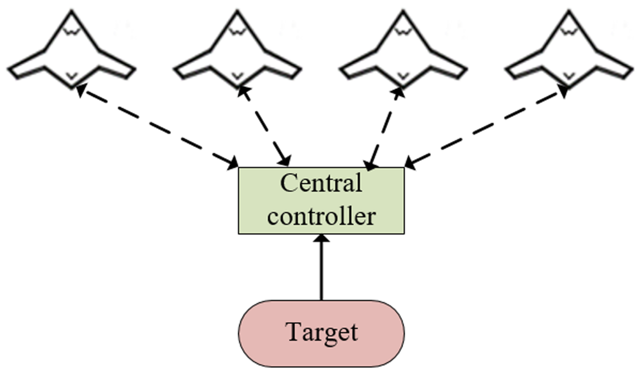

FIGURE 18 Centralized formation control

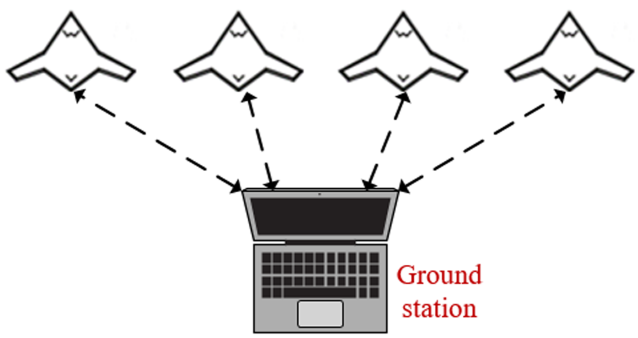

FIGURE 19 Ground station based centralized control

5.1.1 | Ground station-based centralized control

Taking the ground station as the control center means that the UAV formation is controlled by the ground station through the wireless data link, where the mission control algorithm is deployed on the ground station [108]. The ground station effectively supervises, commands, and controls the flight and communication of the UAV swarm during its mission execution. This control structure does not need the strong decision-making ability of each UAV platform, but has high requirements for the decision-making ability of the ground station.

As shown in Figure 19, the ground station needs to have good interconnection, interoperability, and interoperability with the UAV swarm. The ground station receives the UAVs' current states and detected environmental information from the UAVs. At the same time, the ground station transmits mission instructions and control commands to them and can even directly control the UAV to flight in some cases. These information interactions can be initiated automatically at some particular time intervals or by the ground station at any time as needed.

The ground station is utilized as the only central control center, which can reduce the structural complexity of the control system. However, all information fusion and auxiliary decision making are concentrated on the ground station, which requires the ground station to have a large amount of computing power. For large-scale complex problems, it takes a long time, and it is difficult to find the optimal solution [109]. Moreover, due to the time delay between the UAV and the ground station, the real-time control requirements of UAVs may not be satisfied, which will lead to a decrease in control performance, and even some UAVs will be out of control.

5.1.2 | Fixed central UAV-based centralized control

In many tasks, the UAV formation flies in the region that is far from the ground station, which is accompanied by large communication interference that inevitably affects the reliability of communication between the UAVs and the ground station [110]. To solve this problem, the control center is moved from the ground station to a certain central UAV in the formation. All other UAVs in the formation transmit their status information and perception information to the central UAV, and the central UAV makes unified decisions. One of the typical methods is the leader–follower control method. As illustrated in Figure 20, the leader–follower-based formation control method divides the UAVs into two categories: UAV leader and UAV followers, where the UAV leader is the control center of the formation. The UAV followers will move according to the position of the UAV leader and the preset formation shape [111]. The formation control problem is decomposed into: (1) The UAV leader calculates the trajectory of the UAV followers according to the relative distance between the UAV leader and the UAV followers, and (2) the UAV followers track the scheduled trajectory.

A leader–follower control algorithm is adopted in Yun et al. [112] to maintain a fixed geometrical formation while navigating the UAVs to follow desired trajectories. In AnhDuc and Horn [113], the artificial potential field strategy is combined with state feedback control to make the leader-following UAV swarm following a moving target. The advantage of the leader–follower formation control method is that it is easy to be implemented. The behavior of the swarm is determined by the UAV leader, which can reduce the requirements of the communication network [114]. It can also provide a highly accurate formation shape for the UAV swarm. However, the performance of

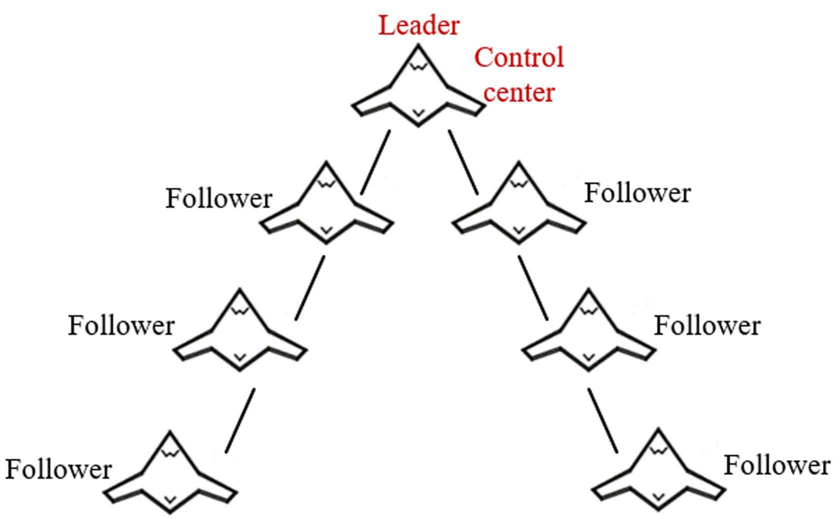

FIGURE 20 Leader–follower-based formation control

the formation highly depends on the robustness of the UAV leader; that is, once the leader is destroyed, the formation cannot be maintained. Moreover, for the formation with large numbers of UAVs, it brings a huge burden for the real-time communication network, which may result in loss of control of the entire formation [115].

5.1.3 | Variable central UAV-based centralized control

In practical applications, when the central UAV fails or crashes, the formation will lose the control center, and cannot continue to perform the mission. As an improvement, using the variable central UAV (leader) to replace the fixed control center has become a desirable centralized control method. The central UAV in the formation is chosen through the competition mechanism and can update at a certain time interval, which can not only increase the flexibility of the formation but also improve the stability of the formation. The contract network protocol [116, 117] is a typical competition mechanism. As shown in Figure 21, the UAV leader in the formation, namely, the control center, is changed through the inviting-tender-winning mode.

In the contract network algorithm, all UAVs in the formation are divided into three roles: tenderer, bidder, and bid winner. The tenderer is the current control center, which is responsible for the collection of the UAVs' information, the release, and management of control instructions [118]. The bidders are all UAVs in the formation, which evaluate the responsibility of the control center based on their own information and resources to determine whether to participate in the bidding. If it participates in the bidding, it sends a request to the bidder. The tenderer selects the next central UAV based on the request submitted by each bidder [119]. Then, the winning bidder is the UAV that becomes the new control center and takes over the task of the previous central UAV.

The formation control method based on the contract network protocol can automatically update the control center (leader) according to the preset period and constantly alternately select different central UAV to avoid the control center being damaged and the entire formation out of control. This control method can quickly reselect the central UAV in emergencies, thus ensuring the integrity of the formation and subsequent mission decisions and actions. Note that during the period when the control center is determined, fixed central control algorithms, such leader-follower method [112], can be used for formation control of the UAV swarm.

5.2 | Distributed formation control

The main feature of the distributed formation control is that there is no control center in the formation. All UAVs

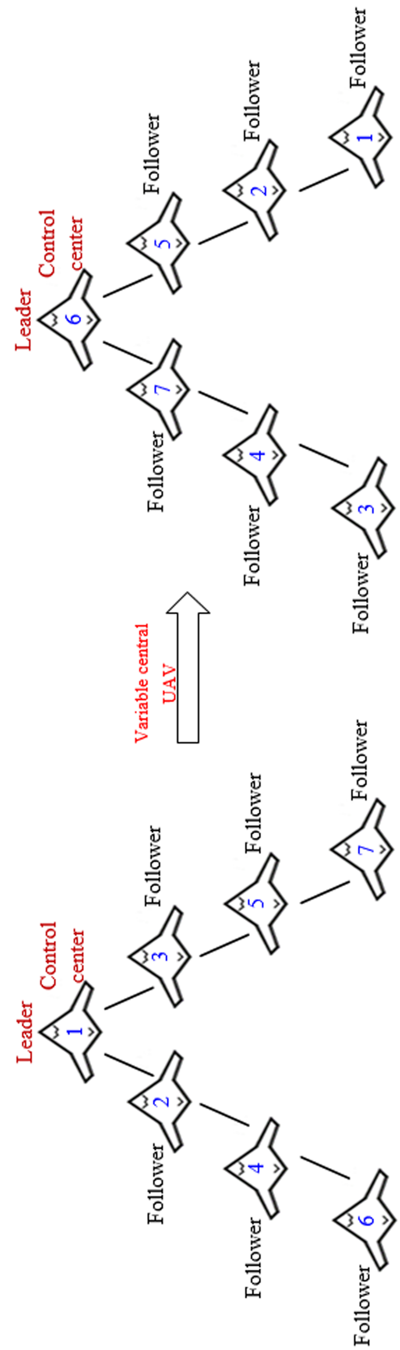

FIGURE 21 Variable central UAV-based centralized control

are equal in status and complete tasks through cooperation. Under the distributed control structure, the global control problem is decomposed into multiple subproblems and solved independently by the controller in each UAV [55]. Each UAV has a certain degree of autonomous control and decision-making capabilities and can interact with other UAVs based on the communication network, as shown in Figure 22.

Since the UAVs only interact with their neighboring UAVs under the distributed formation control structure, it can reduce the data processing pressure between UAVs without sacrificing the control quality [120]. The distributed structure makes the UAV swarm no longer rely on a unified control center. Each UAV can temporarily network with nearby UAVs, and the failure or damage of any UAV will not affect the operation of the entire formation. The formation control without a central node has strong fault tolerance, strong robustness, and high flexibility, which can reduce the impact of unexpected accidents on task execution. However, inadequate consideration of global performance can easily cause the problem of weak global optimization performance. Therefore, the distributed control architecture is more suitable for processing tasks with high dynamics and high real-time characteristics. The distributed formation control can be classified into virtual structure method, behavior-based approach, and variable consensus-based strategy.

5.2.1 | Virtual structure approach

The virtual structure-based formation control method treats the expected formation as a rigid virtual structure, and each UAV remains unchanged relative to a preset virtual point on the virtual rigid body [121]. When the formation changes, each UAV can move in synchronization with the virtual point to complete the actual formation. As shown in Figure 23, the virtual structure method uses a virtual point as a reference point; that is to say, this point does not actually exist, and the position of the UAV is in a geometric position relative to the virtual reference point [122]. Therefore, the virtual structure method is essential without a central node. The preset virtual points are mostly virtual UAV leaders, virtual formation geometric centers, or arbitrary virtual reference points. Generally, there are two formation control methods: the virtual UAV leader and the virtual formation geometric center[123].

A feedback formation control strategy using the virtual structure approach is presented in Ren and Beard [124] for the UAV swarm. In the virtual structure method, each UAV has the same status and does not rely on the central UAV to maintain the formation, which has strong robustness. It can achieve a high formation accuracy since the formation position error is utilized as the feedback in the designed control law [125]. But the virtual structure approach also has the drawback that it requires the UAVs to maintain rigid motion as a whole, which makes the formation movement inflexible, especially when the formation needs to avoid obstacles.

5.2.2 | Behavior-based approach

The behavior-based UAV formation control strategy is a distributed method, which controls the UAVs based on the

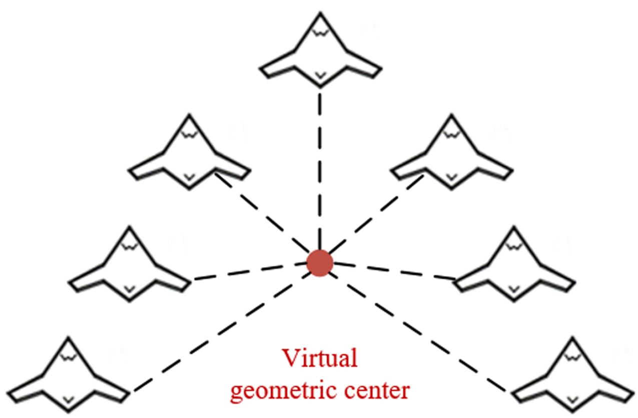

FIGURE 23 Virtual structure: Virtual geometric center

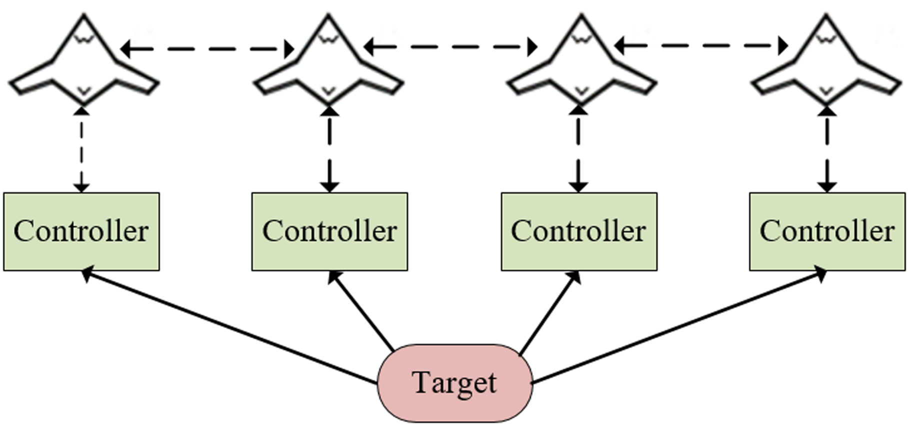

FIGURE 22 Distributed formation control

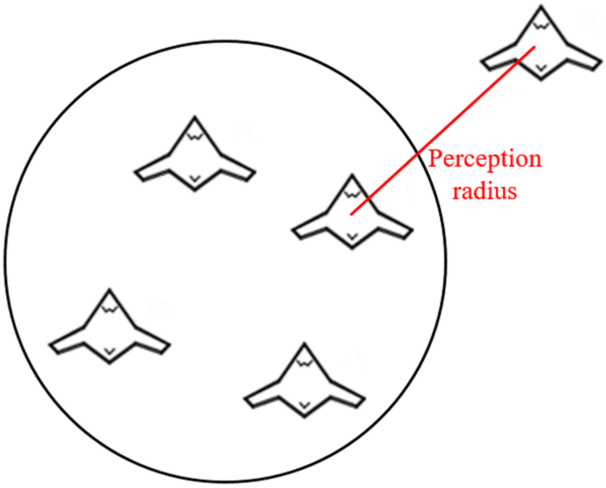

FIGURE 24 Behavior-based approach

basic behavior rules of UAVs. For example, it designs the rules for the separation, aggregation, and speed matching of the UAV swarm [126]. Each UAV uses its own sensors to obtain information of the UAVs in its surrounding sensing range and moves according to these rules, and then a group behavior will be formed in the formation, as shown in Figure 24. The behavior-based strategy focuses on the coordination mechanism between various basic behaviors and efficient coordination mechanism between behaviors, that is, how to choose behaviors based on the information of its adjacent UAVs [127]. It is essentially a distributed control method and will not be affected by the scale of the UAV swarm.

A behavior-based formation control algorithm is proposed in Tanner et al. [128], where a gradient-based term and a velocity consensus term in the control law are utilized for cohesion/separation and alignment of the UAVs, respectively. By combining the consistency and virtual navigation algorithms, a distributed self-organizing behavior-based UAV formation is proposed in Li et al. [129].

The behavior-based method requires relatively low communication volume and has high tolerance to individual UAV failures. Moreover, each UAV only needs its adjacent UAVs' information, which can be expanded the large-scale formation. However, it is difficult to directly intervene in the spontaneous behavior of the UAV swarm. This strategy cannot directly control the actual density, spacing, and shape of the formation, and it is hard to be used for the formation optimization.

5.2.3 | Consensus-based approach

In the consensus-based approach, the UAV swarm is treated as a multi-agent system, where each agent updates its state according to the state information of neighboring agents [130]. The consensus algorithm is constructed based on the distributed control structure and the network topology, which realizes that the state of the agent is consistent with the expected one. The consensus-based formation control method uses graphs to show the interaction between the UAVs in the formation and analyzes the formation problem in combination with graph theory and control theory [131]. The basic idea is controlling the speeds and relative positions of the UAVs within a certain range consistent, thus making the difference of all the UAVs' states convergence to zero. In the consensus-based formation control strategy, the problem is generally transformed into a consistency problem through the method of state transformation or matrix decomposition, and then an appropriate consistency theory is selected to analyze it.

The consensus control method adopts a distributed topology network structure, which has a strong robustness and high real-time performance [132]. It can be easily extended on a large-scale swam with more UAVs. However, it requires a high network communication quality with short communication delay.

5.3 | Comparison

In summary, the UAV formation control methods can be mainly divided into two types: centralized and distributed. The centralized formation control is based on a control center to collect information from each UAV, use global information for analysis and decision making, and send the control signals to the UAVs. But its weakness is that after the control center is destroyed, the formation tasks may fail directly, which demonstrates that the centralized control structure has poor anti-destroy ability and robustness. The distributed formation control does not specify a control center, and each UAV in the formation has an equal status and collaborates to complete tasks. The performance comparison of the above-mentioned formation control strategies is shown in Table 3. From the perspective of control algorithm, the distributed structure is easier to implement than the centralized structure, and it has good scalability and robustness. In practical applications, the UAV formation under the distributed control strategy is more autonomous than centralized one to work in the complex and changeable mission environment, which can flexibly respond to the emergencies. To the best of our knowledge, the centralized control strategies have been applied in real-world scenarios, such as target searching and drone light shows, while the distributed formation control strategies are still in the stage of laboratory research. It still has a long way for the practical applications of distributed formation control.

TABLE 3 Comparison of different formation control strategies

	Types	Advantages	Disadvantages
Centralized formation control	Ground station-based centralized control	1. Strong global optimization performance 2. Easy to implement	1. Large calculation burden 2. Poor anti-destruction
	Fixed central UAV-based centralized control [112, 113]	1. Easy to implement 2. Strong global optimization performance	1. Poor anti-destruction 2. Low autonomy 3. Large calculation burden
	Variable central UAV-based centralized control	1. High anti-destruction	1. High requirements for communication capacity 2. Large calculation burden
	Virtual structure approach [124]	1. High anti-destruction 2. High autonomy	1. Inflexible movement
Distributed formation control	Behavior-based approach [128, 129]	1. High anti-destruction 2. High autonomy	1. Hard for formation optimization
	Consensus-based approach [131, 132]	1. High anti-destruction 2. Quick response	1. Requirement of short communication delay

6 | CHALLENGES AND PROSPECTS

6.1 | Challenges

With the development of technology, using the UAV formation to perform missions has become a mainstream trend. However, the task environment of the UAV formation becomes more and more complex nowadays, and there is increasing electromagnetic interference in the communication transmission. They will all bring severe challenges to the mission of the UAV formation.

6.1.1 | UAV dynamics constraints

In most of the traditional formation control methods, each UAV is treated as a mass point and a simplified motion model is proposed to describe its dynamics. It ignores the actual complicated dynamic characteristics of the UAV to simplify the calculation process and reduce the complexity of the formation system. However, the UAVs' aerodynamics is very complex, and there exist many dynamic constraints, which results in that actual UAVs may fail to follow the desired trajectory.

6.1.2 | Uncertain environmental threat

The safety of the UAVs in the formation is one of the keys to the successful execution of the mission. The threats of UAVs mainly include the potential threat caused by the mission environment and other UAVs in the formation.

On the one hand, the mission environment of drone formations is increasingly complex, such as an urban environment with dense buildings, a mountain environment with mountain peaks and cliffs, and a forest environment with trees and birds. In addition, there are various uncertain flying objectives in the environment. The UAV formation easily faces the danger of collision.

On the other hand, the number of UAVs continues to increase in a modern formation, and the UAVs in the formation are most likely to collide or cause conflict due to factors such as path crossing or flight uncertainty during the task of formation shape changing.

6.1.3 | Communication constraints

The communication network is one of the foundations of the coordinated formation control. The communication generally considers the communication between the UAVs and the ground control station, and the communication between the UAVs in the formation. Due to the large number of UAVs, multiple types of tasks, fast UAV flight speed, frequent changes in the relative time–space relationship, and the immediacy and suddenness of information transmission, it makes a great challenge to the communication network in the UAV formation.

1) **High packet loss rate:** In the network, such as an ad hoc network, the network connection usually changes frequently, and the rapid change in the physical layer will make the original topology path unreliable, resulting in the loss of a large number of data packets, which severely limits the mission execution ability of the UAV formation.
2) **High network attack risk:** The wireless link makes the communication network vulnerable to cyber attacks, including passive eavesdropping and active counterfeiting, information replay, and information destruction. The communication device equipped in the UAV lacks physical protection when roaming in the enemy environment, which may cause the drone to be controlled by the enemy.

6.2 | Prospects

The research of UAV formation involves many aspects such as flight mechanics, automatic control, aerodynamics, network communication, decision making, and so on. It is a complex interdisciplinary research problem. With the in-depth study of various UAV formation algorithms, distributed control methods, consensus theory, network communication technology, and UAV formation control technology have been greatly improved. In the future, the development of the formation control of the UAV swarm gradually tends to the following aspects:

1) **Reasonable trajectory planning:** Most formation control methods ignore the UAVs' complicated dynamic characteristics, which results in that actual UAVs may fail to follow the scheduled trajectory. It necessaries reasonable trajectory planning on the premise of meeting the UAVs′ dynamics constraints and the formation mission.
2) **Intelligent UAV swarm:** The UAV swarm may face various emergencies during the execution of missions, e.g., unexpected collision threats. The complex mission terrain and moving or hidden targets also increase the difficulty of the mission. How to deal with these emergencies requires the UAVs in the formation to have a high degree of autonomy, be able to make autonomous decisions, change tasks in time, and automatically return to the formation. When some UAVs actively or passively leave the formation, the new formation can quickly be formed and remain stable. Some machine learning technologies, such as reinforcement learning, can be good solutions for decision making of the UAV swarm. The UAV swarm is trained to obtain the optimal behavior corresponding to the greatest reward, where the reward functions are set to be related to the mission target. After training, the UAV swarm can autonomously realize collision avoidance and other tasks.
3) **Decentralized control structure:** At present, most of the existing formation control strategies of the UAV swarm are centralized based. Through decentralization, the UAV swarm can use self-organizing network technology to realize information interaction between UAVs in the formation under a high dynamic communication network, and at the same time improve the anti-failure ability.

7 | CONCLUSION

The UAVs play an increasingly significant role in numerous applications such as reconnaissance, agricultural plant protection, electric power inspection, and emergency rescue and disaster relief due to their advantages of simple structure, low cost, and rapid maneuvering. In this paper, a comprehensive review and comparison of the UAV formation control are provided. First, the most commonly used UAVs are introduced and compared. Then, the entire process of the formation task is detailed described, and the widely used communication networks are analyzed. Finally, the existing formation control strategies of the UAV swarm are compared, which shows that the distributed formation control is superior to the centralized method. The challenges and prospects of the formation control are also provided. It demonstrates that the decentralization and intelligence are the future development trends.

AUTHOR CONTRIBUTIONS

Quan Ouyang: Conceptualization, investigation, methodology. **Zhaoxiang Wu:** Data curation. **Yuhua Cong: Zhisheng Wang**.

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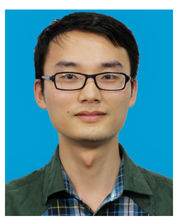

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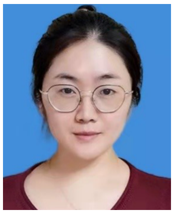

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