EAI Endorsed Transactions
on Industrial Networks and Intelligent Systems Research Article **EAI.EU**

Formation Control Algorithms for Multiple-UAVs: A Comprehensive Survey

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Abstract

Unmanned aerial vehicles (UAVs) have been widely deployed in many applications such as transportation, data collection, monitoring, or tracking objects. Nowadays, numerous missions require UAVs to operate in a large area or to complete missions in a stringent period of time. Using a single UAV may not meet the performance requirements because of its small size and limited battery. In this situation, multiple Unmanned Aerial Vehicles (UAVs) have emerged as an effective measure that can address these limitations. A group of UAVs cooperatively working together could offer a solution that is more efficient and economical than using a powerful UAV alone. To better utilizing the multiple-UAVs system, control of formation UAVs is a critical challenge that needs to overcome. Therefore, formation control has become an active research topic that gains great attention from researchers. Extensive research efforts have been dedicated to studying the formation control problem with numerous control protocols which have been proposed. This paper reviews the profound studies on formation control in literature. Each approach is investigated based on different criteria, which highlights its distinct merits and demerits. The comparison is provided to facilitate the readers in their future researches in the field of formation control. Finally, some open challenges and research directions are also discussed.

Received on 23 May 2021; accepted on 06 June 2021; published on 10 June 2021

Keywords: Unmanned aerial vehicles (UAVs), formation control, distributed, centralized, consensus, intelligent, behavior.

doi:10.4108/eai.10-6-2021.170230

1. Introduction

Unmanned aerial vehicles (UAVs) facilitate many applications in either military or civil fields. A UAV that does not carry a human operator, can work autonomously or remotely piloted, and can carry payloads for mission requirements [1, 2]. A group of UAVs is often used in traffic monitoring [3, 4], load transportation [5], or smart agriculture [6]. Besides the civilian applications, UAVs can operate in hazardous conditions, which makes UAVs become suitable solutions for military and missions in dangerous environments including battlefield surveillance, search and rescue in disaster recovery tasks.

In practice, a single UAV may not handle a complex mission effectively, such as searching a vast area. A group of UAVs can offer more advantages in terms of time-efficient, cost-reducing, fault-tolerant capabilities, etc [7]. Due to the above merits, the multiple UAVs problems are extensively studied in the literature such as the communication and networking architectures [8], energy problems [9, 10], dynamical models and control algorithms, remote sensing, and estimation in [11].

While working in a group, each individual UAV travels to different places and collaborates with its neighbors to complete a given task. The group of UAVs needs to avoid collisions from obstacles and also

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Acknowledgements: the authors would like to thank Thai Nguyen University of Technology (TNUT), Vietnam for the support.

among the other partners. In some tasks, the UAVs may be required to autonomously operate in dangerous environments that easily causes failures of UAVs and communicating interruption between the group. This degrades the mission performance. Recently, formation control problem is received great attention from many researchers to develop effective algorithms that hopefully overcome the challenges. Hence, formation control algorithms should be considered to increase the group's performance. The formation control aims to generate the appropriate control signals for UAV formation to achieve the missions while taking into account their dynamic and environmental constraints. Various strategies have been proposed to solve the challenges in formation control problems including leader-follower, behavior-based, etc. As far as missions for UAVs become more complicated with more strict constraints in terms of robustness, scalability, etc., it is necessary to have an overview of the control strategies with advantages and limitations. This leads to preparations for the upcoming challenges of formation control.

In this paper, we aim to present a comprehensive review of the existing researches on the formation control of multiple UAVs. This survey classifies control schemes based on computation and communication structures with two main categories including centralized and distributed scenarios. This review of control strategies emphasizes specific manners on how the control signal is driven. The advantages and limitations of each strategy are provided, which supports researchers to easily choose suitable control design methods for their specific problems. The survey also presents existing challenges and discussions about some potential directions in future development.

The rest of the paper is organized as follows. Section 2 provides preliminary work including the fundamental basis on graph theory and formation control of multiple UAVs. Sections 3 and 4 address formation control schemes and mechanisms, respectively that clarify research directions in the fields. Benefits and challenges of each method are also discussed in the sections. Section 5 discusses and evaluate more about the methods to point out research directions. Finally, the conclusions and future developments are provided in Section 6.

2. Preliminaries

In this section, we present the fundamentals of graph theory which is an important tool to analyze the characteristics of the interconnected system including formation stability and control ability. Then, the control structure flight control system for multiple UAVs is given.

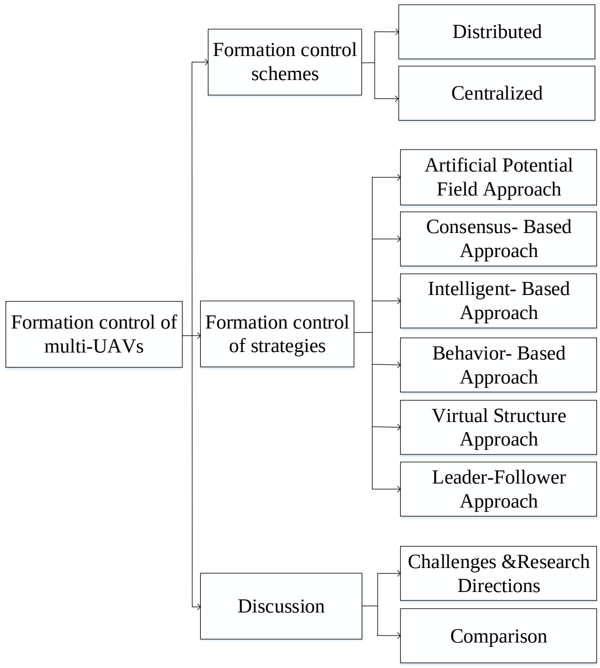

Figure 1. Formation Control of Multil-UAVs system

2.1. Graph Theory

Graph theory is a powerful tool to analyze formations. A typical network of the formation includes three different kinds of topology, namely sensing topology, actuation (control) topology, and communication topology [12]. The graph can be used to model the network topologies. The basics of graph theory are reviewed in this subsection. Further details can be found in [13, 14].

Interactions among agents can be expressed by directed or indirected graph $G = (V, E)$, where $G = (v_1, v_2, ..v_N)$ denotes a set of agents in the formation and $E \subset V \times V$ represents the set of edges. Defining the agent i, the set of neighbors of agent i is defined $N_i := \{j \in V : (i, j) \in E\}$. The edge is denoted as $e_{ij} = (v_i, v_j)$, which presents the information exchange between two nodes i and j. The graph is called strongly connected if there exists a path connected node v_i to v_j for any $v_i, v_j \in G$. For a directed graph, if there are directed paths from a node v_i to all other nodes in the graph, then the node is said to be a directed rooted tree. The directed graph having the root with no parent is defined as the directed tree. The spanning tree is the directed tree which contains all the nodes in graph G.

The degree matrix D of the graph is defined as $diag(d_G(i))$. The adjacent matrix $A := [a_{ij}] \in R^{N \times N}$, where $a_{ij} = 1$ if $(j, i) \in E$ and $a_{ij} = 0$ otherwise. The Laplacian matrix $L = [l_{ij}] \in R^{N \times N}$, where $l_{ii} = \sum_{j=1} a_{ij}$ for all $i \in V$, and $l_{ij} = -a_{ij}$ for all $i, j \in V, i \neq j$. The Laplacian matrix can also be defined as $L = D - A$.

2.2. Problem of Formation Control

We can classify UAV-type into different categories in terms of their structures. With different structures, the UAVs will introduce their distinct dynamics. Therefore, different control variables could be modified in order to adapt to control requirements. These types of UAVs can be classified by the form of wing function [15].

A flight control system of a single UAV consists of two stages. The inner loop contains the attitude and stabilization controller, as shown in Figure 2. The attitude controller modifies the orientation of the UAV by controlling the pitch and roll angle, which determine the attitude of the vehicle. Due to its small size, the stability of the UAV is normally poor. The stabilization loop is used to assure the stability of the system during the mission.

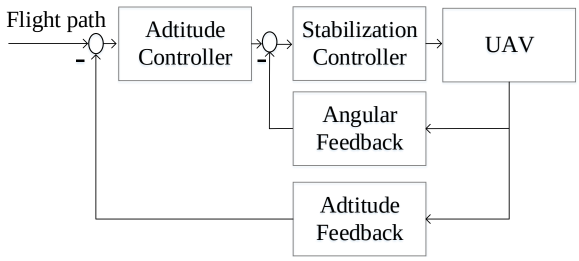

Figure 2. Inner loop of flight control system for a single UAV.

The outer loop is the navigation and guidance controller. This loop determines the flight path for the vehicle. Autonomous working is an important requirement for the UAVs since it usually has to work remotely without directed guidance from a human. In navigation and guidance control, longitudinal control and lateral control are taken into account. The entire flight control system is shown in Figure 3.

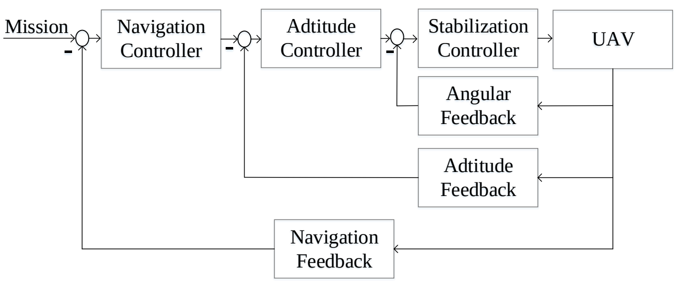

Figure 3. The flight control system for a single UAV.

For multiple UAVs working together, other issues of flight control of UAVs are drawn. The control system now has to deal with the cooperation among agents in the group. The control issue is known as cooperative control. And formation control is considered a special type of cooperative control. According to [16, 17], formation is the network in which the agents in the network have solidated relationships with their neighbors. The formation control is defined as the cooperative control in which the agents must retain the specific topology with relative distances to the neighbor agents. As working in the team, each action executed by an UAV may have effects on the performance of the whole system. This concern is referred to as coordination which is the cooperation task requiring communication among the agents. An agent must consider the action of other agents in the team before introducing its own action. The control structure for UAV formation is addressed in Figure 4.

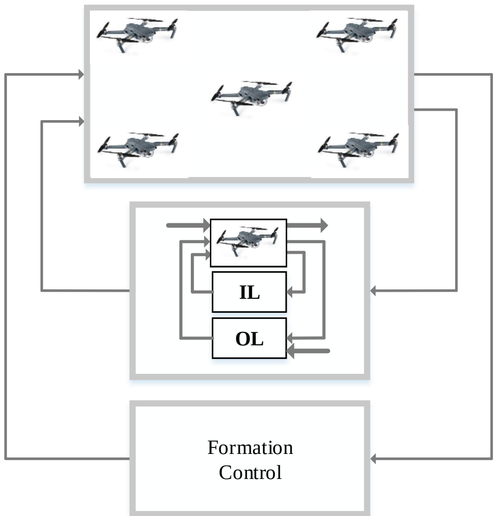

Figure 4. The flight control system for multiple UAVs.

In [18, 19], the formation control problem is addressed as follows. The formation with N agents as shown as $\begin{cases} \dot{x}_i = f_i(x_i, u_i) \\ y_i = g_i(x_1, ..., x_N) \\ z_i = h_i(x_i) \end{cases}, i = 1, .., N$, where x_i, y_i, z_i are the state, the measurement, and the output interest of the agent i, respectively. The formation is achieved as the constraint that is achieved as $(z) = F(z^*)$. This formation control is to design the control law assure that the outputs stably converge to the desired set of $z^* = x : F(z) = F(z^*)$.

3. Formation Control Schemes

Sharing information and computational mechanisms are the major concerns on formation control designs. The mechanism that make a decision has to take into account numerous requirements such as tolerance ability, energy efficiency. This section presents two main control schemes including are centralized and decentralized or distributed schemes, and provides their advantages and disadvantages of each scheme.

3.1. Centralized

In the centralized scheme, the core processing unit is introduced. It can be a base station on the ground or an agent with strong computational ability in the formation. As shown in Figure 5, the core unit monitors the coordination of the team in order to complete the global task based on the information collected from all remaining agents. All agents must keep the connection with the core unit. The centralized scheme introduces several demerits, such as less robustness, large energy wasted. Due to the key function of the core unit in monitoring the global task of the team, the fault of the core will introduce the failure to the whole formation. The computational capability of each agent is not utilized, and the connection links required between the core unit and other members also introduce a burden on communication resources.

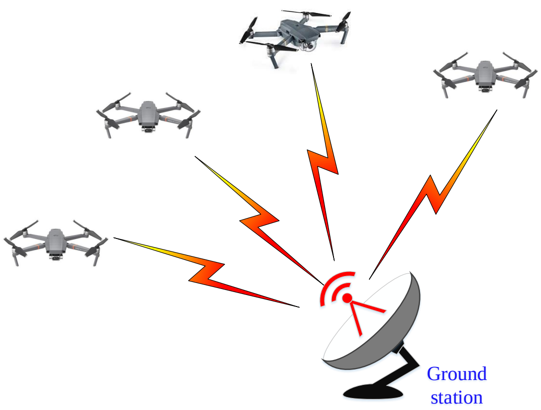

Figure 5. The centralized control scheme for multiple UAVs.

In [20], the leader-follower approach is considered as a centralized scheme, in which the leader can freely move and have entire access to the global information. Ignacio Mas and Christopher Kitts [21] propose a centralized approach using a cluster frame. The agents are grouped as in a cluster. The desired path and control signal are conducted in cluster space. The control actions for the robots are converted by the inverse Jacobian relationship. This approach simplifies the complexity of robot motion by making simpler cluster specifications. In [22], the multi-layer control scheme for a centralized formation is proposed. The formation is considered as a single entity and defined by formation pose and structure shape. The control layer generates the control signal by the formation error, then the control signal for an individual UAV is obtained by the inverse kinematic transformation. The stability of the closed-loop system is analyzed by Lyapunov stability.

3.2. Distributed

In the distributed or decentralized scheme, the formation does not require the core unit for organization purposes. The agents in the formation can communicate and share information with other members, as illustrated in Figure 6. The processing unit is available on the agent itself, and the decision is made by the agents based on the local observation. The bottlenecks of the centralized approach in terms of computation and communication are overcome. The distributed systems are more robust and scalable. However, the implementation is much more difficult for the distributed system.

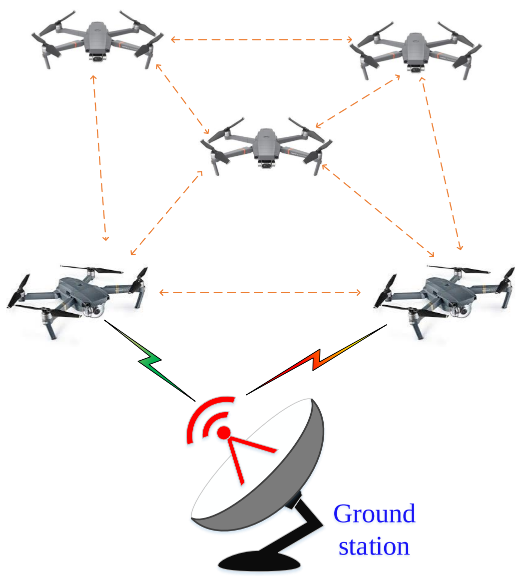

Figure 6. The distributed control scheme for multiple UAVs.

In [23], the virtual structure approach is modified in a decentralized way. Instead of having only a central discrete event supervisor and a formation control module, these two components are available in every agent. The formation patterns are defined by the local supervisors that generate the formation patterns. Then, the formation control module utilizes formation from the supervisor to drive the initial coordination of the agent to the desired formation pattern. The agent coordination is synchronized with its neighbors. Dong Hun Kim, Hua Wang, and Seiichi Shin [24] presented a decentralized control scheme based on artificial potential functions to solve the problem in path planning and collision avoidance. The framework provides the formation with the ability to retain the flexible formation while the formation operates in an environment with obstacles. The collision avoidance among agents in the formation is also addressed. In [25], the optimal control strategy is proposed for controlling multiple UAVs with three cost functions, namely consensus formation cost, the obstacle/collision avoidance and tracking cost, and the control effort cost. The control algorithm only requires the local information of neighbors since the control law is a linear function of the Laplacian matrix. Wei Lin [26] designs a distributed formation control algorithm using differential game theory. The formation requirement is expressed as a performance index in which the UAV in the formation attempt to minimize the formation error as well as the velocity error and the control effort while operating. This work proposes an estimation law in which an agent can estimate its position and velocity by exchanging information with the neighbors. The control strategy based on classical open-loop Nash equilibrium can be implemented in a distributed manner.

4. Formation Control Mechanisms

There are three integral problems that need to be considered in the formation control problem. The first problem is the formation generation task which drives the agents which are in random situations to form the desired formation topology. Second, the control strategy has to ensure that the desired shape of the formation must be retained while the group performs the operations. The third one is the formation reconfiguration. While operating in the environment, the formation may be subjected to different types of faults such as facing obstacles, loss of connections among the agents, etc. When the group encounters these kinds of problems, the formation topology must be reestablished in order to adapt to the new conditions. Various control strategies have been proposed in both centralized and distributed manner to fulfill these formation control issues.

4.1. Leader-Follower

The leader-Follower approach is the most common method in formation control due to its simple control structure and scalable ability [27]. In this method, a member in the group is nominated as a leader, whereas the other members are considered as followers, as shown in Figure 7. The leader has full access to the global information and its trajectory is the reference for the rest of members. All the followers are able to sense the relative distances between them and the leader. And the local control strategy for the followers is to maintain these relative distances.

There were two types of feedback controllers for controlling multiple robots or UAVs in the leader-follower manner which are $l-l$ and $l-\psi$ controllers [28]. As shown in Figure 8, the control objective in $l-\psi$ controller is to retain the length l_{12}^d and the relative angle ψ_{12}^d at the desired values. By exploiting input/output feedback linearization, both l_{12}^d and ψ_{12}^d can be derived to the expected values by the designed controller. In $l-l$ controller, the controller mainly deals with the relative positions between the leader and followers, as illustrated in Figure 9. The controller is also designed by the input/output feedback linearization technique. The framework for formation flight is developed based on both $l-l$ and $l-\psi$ controllers in [29]. Other techniques found in literature include back-stepping [30, 31], sliding mode control [32–34].A hierarchical scheme is proposed in [35]. The formation is divided into branches, each

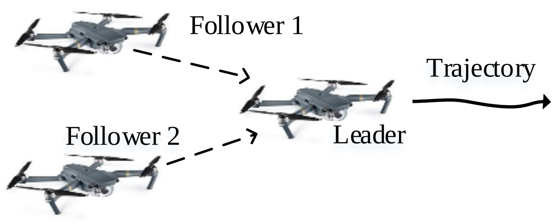

Figure 7. Leader-Follower configuration.

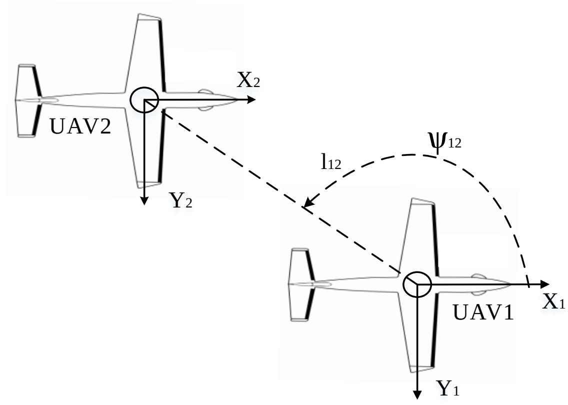

Figure 8. $l-\psi$ controller

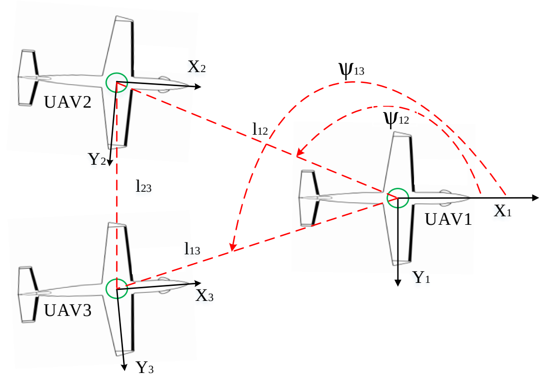

Figure 9. $l-l$ controller

branch is a string of several UAVs. A UAV tracks the movement of its advanced UAV which is called a local leader. The root is a UAV considered as a global leader, and its trajectory is the reference for local leaders. In [36], a novel leader-follower scheme for the formation with multiple leaders is investigated, which yields better performance in terms of bandwidth limitation problem and system robustness.

The disadvantage of the leader-follower scheme is that the scheme is less robust. The failure of the leader causes the fall of the entire formation. In order to compensate to this demerit, another approach in the leader-follower mechanism is proposed as virtual leaders. In [37, 38], Olfati-Saber develops a framework for flocking of multi-agents based on a virtual leader. The framework is a combination of three algorithms. The first algorithm deal with three heuristic rules of Reynolds [39]. The second algorithm is the core of the framework. In algorithm 2, the navigational feedback provided in every agent allows the formation to track the virtual leader trajectory. The third algorithm is to tackle the obstacle avoidance problem. In [40], the control algorithm based on the novel back-stepping approach is proposed to tackle the control problem for a formation in polygon form with a virtual leader at the center of the geometric structure. The results provided fast dynamic response and small tracking error.

4.2. Virtual Structure

The virtual structure (VS) approach is firstly introduced in [41] for controlling the formation of mobile robots. In this work, the VS is defined as a collection of elements (unmanned vehicles), which maintains a rigid geometric relationship to each other and to a frame of reference. The concept of this approach is that the shape of the formation is treated as a rigid body, the desired formation is established by fitting the physical position of the formation to the position of the virtual body. The idea is implemented by a bi-directional control scheme. The trajectories for each vehicle in the formation are given by the virtual force produced as the deviation between the VS and the actual formation shape. The positions of VS are defined by formation positions in the environment.

The proposed control strategy consists of three main stages [42]. First, as the formation is initialized, the alignment process is executed by minimizing the error between positions of the vehicles and the corresponding positions in the virtual structure. The objective function to minimize the errors is given as

$$f(X) = \sum_{1}^{N} d(r_i^W, I_r^W(X) \cdot p_i^R), \tag{1}$$

where, N is the total number of vehicles in the formation, $d()$ is the distance function, r_i^W is the vehicle position in the global coordinate, p_i^R is the vehicle position in the coordinate of VS, and $I_r^W(X)$ is the transformation function between the global coordinate and VS coordinate. Second, the VS considers the mission goal and the dynamic behaviors of the vehicles to generate the next position for the VS. The last stage is that actual members move to the new position with respect to their corresponding positions in the VS. The illustration is shown in Figure 10.

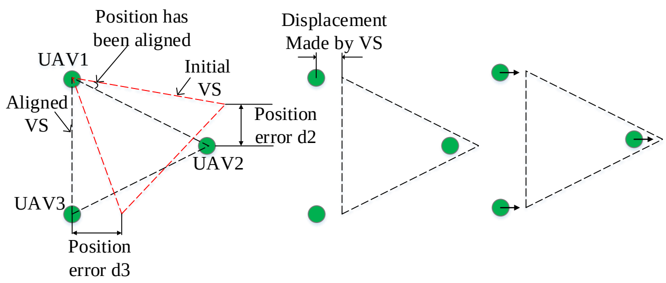

Figure 10. Virtual Structure control scheme

In papers [43, 44], an improved virtual structure approach is introduced for controlling the formation of mobile robots and spacecrafts, respectively. The formation feedback is integrated into the control structure, which provides better performance in terms of stability and robustness. The concept of formation feedback is exploited to deal with control problems for UAV formation [45]. Due to the under-actuated and dynamic-aerodynamic coupling characteristic of the UAV, the formation feedback method cannot be directly applied to control the UAV formation. Therefore, the proposed control laws are the combinations of formation feedback and dynamic inversion method in order to deal with the dynamic behaviors of UAVs. Norman and co-researchers [46] present an upgraded VS control scheme by coupling the position error and the synchronization error to be able to calculate the trajectory commands. Chang Boon et al. [47] utilizes the curvilinear coordinates to define reference points for the virtual structure. This approach enables a flexible formation structure, which improves the performance of the formation in terms of the heading profile tracking problems. In literature [48], Peterson and Barton develop a control algorithm for managing the formation of UAVs in the presence of wind. The commands for each UAV are based on the desired trajectory of the formation and deal with the effect of the wind on the UAVs. The combination of virtual structure and potential fields approach is proposed in [49, 50]. The flying result for each member is tracked by the flatness-based feedback control.

4.3. Behavior-Based

The behavior-based control is a hybrid control structure that combines various vector control functions. By realizing the natural formation behaviors such as flocking, shoaling, and schooling in formation control algorithms, the desired behaviors are integrated to form command signals to complete the mission goal. The concept of a behavior-based control scheme is firstly introduced in [51]. The desired behavior can be measured by sensors. Each behavior has a distinct gain which represents a priority of the behavior. The final command to control a robot is calculated by combining the product of the outputs of the behavior and its gain. For example, different behaviors, namely obstacle avoidance (u_1), formation keeping (u_2), and goal-seeking (u_3) are implemented to construct robot behavior. The final control command is determined by the function as $u = u = a \cdot u_1 + b \cdot u_2 + c \cdot u_3$, where a, b, c and d are the gains of the behaviors. The formation control-based behavior approach is depicted in Figure 11.

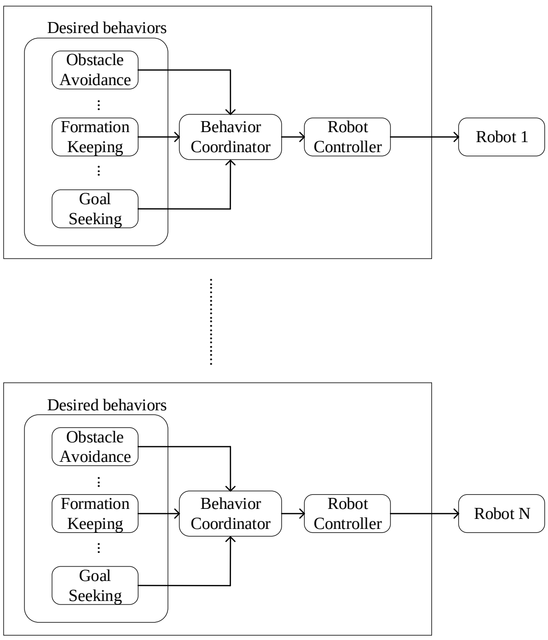

Figure 11. Behavior-based approach

Giulietti et al. exploits the behaviors of migrating birds into formation flight control [52]. The control signal is constructed by summing outputs of two sub-controller, a trajectory controller and a position controller. The gains for two controllers are determined by minimizing a quadratic cost function. Swarm intelligence scheme for multiple aerial vehicles is studied in [53]. Three behaviors, namely collision avoidance, velocity matching, and flock centering are combined to attain the procedures to reach the goal, while the proposed steering behaviors are used to describe complex formation maneuvers. In addition to the swarm intelligence, the collision avoidance scheme between an UAV and the others is investigated in [54]. In [55], an optimal controller for formation flight control of UAVs is proposed. The control law regarded to global convergence and formation keeping behavior is designed by introducing a Lyapunov candidate function. The weight matrices corresponding to two desired behavior are obtained by solving a cost function. Wang and co-researchers [25] develop a control framework for multiple UAVs considering formation control, trajectory tracking, and collision avoidance behaviors.

4.4. Artificial Potential Field

The concept of artificial potential field (APF) was first introduced by Khatib [56] to deal with collision avoidance problems. The main idea is to generate the control action based on the attractive forces and repulsive forces. These forces are the negative gradients of the attractive potential field and repulsive potential field, respectively. While the attractive force guarantees the formation convergence, the repulsive force ensures the non-collision characteristic, as shown in Figure 12.

Considering the UAV formation having N members, p_i is the current position of i^{th} UAV. The attractive field and repulsive field between the i^{th} UAV and the j^{th} UAV (which $i, j \in N$) are given as

$$J_{ij}^{att} = \frac{1}{2} K_{att} d_{ij}^2, \tag{2}$$

$$J_{ij}^{rep} = \frac{1}{2} K_{rep} (\frac{1}{d_{ij}} - \frac{1}{d_{min}})^2, \tag{3}$$

where K_{att} and K_{rep} are the gain coefficients, $d_{ij} = p_j - p_i$; $i, j \in N, i \neq j$, d_{min} is the safe distance between two the UAVs.

The attractive force and repulsive force can be calculated as

$$F_{ij}^{att} = -\nabla J_{ij}^{att} = K_{att} d_{ij}, \tag{4}$$

and

$$F_{rep} = -\nabla J_{ij}^{rep} = K_{rep} (\frac{1}{d_{ij}} - \frac{1}{d_{min}}) \frac{1}{d_{ij}^2} \cdot \frac{\partial d_{ij}}{\partial p_i}. \tag{5}$$

The resultant force on the i^{th} UAV is addressed as

$$F_i = \sum_{j \neq i, j \in N} (F_{ij}^{att} + F_{ij}^{rep}). \tag{6}$$

Based on the typical protocol in Equation (6), Yuanchen Zhao et al. propose the modified the APF to deal with the obstacle avoidance while the formation

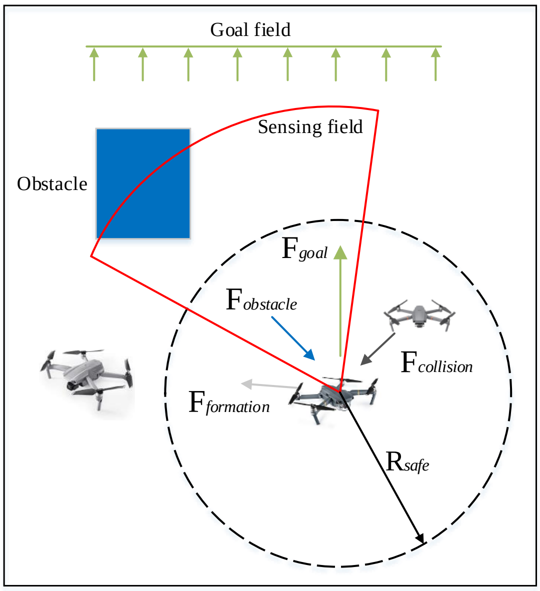

Figure 12. Artificial Potential Field approach

operates at high-speed [57]. The APF approach is extensively applied to the multi-UAVs system. The path-planning for multiple UAVs operating on the battlefield based on APF is proposed in [58]. The hybrid control structure composing virtual structure approach and artificial potential field approach is introduced in [59]. The limited velocity of the vehicle is considered to generate the resulting force so that the vehicle can utilize the maximum speed while operating. In [60], an APF approach is presented to tackle path planning tasks for the formation of UAVs. The additional force is combined with the resultant force calculated by APF. The additional force is solved by the optimal control method to fulfill the shortest path and energy constraints. The novel algorithm introduces an additional potential function for obstacle avoidance which takes into account the relative angle and the relative velocity of the UAV with respect to the obstacles. Sun et al. [61] modify the potential function of the repulsive force to address the unreachable targets and collision avoidance problems. Cui et al. [62] propose the design procedure based on back-stepping control design to deal with input saturation issues.

4.5. Consensus-Based

The consensus-based strategy is a powerful approach to solve the control problems in UAV swarm systems. The objective of consensus is to drive the states of all members in the group to the same constant value. This provides a general framework in which the previous schemes, leader-follower, virtual structure, or behavior-based approaches could be expressed as the special case of the consensus-based strategies [63].

The typical formulation of consensus protocol is presented in [64]. Considering the multi-agent system having n agents, the graph is used to describe the information flow of the system. The dynamics of an agent is modeled by first-order integrator equation as

$$\dot{x}_i = u_i, \ i \in N\{1, 2, ..., n\}, \tag{7}$$

where x_i and u_i are the state of i^{th} agent and the control input. The consensus protocol is designed as

$$u_i = \sum_{j \in N_i} a_{ij}(x_j - x_i). \tag{8}$$

The consensus protocol is also extended for the second-order integrator dynamic system. The system is described as

$$\dot{x}_i = v_i, \ \dot{v}_i = u_i, \ i \in N\{1, 2, ..., n\}, \tag{9}$$

where x_i, v_i and u_i are the position, velocity, and the control input, respectively. The consensus protocol for second-order integrator system:

$$u_i = \sum_{j \in N_i} a_{ij}((x_j - x_i) + \gamma(v_j - v_i)), \tag{10}$$

where $\gamma > 0$ is the scaling factor. The consensus is achieved as the information flow that forms a spanning tree [64].

In [65], the consensus protocol and the sufficient condition to achieve consensus are investigated in the different communication topologies. Consensus protocol is exploited to deal with the control of formation by switching topologies [66, 67]. In papers [68, 69], the time-varying formation problem is converted into the consensus problems. The Riccati equation is used to determine the parameters of the controller. Yahui Qi et al. [70] propose a method to design the protocol by solving linear matrix inequalities which reduces the computational requirement. Different variances of consensus protocol are introduced to tackle the problems of formation assembling, formation maintenance, velocity tracking, and formation transformation, while the effect of communication time delay is also studied in [71]. In the concern of the obstacles avoiding problems, the consensus-based approach is combined with some other strategies to improve the performance of the formation while encountering the obstacles. The authors in [72] modify the consensus protocol by introducing the usage of the artificial potential field as mentioned in Figure 12.

Strategies	Advantages	Disadvantages
Leader-Follower	Simple design and implementation Good formation tracking performance	Dependence on the leader No feedback from the followers to the leader
Virtual Structure	High stability	Not flexible Poor ability in obstacle avoidance
Behavior-Based	Dealing with multiple-goal mission	Difficult to model Low stability
Artificial Potential Field	Smooth trajectory generation Short calculation time Good ability in obstacle avoidance	Not efficient in complex environment
Consensus	Capable of managing the formation under limited and dynamic changing communication topology	Not fully consider the dynamics of the agents
Intelligent Control	Do not require precise model Adaptive and learning ability	Requies large computational effort

Table 1. Comparison of formation control strategies

4.6. Intelligent control approaches in formation control

Computational intelligence has emerged as an effective solution to address the control problems in complex systems. The fuzzy logic is often used to design the control protocols. Y. Li and co-researchers [73] develop a fuzzy-based control protocol for fixed-wing UAVs with unpredictable disturbances. In [74], the speed and attitude of the followers can be tracked by the fuzzy logic controller. And the desired formation is obtained only considering the kinematic equations of UAVs. The modified virtual structure approach is derived in [75]. The control command is calculated by the position of neighbors, which is only required the passive sensors to determine the neighbor positions. The synchronization gain of the control law is obtained by the fuzzy inference.

Neural networks and adaptive learning methods have also been studied widely in the literature. In [76], a framework for the leader-follower scheme is presented. The dynamic of the UAV is learned by the novel neural network including the unmodeled dynamics. The adaptive leader-follower protocol is proposed in [77]. The uncertainties are compensated by the radial basis function neural networks. The multi-variable model reference adaptive control is utilized to design the consensus protocol for formation flights of multiple UAVs [78]. The results show the good tracking ability of the followers, but the uncertainties of the leader and external disturbances are not covered.

In [79], the authors consider the formation reconfiguration problem as an optimization problem in which the hybrid PSO-GA (Particle Swarm Optimization - Genetic Algorithm) is presented to solve the objective function. The work in [80] proposes the angle-encoded PSO algorithm to generate the optimal path for each UAV while the formation transforms. These results show promising points.

5. Discussion

The aforementioned main control protocols are summarized and compared in Table 1. The leader-follower strategy is most widely utilized in practical applications as this strategy is simple to design and implement. The mechanism is simple that the members in a group follow the selected leader. Hence, the formation relation is easily analyzed. The low complexity of the communication network is another merit of the leader-follower approach since the members in the group only need to have a connection with the leader. The dependence on the leader is the critical limitation. An error of the leader may cause the failure of the whole system. The virtual structure approach possesses excellent ability in maintaining the formation structure. However, the rigid structure restricts the flexibility of the formation while traveling. This leads to poor performance in avoiding obstacles or operating in a narrow-space environment. The formation reconfiguration may increase the computational burden for the members in a group, which is undesirable in practical application. The behavior-based strategy is the most suitable strategy for multi-goal missions. The control signal generated by the behavior-based protocol can accomplish the requirement for different tasks. The demerit of this approach is that the model of formation dynamic is very complicated. Therefore, the stability of the system is difficult to be analyzed. The control given by the Artificial Potential Field protocol could quickly provide a smooth trajectory when the UAVs avoid obstacles or collisions. However, this protocol does not guarantee shortest paths. The distribution of the obstacles is not considered by the Artificial Potential Field protocol, so this protocol is not efficient in the complex environment. The consensus strategy is able to provide the distributed protocol which guarantees that the states of the members in the formation can converge to the common value. Many research studies about consensus protocols in different scenarios including dynamic communication networks are presented, including time-delay in asynchronous consensus [81]. However, most of the studies only consider simple dynamics such as single-integrator or second-integrator dynamic. The higher-order and nonlinear dynamic could be further investigated to provide better control performance for UAVs. The combination of computational intelligence methods and other control protocols can improve the robustness of the system, since the protocol is independent from the model uncertainty or external disturbance which are difficult to model. The disadvantage of the intelligent approach is that it requires big computational resources and calculation time.

Although numerous studies have been conducted, the formation control problems still pose many challenges. As the aforementioned discussions, each approach has different advantages and disadvantages. Since a mission may contain several sub-missions, there is no approach that is suitable for all sub-missions. A hybrid mechanism that is able to combine some of the traditional approaches depending on specific mission requirements that can be a promising solution for the future research directions. Next, most of the existing studies only take into account the coordination in one platform. There are many applications that require the cooperation between different types of mobile robots. In [82], the combination of a UAV and multiple autonomous underwater vehicles (AUVs) is used for navigation in the ocean. The data collection is performed by a team including UAVs and unmanned ground vehicles (UGVs) [83]. The dynamic behavior is different from each type of vehicle. So, the control problem for the formation becomes more complex. In addition, control algorithms should consider some special needs of specific applications to efficiently perform missions. In [84], a device-to-device-based framework for communication networks in disaster areas is proposed. To maximize wireless communication networks, the clustering and routing paths are designed considering the status of devices such as positions, battery levels. Based on the information from the clusters and routing paths, UAVs could be driven to follow an appropriate trajectory. In [85], the trajectories of UAVs are optimally designed concerning different missions such as the network coverage, data collection in wireless sensor networks (WSNs).

6. Conclusions

This paper provides a comprehensive review of the control protocols for controlling UAV formation. The typical control structures of formation UAVs are presented as attitude-stabilization loop, navigation-guidance loop, and formation control loop, and formation control problem which are defined and analyzed. Common control schemes, centralized and distributed, are classified based on communication and computational mechanisms. The various control mechanisms are reviewed including leader-follower, virtual structure, behavior-based, artificial potential field, consensus, and intelligent approach. Control protocols that are investigated with respect to different aspects such as robustness, adaption, stability, or tracking performance are addressed with details. A brief summary of control strategies is provided and compared in Table 1. The comprehensive evaluation that may help to select the proper approaches for future developments is delivered. Pros and Cons from the methods are evaluated to lead some directions. Based on the contents, in the future works, the hybrid control strategy could be developed to adapt the complex missions. The design methodology should take into account the dynamics of heterogeneous systems.

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