

A Survey of UAV Swarm Task Allocation Based on the Perspective of Coalition Formation

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ABSTRACT

Coalition formation of unmanned aerial vehicle (UAV) swarms, an effective solution for UAV swarm task allocation, is an important technology for UAV swarms to perform real-time and efficient collaborative task allocation in a dynamic and unknown environment. This paper summarizes the task allocation methods of UAV swarm coalition comprehensively and systematically. First, starting with the related work of UAV swarm coalition task allocation, this paper introduces the basic concept, general model, and constraint index of UAV swarm coalition task allocation. Then, the specific content, research status, advantages, and disadvantages of the coalition formation methods are analyzed, respectively. Third, the commonly used solution algorithms and research status of coalition task allocation are introduced, and the advantages and disadvantages of the existing coalition formation solution algorithms are compared and analyzed. Finally, it provides significant guidance for future related research.

KEYWORDS

Coalition Formation, Research Status, Task Allocation, Unmanned Aerial Vehicle Swarm

1. INTRODUCTION

With the development of modern information and communication technology and artificial intelligence technology, UAV swarm warfare with autonomous capability has attracted much attention (Qi et al., 2020). *UAV swarm task allocation* is the premise and guarantee to determine whether the swarm can effectively complete combat tasks. Traditional task allocation methods often abstract task allocation problems into classical combinatorial optimization problems, such as the traveling salesman problem (TSP), the vehicle routing problem (VRP), and the multi-dimensional multi-choice knapsack problem (MMKP). In addition, it is under the assumption that a single UAV in the swarm has the ability to complete tasks independently, and the UAV swarm has the ability to communicate fully. The main problems of traditional task allocation methods are: (a) the heterogeneity of UAVs and the consumption of resources are not taken into account; (b) the algorithms are highly complex, so it is difficult to give

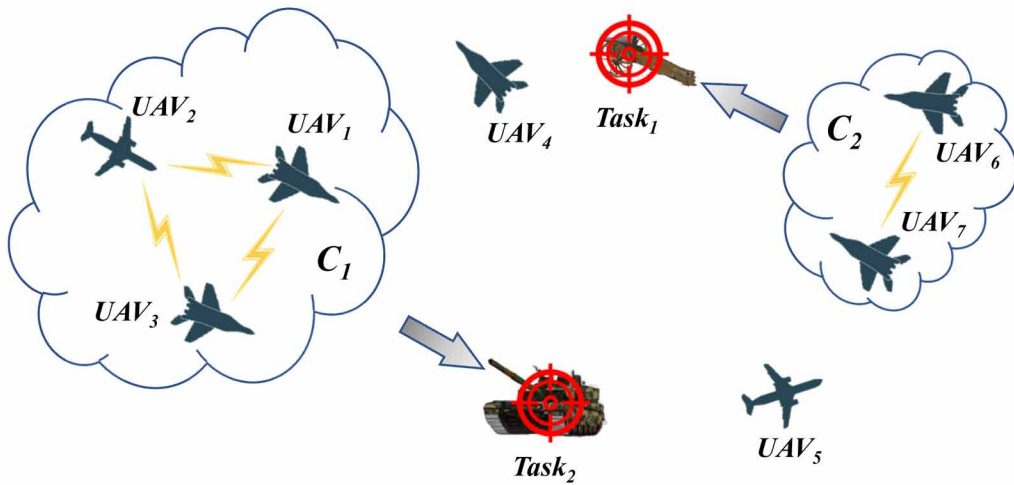
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real-time allocation results; (c) most of the research is only based on a single UAV performing a single task; and (d) in previous research, the overall battlefield information had to be obtained in advance, making it difficult to realize collaborative task allocation in an unknown environment. When the task is simple, the traditional task allocation method can solve the problem well. However, in the face of the increasingly complex modern battlefield environment, and due to the limited functions played by single UAVs, many combat tasks need to be completed by multiple UAVs in the swarm (Yao et al., 2014). It is difficult to meet the needs of actual tasks by applying the traditional task allocation methods because the actual combat environment continues to change dynamically (Wei et al., 2013).

Figure 1. Schematic diagram of UAV alliance task execution



In reality, it is difficult for a single UAV in the UAV swarm to complete dynamic tasks with complex resource requirements independently. They often need multiple UAVs to form a coalition for a collaborative operation to complete tasks more efficiently and quickly. In recent years, coalition formation has become a key issue of UAV swarm task allocation, which has gained extensive attention from researchers. As shown in Figure 1, a coalition is a way to describe the form of cooperation, which means that some UAVs form a coalition to jointly complete tasks in a cooperative manner. Compared with taking a single UAV as the task execution unit in the swarm, the UAV coalition, as a UAV collection, has stronger task execution capability. At the same time, UAVs can be combined flexibly, and appropriate allies can be selected according to the task, to form the most effective coalition to complete the task and obtain the maximum benefits at the least cost. Coalition formation belongs to a special task allocation problem, which is consistent with the requirements of the dynamic and unknown battlefield environment. That is, it can ensure that UAVs can carry out real-time and efficient collaborative task allocation in the dynamic and unknown battlefield environment.

The coalition method was proposed by Shehory and Kraus (1996) and has successfully solved the task allocation problem in a multi-agent system (MAS; Rahwan et al., 2009; Zhang et al., 2010; Diao et al., 2014; Shehory and Kraus, 1998; Sarkar et al., 2022) and multi-robot system (MRS; Vig & Adams, 2006; Ahmadoun et al., 2021; Mazdin & Rinner, 2021). Since Sujit et al. (2008) first introduced the concept of the coalition into the multi-UAV system, the coalition formation method has become one of the hot methods to solve the UAV swarm task allocation problem (Wu et al., 2018; Luan et al., 2020; Ruan et al., 2021; Fei et al., 2022). Coalition formation (Sandholm et al., 1999; Shen

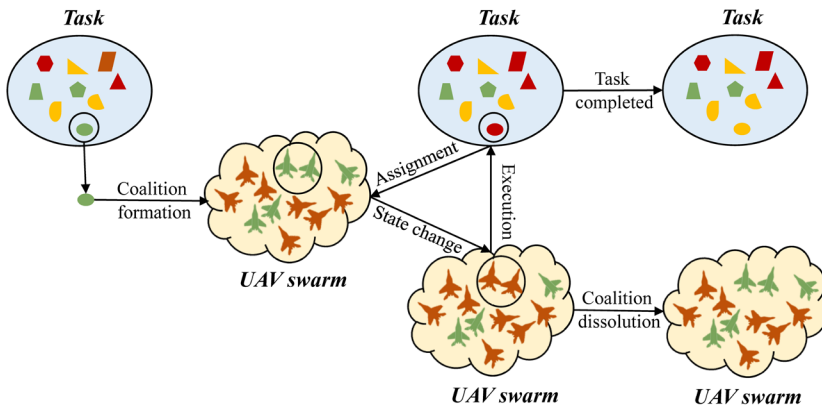
et al., 2006; Xing et al., 2019) could effectively and quickly organize UAVs in the swarm to form a task coalition so that the swarm can flexibly and efficiently complete tasks, avoid task deadlock and resource waste, give full play to the advantages of the system, reduce task costs, and improve work efficiency. Therefore, the formation of UAVs as an operational coalition to execute combat tasks is essentially a mixed problem of sequence determination and task allocation for task execution. However, as the number of UAVs increases, the number of eligible UAV coalition will increase exponentially, so solving the coalition with maximum interests is a dynamic NP-hard (Sandholm & Lesser, 1997). To solve this problem, researchers have achieved a series of research results around coalition structure (Voice et al., 2012; Zick et al., 2014), coalition clustering (Kashef & Kamel, 2010), solving algorithm (Macarthur et al., 2011), and formed a certain theoretical and technical foundation.

2. TASK ALLOCATION DESCRIPTION OF UAV SWARM COALITION

2.1 Task Description

Heterogeneous UAV swarms mainly perform tasks on a large number of known and unknown targets in the task environment. Considering that performing tasks on the target needs to meet the resource constraints of the target, the resources carried by a single UAV are limited and may not be able to meet the requirements. For known targets, heterogeneous UAV swarms can directly select tasks and form UAV coalitions to execute them; for unknown targets, the UAV swarm continuously discovers new targets and triggers task allocation for the new targets until the UAV swarm completes all tasks within the task area. As shown in Figure 2, the basic process of task allocation of a UAV swarm coalition mainly includes five basic steps: task selection, coalition formation, task execution, task completion, and coalition dissolution. The task allocation problem of a heterogeneous UAV swarm coalition can be represented by the six-tuple $\langle U, M, T, E, C, O \rangle$, where U is the set of UAVs in the swarm; M refers to the collection of targets in the mission area, including enemy positions, vehicles, and equipment; T is the task type set contained by each target, including reconnaissance task, and attack task; E refers to the mission environment, such as environmental threat, and no-fly zone; C is the set of constraints related to the task execution of heterogeneous swarm; and O is the overall goal of UAV swarm to complete tasks, such as the shortest time and the lowest track cost.

Figure 2. Basic process of UAV swarm coalition task allocation



2.2 Constraint Conditions

When forming a coalition for UAV swarms, one should not only consider constraint conditions such as resource allocation balance, task dynamics, UAV communication range, and communication delay within the swarm but also pay attention to various types of constraints such as UAV kinematics constraints, target resource constraints, UAV arrival time constraints, and UAV collision avoidance constraints. Generally, the formed coalition needs to meet the following constraints and conditions:

1. In order to improve the efficiency of task completion, it is required to complete tasks in the shortest time.
2. In order to improve the utilization of UAV resources and the number of tasks completed within unit time, the size of the coalition is required to be the smallest. If the size of the coalition is minimized each time, more UAV coalitions can be formed.
3. In order to ensure the rapid completion of tasks and the success rate of completion, all coalition members are required to perform tasks at the same time.
4. In order to ensure that the task can be completed, the total resources owned by all coalition members in the coalition are required to meet the resource requirements of the task.

2.3 Mathematical Model

It is assumed that there are N_M targets, and each target has N_T tasks and a UAV swarm composed of N_U UAVs. The task allocation problem of heterogeneous UAV swarm coalition can be generally described as: In the task environment, under the requirements of meeting all constraints, seek a scheme for the formation of a UAV swarm coalition, to complete the current task to the greatest extent and optimize the overall objectives of task allocation, such as cost and benefit. Then the general mathematical model (Whitten, 2010; Butler & Hays, 2015) of the task allocation problem of heterogeneous UAV swarm coalition can be expressed as follows:

$$\begin{aligned} \max & \sum_{i=1}^{N_U} \sum_{j=1}^{N_M} \sum_{k=1}^{N_T} x_{ij}^k \cdot r_{ij}^k \\ \text{s.t.} & \begin{cases} x_{ij}^k \in \{0, 1\} \\ C(x_{ij}^k) \geq 0 \end{cases} \end{aligned} \quad (1)$$

where r_{ij}^k is the benefit of UAV_{*i*} ($i = 1, 2, \dots, N_U$) performing the k th ($k = 1, 2, \dots, N_T$) task of target j ($j = 1, 2, \dots, N_M$); x_{ij}^k is the task allocation decision variable $x_{ij}^k \in \{1, 0\}$; $x_{ij}^k = 1$ indicates that UAV_{*i*} executes the k th task of target j —otherwise, $x_{ij}^k = 0$ - and $C(\cdot)$ is the relevant constraint.

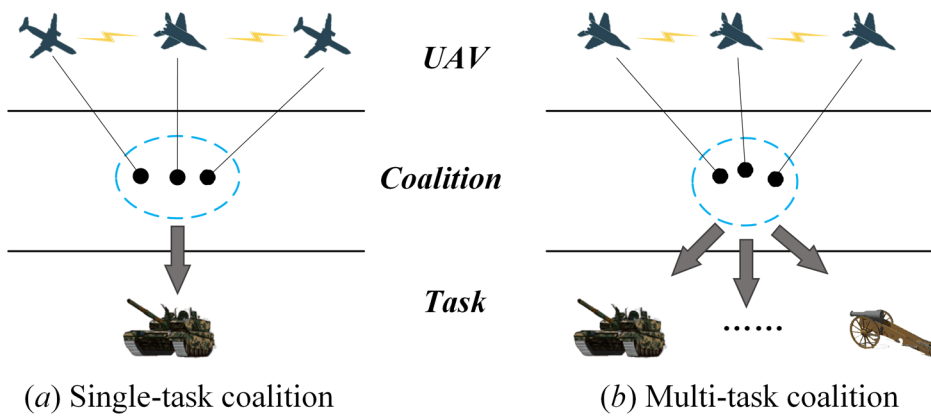
It should be noted that this formula represents a general model of task allocation for UAV swarm coalitions. In the specific task allocation process, the model needs to be modified and refined according to the specific task background and actual task environment so as to meet the actual requirements of the tasks.

3. COALITION FORMATION METHOD OF UAV SWARM

UAV swarms form coalitions to perform tasks that cannot be accomplished by a single UAV, effectively improving the success rate and efficiency of task execution. The difference way of forming the coalition directly affects the efficiency of the UAV swarm in completing the task. Therefore, since coalition formation was used for UAV swarm task allocation, domestic and foreign scholars have carried out

a lot of research and achieved fruitful results. Coalitions can be divided into different types based on different perspectives. From the perspective of coalition generation, it can be divided into serial coalition and parallel coalition. From the perspective of coalition structure, it can be divided into simple coalitions and complex coalitions. From the perspective of the number of tasks performed by the same coalition, it can be divided into single-task coalitions and multi-task coalitions. This section reviews the coalition formation methods regarding two aspects: the single-task coalition and multi-task coalition.

Figure 3. Schematic diagram of UAV swarm coalition



3.1 Single-Task Coalition

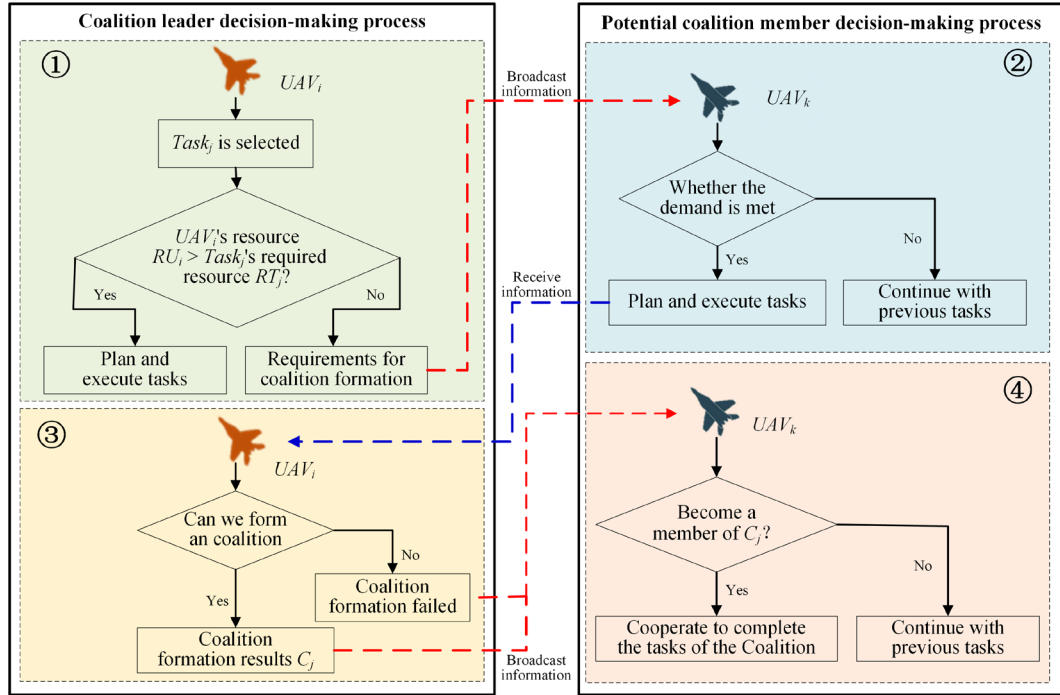
As shown in Figure 3(a), in a task environment, a coalition that only undertakes one task is called a single-task coalition. “Specific task – Specific coalition” is the main form of single-task coalition. The formation of a single-task coalition is to find a UAV coalition that can complete a certain task and has the best coalition result in a UAV swarm. The formation methods of single-task coalition mainly include serial coalition formation method and parallel coalition formation method.

3.1.1 Serial Coalition Formation Method

The serial coalition formation method refers to finding the UAV coalition with the largest global benefit for each current task in turn in the task environment. The main process of the method is as follows: The UAV swarm first determines the task priority according to the relevant requirements of the task execution and then selects the global optimal UAV for the task with the highest current priority in the task priority sequence in turn. As shown in Figure 4, when the UAV carries insufficient resources to complete the strike task of the target alone, the UAV becomes the initiator of coalition formation and broadcasts the specific information of the discovered target to other UAVs in the swarm (Wang et al., 2005). Then, other UAVs respond to the coalition initiator according to their own resources. The initiator of the coalition integrates all the feedback information, weighs the overall interests, and forms the current global optimal coalition to respond to the task. After the current task is completed, the UAV coalition will be dissolved, and coalition members can continue to participate in other tasks. This method is simple and widely used, but it has the following problems: First, the determination of task priority is greatly influenced by subjective factors, and the distribution results are random. Second, each task is solved in turn, which requires high computing power in the system. Third, the evolution of the coalition is not considered. Whenever new tasks are added to the task set, they need

to be re-aligned according to the formation method, which will inevitably have a lot of computing and communication overhead, resulting in a great waste of computing resources.

Figure 4. Schematic diagram of the serial formation method of single-task coalition



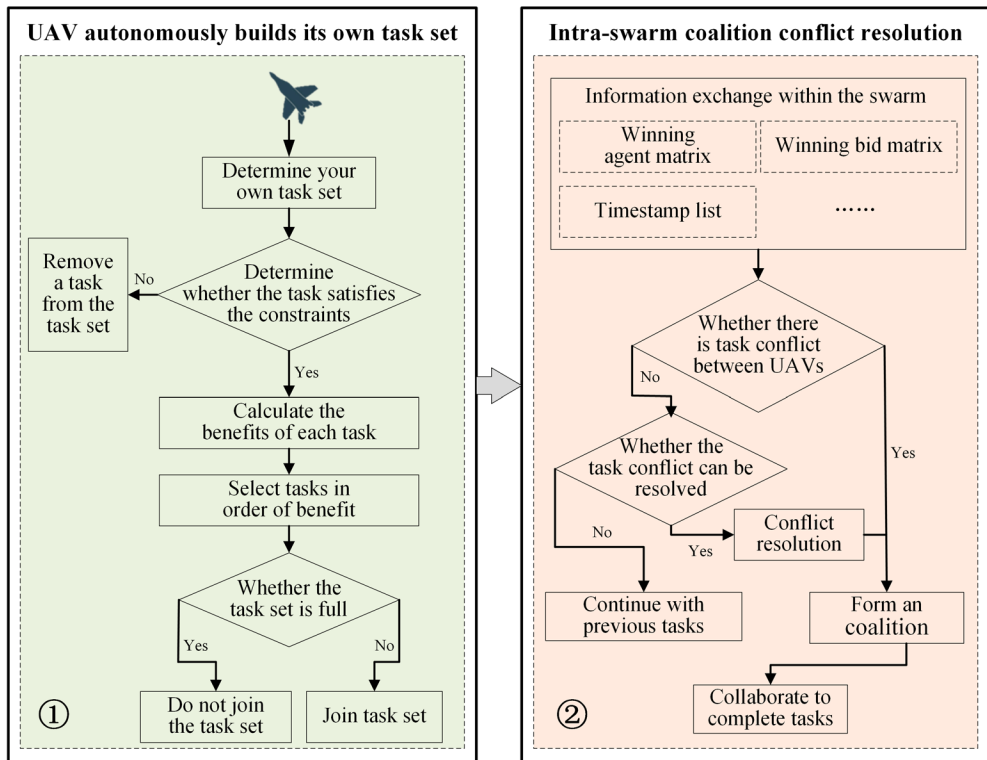
In order to avoid coalition deadlock and resource waste, Wang et al. (2005) proposed a coalition formation strategy based on an improved task matching calculation method. When dealing with the current task, this method can selectively learn from the historical experience of the system and give full play to its learning ability. It can effectively reduce the search time and computation of the coalition generation and has good realizability. Han and Yao (2018) decomposed all tasks into different types of sub-tasks and built a manned-UAV swarm holon coalition (SHC) formation model according to UAV combat capabilities and sub-task resource requirements. The model can effectively solve the problem of SHC formation, but it does not consider the execution time and execution situation of the task, and the execution of the task is difficult to continue in case of emergencies. Lin et al. (2013) put forward an online task allocation problem model based on an idle time window, which considered the time constraints and efficiency requirements of multi-UAV task allocation problem, and effectively solved the real-time and effectiveness of solving the multi-UAV task allocation problem. Liu et al. (2015) designed a coalition formation method for heterogeneous multi-UAV cooperative search and strike in an unknown environment, minimizing target strike time, minimizing coalition size as optimization indicators, and satisfying simultaneous strike and resource requirements as constraints. This method has high real-time performance and can be well adopted in unknown environments.

3.1.2 Parallel Coalition Formation Method

Compared with the serial coalition formation method, the parallel coalition formation method has its uniqueness: in the task environment, the coalitions are searched for multiple tasks at the same time to

maximize the overall benefit. Due to the existence of multiple coalitions generated at the same time and the arbitrary splitting and combination of individual abilities, there will be countless possible solutions to the problem, which requires a large amount of calculation and high system performance. Usually, parallel coalition formation methods include two processes: UAV task set construction and coalition formation conflict resolution. During the task set construction process, each UAV selects tasks to add to its own task set for the purpose of maximizing its own benefits. After the task set is constructed, the UAV needs to exchange information with other UAVs in the swarm, mediate task conflicts according to certain action rules, and form a UAV coalition suitable for each task to obtain conflict-free task allocation results.

Figure 5. Schematic diagram of a parallel formation method of a single-task coalition



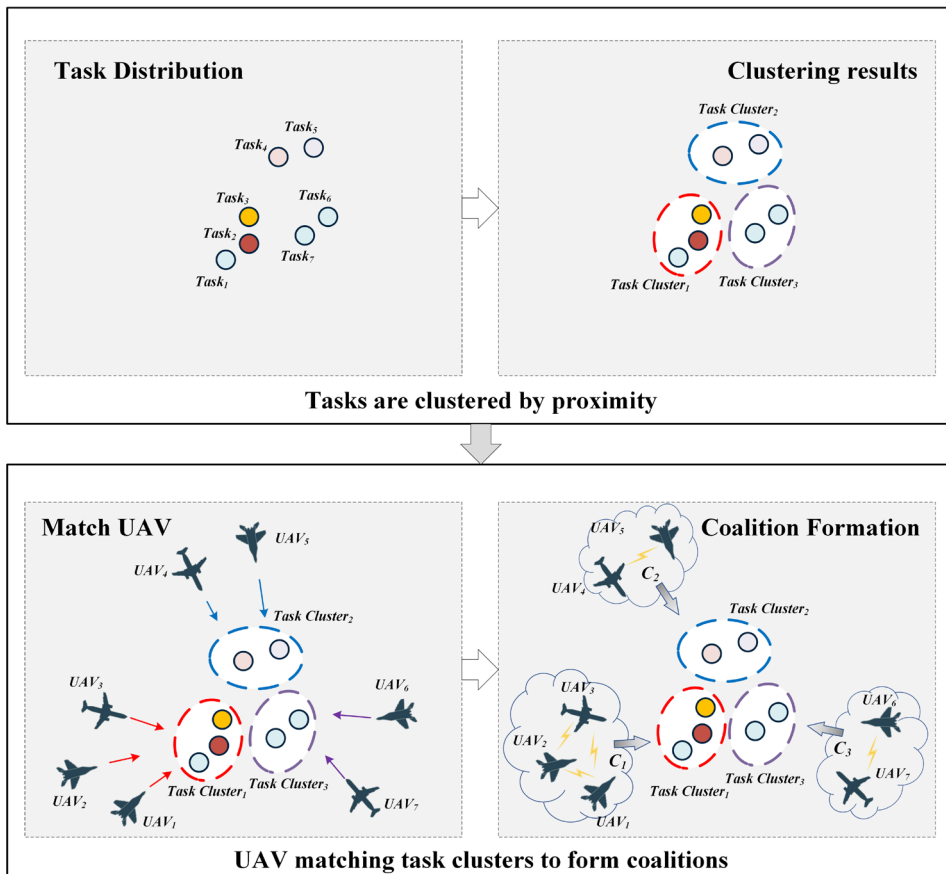
Tang et al. (2020) extended the distributed consistency package theory to solve the task allocation problem of the heterogeneous multi-UAV coalition under the conditions of task load resource constraints, task-coupling relationship constraints, and execution window constraints. First, each UAV selects tasks to construct its own task set according to the principle of maximum benefit. Second, after UAVs share the winning agent matrix, winning bid matrix, timestamp list, and other information with adjacent UAVs, the conflict mediation of task allocation decision of heterogeneous multi-UAV coalition is realized based on the improved coordination principle. Li et al. (2020) aimed at the task allocation problem of the heterogeneous multi-UAV dynamic coalition under complex constraints. Based on the method proposed by Tang et al. (2020), this approach obtained efficient and reasonable allocation results, providing three dynamic allocation strategies: a no-re-planning dynamic allocation strategy, a fully re-planning dynamic allocation strategy, and a partially re-planning dynamic allocation

strategy. At present, insufficient consideration has been given to task timing constraints and execution time windows in related research, and there is a lack of research on dynamic task allocation of multi-UAV coalition under timing coupling relationship and time window constraints.

3.2 Multi-Task Coalition

As shown in Figure 3(b), a UAV coalition that undertakes multiple tasks at the same time during the execution of a UAV swarm is called a *multi-task coalition*. The *task-cluster coalition* is the main form of multi-task coalition. The formation of multi-task coalition mainly includes two processes: task clustering and UAV matching task clusters. That is, during task execution, all tasks to be executed are clustered into several task clusters according to certain principles, and then the task clusters are assigned to the UAV coalition for execution. The formation of a multi-task coalition needs to solve the following two problems: (a) ensuring that tasks with similar characteristics in all tasks are clustered into one cluster, so as to effectively reduce the range cost of UAV swarm tasks, and (b) determining UAVs are responsible for the corresponding task clusters, so as to effectively reduce the cost of capabilities including communication and resources. Therefore, in the process of coalition formation and evolution, it is necessary to consider the characteristics of task distribution, dynamic uncertainty of battlefield environment, UAV swarm capability, and other factors, and use simple rules and protocols to realize the matching quickly and efficiently between task clustering and UAV optimal coalition.

Figure 6. Schematic diagram of the formation method of multi-task coalition



Scholars have done a lot of research on the formation of multi-task coalitions. Hu et al. (2015) divided the multi-UAV task allocation problem into three sub-problems: task clustering, task cluster allocation, and task allocation within a cluster. Each UAV formed an actual coalition to execute tasks within each cluster. This method reduces the scale of problem-solving and has great advantages in real-time allocation. Wan et al. (2013) used the coalition formation strategy, “first task grouping, then platformed matching to task group,” which effectively solved the problem of forming a coalition when manned or unmanned aerial vehicles perform tasks. Zhong et al. (2017) adopted the phased formation strategy of task clustering – platform matching and successfully solved the problem of the manned–unmanned aerial mission coalition formation. In general, the existing research on the formation method of UAV swarm multi-task coalition has made great progress, but there are still several aspects that need to be improved. First, the quality of task clustering results will directly affect the subsequent coalition formation process, and the clustering method needs to be improved. Second, in the process of platform matching, since there may be multiple optimization objectives, the solution quality still needs to be improved.

3.3 Comparison of Coalition Formation Methods

Based on the relevant research at home and abroad, Table 1 specifically compares and analyzes the basic situation of the formation method of the UAV swarm coalition.

Table 1. Comparison of UAV swarm coalition formation methods

Method		Typical References	Implementation Approach	Advantage	Key Points and Difficulties	Research Status
Single-task coalition	Serial coalition formation method	Wang et al., 2005; Han and Yao, 2018	Determine task priority; Form coalitions according to task priorities.	It is simple and easy to implement, and both are the current optimal solutions.	(1) Determining the priority of tasks is greatly affected by subjective factors. (2) High computing power is required.	(1) Alliance evolution is not considered; (2) The mission scenario is simple and small in scale.
	Parallel coalition formation method	Li et al., 2020; Tang et al., 2020	At the same time, find coalitions for multiple tasks respectively.	Simple and easy, with a certain dynamic.	Large solution space and a large amount of calculation require high system performance.	Inadequate consideration of task timing constraints and execution time windows.
Multi-task coalition		Hu et al., 2015; Wan et al., 2013; Zhong et al., 2017	The tasks are clustered into several task clusters, and then the task clusters are formed into coalitions, respectively.	Reduce the scale of problem-solving and have a great advantage in allocating real-time performance.	(1) Task clustering has a great impact on coalition formation. (2) The task is complex, and the solution quality is difficult to guarantee.	(1) The clustering method needs to be improved. (2) The solution quality needs to be improved.

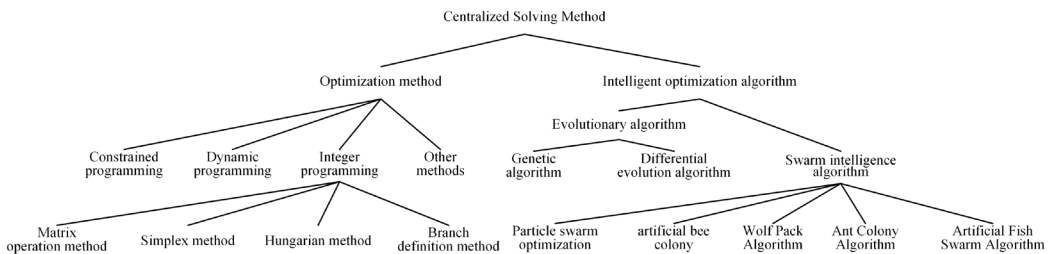
4. SOLUTION METHOD OF TASK ALLOCATION FOR UAV SWARM COALITION

The main purpose of the task allocation problem for a UAV swarm coalition is to select an appropriate coalition for tasks, which is essentially a combinatorial optimization problem. Therefore, choosing an efficient solution method is a necessary condition to successfully solve the coalition task allocation problem. At present, there are two main methods for solving the task allocation problem of the UAV swarm coalition: the centralized solution method (Guruacharya et al., 2013; Klusch & Gerber, 2002; Das, Misra, & Roy, 2015; Anderson et al., 2004; Lerman et al., 2006; Wang & Liu, 2021) and the distributed solution method (Michalak et al., 2010; Tanzil et al., 2016; Kong et al., 2017; Johnson et al., 2011; Das, McGinnity, et al., 2015; Stranders et al., 2012).

4.1 Centralized Solution Method

The main research ideas of the centralized solution method can be summarized as follows: Based on the global environment information, the task allocation is modeled into the corresponding resource allocation model, and then the centralized algorithm is used for the solution. As shown in Figure 7, the commonly used centralized solving methods are divided into two categories: optimization methods and intelligent optimization algorithms.

Figure 7. Commonly used centralized solving methods



4.1.1 Optimization Method

The *optimization method* solves the optimal solution of the problem under the condition of satisfying the multiple current constraints. The commonly used optimization methods mainly include integer linear programming method (ILP), constraint programming method, and dynamic programming method.

4.1.1.1 Integer Linear Programming Method

The *integer linear programming* (ILP) method establishes the objective function and related constraints and seeks a solution for its extreme value. Although the ILP method is flexible, easy to operate, with relatively fast solution speed, the model built by this method is relatively simple, which cannot represent the complex task environment with poor fault tolerance and is not ideal for solving multi-machine and multi-objective allocation problems with different models. The commonly used integer programming methods are the matrix homework method, the branch and bound method, and the mixed integer linear programming algorithm (MILP). Shetty et al. (2008) abstracted the cooperative allocation and path planning problem of multiple UAVs attacking fixed targets into a MILP problem, used a centralized algorithm to solve it, and achieved good results, but the real-time performance of the solution was poor.

4.1.1.2 Dynamic Programming Method

Dynamic programming refers to a method of transforming multi-stage decision-making problems into single-stage optimization problems in order to reduce the difficulty of decision-making problems. *Dynamic* refers to the changes and transitions of states caused by changes in the decision sequence and steps in the multi-stage decision-making of a problem. The algorithm has no definite steps, and the corresponding optimization algorithm needs to be designed in combination with the idea of dynamic programming. This method has high implementation efficiency but is prone to the curse of dimensionality. Xu and Liu (2015) designed a coalition constraint dynamic programming algorithm for the coalition structure generation of multi-agent systems, proving that the time complexity of the algorithm was $O(3^n)$, and further discussed the impact of the number of agents and the number of coalition constraints on the algorithm.

4.1.1.3 Other Optimization Methods

Manathara et al. (2011) took the minimum strike time and minimum coalition size as the goal and proposed a polynomial-time formation strategy for UAV cooperative coalitions to perform inspection and strike tasks on fixed targets. On the method proposed by Manathara et al. (2011), Sujit et al. (2014) considered the limited communication range and target movement of UAVs, avoided the network congestion caused by broadcasting, and adopted the resource distribution strategy one by one, but did not consider the impact of the resource distribution strategy on the execution of subsequent tasks in the current task execution. Zhong et al. (2017) established a mathematical model with minimizing task completion time as the objective function for heterogeneous multi-UAV multi-task execution and designed a phased greedy planning algorithm (PGPA) to solve the model, which improved the collaborative ability of multi-UAV multi-task execution. Bayram and Bozma (2016) came up with a coalition formation algorithm based on merge and split (CF-MS). The algorithm can be well applied to the formation of robot coalitions in dynamic scenarios, but it is difficult to deal with the formation of large-scale coalitions.

According to the current research results, the optimization method is simple, flexible, and easy to implement, and it can flexibly deal with constraints to seek a solution for practical problems. In the case of small-scale tasks, the optimization method can quickly find the optimal solution for task allocation. However, when the task allocation scale is large, the time consumed by the algorithm increases sharply, and the optimization method is difficult to meet the real-time requirements in a dynamic environment. Therefore, the optimization method is only suitable for task allocation of an off-line coalition for UAV swarms which has low requirements on time and a small number of tasks.

4.1.2 Intelligent Optimization Algorithm

An *intelligent optimization algorithm* (Yang et al., 2018; Wang, 2001) is a random search method developed under the inspiration of natural phenomena or social behaviors. This kind of algorithm is widely used and can be applied to large-scale and nonlinear problems with strong universality. The algorithms commonly used in UAV swarm coalition task allocation are the evolutionary algorithm and the swarm intelligence algorithm.

4.1.2.1 Evolutionary Algorithm

An *evolutionary algorithm* (Zheng, 2007) achieves the purpose of searching for the optimal solution by simulating the biological evolution process proposed by Darwin. Based on this algorithm, in the task allocation stage, different actions are taken to perform task allocation for different goals and tasks, so that the overall allocation can be optimized. Representative algorithms in evolutionary algorithms include genetic algorithms (GA; Zhang et al., 2012) and differential evolution algorithms, which are widely used in UAV swarm coalition task allocation. Wu et al. (2017) took the heterogeneous multi-UAV cooperative air defense suppression task as the background and applied an improved genetic algorithm to solve the multi-UAV agent cooperative task allocation problem considering constraints such as aircraft load type and end entry target angle. Xiao et al. (2018) aimed at the target search and strike task of multiple heterogeneous UAVs in an unknown environment, focused on the

UAV resource constraints, and designed a rapid coalition establishment method based on a parallel non-dominated genetic algorithm with elite strategy (NSGA-II). This method has high real-time performance but does not consider the impact of communication constraints such as communication distance and communication delay on coalition formation. Rauniyar and Muhuri (2016) presented a genetic algorithm based on random immigration and elite mechanism, which can only quickly seek the optimal solution to the problem of coalition formation in relatively simple application scenarios. It can be seen that the evolutionary algorithm has the advantages of strong global search ability, high search efficiency, and strong robustness, and can find the optimal solution in a short time, but the algorithm is easy to fall into local optimum when solving large-scale combinatorial optimization problems.

4.1.2.2 Swarm Intelligence Optimization Algorithm

The inspiration for the *swarm intelligence optimization algorithm* comes from the behavior of biological groups in nature, which means that multiple individuals representing candidate solutions are formed into a group, and the purpose of optimization is achieved through the information interaction between some or all of them. Commonly used swarm intelligence algorithms include the ant colony algorithm (Dorigo & Stützle, 2003), particle swarm optimization (PSO; Kennedy & Eberhart, 1995), artificial bee colony algorithm (ABC), and wolf pack algorithm (WPA). Sujit et al. (2008) introduced the concept of *coalition* from a multi-agent system into a multi-UAV system for the first time, established a mathematical model for forming an optimal coalition, and used a PSO algorithm to seek a solution. However, for this method, all the information about the task environment needs to be obtained in advance, and the real-time performance is low. Jiang et al. (2009) introduced a discrete particle swarm algorithm to solve the problem of coalition formation. The random disturbance of particles was used to avoid the premature of the algorithm. A binary coding was designed to realize the parallel generation of a complex coalition. Through the coding feasibility check, conflict resolution, and compensation strategy, the resource conflict and coalition deadlock in the solution process were avoided.

Dong and Zou (2018) used an improved adaptive variable weight particle swarm optimization algorithm, which can quickly and effectively seek multi-objective optimal task allocation solutions for multi-UAVs formed by the coalition and obtain the optimal task allocation scheme. Diao et al. (2014) used the coalition formation theory to analyze the air combat task allocation under the condition of cooperative guidance, constructed the coalition characteristic function according to the characteristics of air combat tasks, and introduced the discrete particle swarm optimization algorithm to form the coalition, adopted the binary matrix coding form, designed the particle feasibility inspection strategy, and effectively improved and perfected the existing task allocation problem of cooperative air combat. Based on the Holon organization construction theory, Han and Yao (2018) analyzed the task allocation problem of manned and unmanned aerial vehicles swarm for a cooperative swarm operation, divided the total task of the target swarm into different types of subtasks, constructed a multi-objective optimization model, and designed a multi-objective hybrid bee colony algorithm to solve it, which achieved good results.

Wang et al. (2018) studied the task allocation of swarm networking, designed a hierarchical iterative task allocation model, and proposed a task allocation algorithm for UAV swarm networking based on PSO-ICWPA with the swarm intelligence optimization algorithm of low complexity and superior performance as the basis. This method has good convergence and rapidity and is useful for solving task allocation problems of different scales. The research shows that the swarm intelligence optimization algorithm has strong search ability, strong robustness, and strong scalability. It has prominent advantages in large-scale parallel computing and can also be combined with many other algorithms. However, when a large number of coalitions need to be formed in a complex task environment, the swarm intelligence optimization algorithm also shows the shortcomings of slow convergence speed, low operation efficiency, easily falling into local optimization, and low real-time solution.

To sum up, the intelligent optimization algorithm has high computational efficiency. For large-scale task allocation problems, it can also obtain a relatively satisfactory solution, but the feasible solution is not necessarily the optimal solution. That is, the solution is uncertain. In addition, the convergence speed of the algorithm cannot be guaranteed.

4.2 Distributed Solving Method

In recent years, the distributed solving method has received more and more attention and development, and it has become one of the mainstream methods of task allocation and solution in the current UAV swarm coalition (Yang et al., 2022). The main research idea of the distributed solving method can be summarized as follows: complete the computing and decision-making of the coalition in single UAVs based on the autonomous ability of those UAVs and seek a solution for conflict coordination of task allocation through the cooperation between UAVs, so as to improve the calculation speed and efficiency. Compared with the centralized method with a large computing load in the central node, the distributed method can overcome that shortcoming, and the real-time performance is relatively good. However, due to the need for multiple rounds of information collaboration, with the increase of the task scale and the number of UAVs, the communication overhead is large, and the requirements for the communication transmission capacity of the platform are high. At present, the more popular distributed solving methods are mainly two market-mechanism-based methods, namely, the contract net protocol (Smith, 1980; Zhai et al., 2021) and the auction algorithm (Chen, Wei, & Xu, 2014; Di et al., 2013; Ng et al., 2020).

4.2.1 Contract Network Protocol

The *contract network protocol* (CNP), as a negotiation-oriented task allocation and cooperation mechanism, realizes task allocation, dynamic adjustment, and transfer by imitating the “inviting a bid – submitting a bid – winning a bid – signing a contract” mechanism in an economic act. When an agent does not have enough ability to process the current task or when it generates a new task through task decomposition, the bidding information is released, and other agents bid according to their own ability. CNP adopts the method of task bidding, takes the bid value as the control variable of task allocation among the agents, and realizes the dynamic allocation and adjustment of tasks through mutual negotiation and competition. The concept of CNP was first proposed by Smith in 1980 and has been widely used for research in the military field (Qian et al., 2011; Wu, 2017; Atkinson, 2003; Oh et al., 2017; Liu et al., 2010; Liu et al., 2016).

Alighanbari and How (2005) aimed at heterogeneous UAVs’ collaborative search and strike tasks. The idea of a contract network was adopted to improve the coalition formation mechanism, so as to dynamically form coalitions. This method has high allocation efficiency and good real-time performance and is suitable for the rapid allocation of dynamic tasks in a large-scale, uncertain environment. However, due to the strong dependence of a large number of negotiation requirements on the communication status, the communication system load is large. The solution results have a great relationship with the internal negotiation mechanism, so it is difficult to evaluate the quality of the solution. Zhang (2016) solved the problem of dynamic formation coalition generation by using the contract net protocol and proposed an improved contract net protocol based on trust and restricted the minimum structural adjustment to adapt to changes in the battlefield environment.

In order to meet the operational requirements of an aviation cluster to be flexible, highly coupled, multi-task, and multi-target, Zhu et al. (2019) presented a method of coalition formation with low traffic requirements to solve the problem of too much global negotiation information in the classical contract network protocol. This method effectively improves the quality of the solution by designing a hybrid multi-layer interactive network structure suitable for the aviation cluster and improving the bidding process of the classical contract network. Chen et al. (2021) put forward a distributed multi-UAV task allocation method based on a contract network. This method can make each UAV in the

coalition consume resources in a more balanced way under the constraints of communication distance and time delay, but it can only provide a solution for task allocation in the local sense.

4.2.2 Auction Algorithm

The *auction algorithm* (Tang et al., 2010) is important for solving task allocation problems in dynamic environments. An *auction* mainly consists of elements such as UAV, task, revenue function, and cost. UAV assigns tasks by way of bidding, and the highest bidder gets the task. The auction algorithm has the advantages of clear rules and easy operation. However, in order to prevent the information delay when bidders bid to the auctioneer and obtain the optimal task allocation results, the auction process must be transmitted in the same network environment. Scholars have made a lot of improvements on the shortcomings of the auction algorithm and have successfully applied it to the task allocation of UAVs, robots, and other agents (Fu et al., 2019; Buckman, 2018; Kim et al., 2014). In order to solve the problem of coalition formation of manned–unmanned combat agents in cooperative task execution, Wan et al. (2013) designed a coalition formation strategy of “task grouping first and then agent matching task group” based on an auction mechanism. This method efficiently forms the coalition and reasonably assigns the formed coalition to tasks.

Aiming at the problem of dynamic task assignment of multi-UAV agent alliances, Chen, Yao, et al. (2014) proposed a dynamic target allocation method for multi-UAV cooperative operations based on a distributed auction mechanism. Wan et al. (2015) used the auction algorithm to solve the alliance problem of manned and unmanned combat agents, but the model lacked time constraints such as task completion time limit. Wu (2018) put forward a task re-allocation method based on the supervised sequential auction mechanism. For new tasks in the battlefield environment, the auction sequence is randomly generated by the auctioneer, and each UAV sequentially bids to select tasks until all bursts are selected.

4.2.3 Other Distributed Algorithms

In addition to the auction algorithm, the contract network algorithm, and their improvement methods, other distributed algorithms have been applied to solve the formation of UAV swarm coalitions. Zheng et al. (2022) proposed a distributed coalition formation method based on a Monte Carlo tree search for the distributed coalition formation problem of heterogeneous UAV swarms in unknown dynamic environments. This method designed a coalition task automaton and optimized the coalition structure through a two-stage Monte Carlo tree search, which can effectively seek a solution for large-scale distributed coalition formation problems.

To sum up, the distributed solution method forms an optimal coalition by communication negotiation to address all the problems, which can better meet the needs of fast task allocation in a dynamic uncertainty environment. However, the UAV swarm adopts an explicit communication method, which has a strong dependence on communication. When the UAV swarm is large in size, the system communication load is heavy correspondingly.

4.3 Comparison of Solution Methods for Coalition Task Allocation

Based on the relevant research at home and abroad, it is found that for the task allocation problem of the UAV swarm coalition, two methods are mainly used: the centralized solution method and the distributed solution method. The centralized solution method has fast convergence speed and high solution accuracy with low requirements on objective function features. Compared with the centralized method with a large computing load in the central node, the distributed method can overcome that shortcoming and has fast speed, high efficiency, and relatively good real-time performance. Table 2 specifically compares and analyzes the advantages and disadvantages of the commonly used task allocation solution methods for UAV swarm coalition.

Table 2. Comparison of commonly used solution methods for UAV swarm coalition task allocation

Type	Algorithm	Dynamism	Robustness	Accuracy	Applicable	Algorithm
Centralized	MILP	▲	▲▲▲	▲▲▲	▲▲▲	▲▲
	Dynamic programming	▲▲▲	▲▲	▲▲▲	▲▲▲	▲▲▲
	GA	▲▲▲	▲▲▲	▲▲	▲▲	▲▲▲
	PSO	▲▲▲	▲▲	▲▲	▲▲▲	▲▲▲
	ABC	▲▲	▲▲▲	▲▲▲	▲▲▲	▲▲▲
	WPA	▲▲	▲▲▲	▲▲▲	▲▲▲	▲▲
Distributed	CNP	▲▲▲	▲▲▲	▲▲	▲▲	▲▲▲
	Auction algorithm	▲▲▲	▲▲▲	▲▲	▲▲▲	▲▲▲

Note. ▲▲▲ indicates a high degree, ▲▲ indicates a moderate degree, and ▲ indicates a low degree.

5. FUTURE RESEARCH DIRECTIONS

At present, there are many solutions to task allocation for a UAV swarm coalition, and a large number of research results have been achieved. However, the following problems still need to be solved:

1. The research on temporal constraints is not deep enough. With the continuous development of ground air defense weapons, the cooperative execution time of combat tasks by multi-UAVs is more restricted, and the “finishing tasks within a limited amount of time” feature is continuously enhanced. At the same time, for complex combat tasks, it is usually necessary to conduct reconnaissance of the surrounding areas of the target in advance and complete the ground attack after the target characteristics are confirmed. Therefore, there are time constraints between tasks, and certain execution times should be allocated for each task. However, the current related research does not fully consider the task timing constraints and execution time window (“finishing tasks within a limited amount of time” feature) and lacks research on the dynamic task allocation of the multi-UAV coalition under the timing coupling relationship and time window constraints.
2. The communication mechanism needs to be further optimized. When heterogeneous UAV swarms form a coalition, UAVs need to carry out information interaction, which happens through the wireless communication network built by the multiple UAVs themselves. Therefore, the high-speed movement of UAVs, the limited communication capability of single UAVs, and the dynamic change of the topology of the UAV network will cause the network connectivity of local areas to be unable to meet the requirements of dynamic tasks, that is, the communication constraints such as communication distance and communication delay between UAVs will affect the formation of coalitions among heterogeneous UAV swarm. Under the constraints of communication distance and communication delay, how to establish optimal coalitions by using a coalition mechanism for UAV swarm task allocation demands further research.
3. Insufficient consideration of swarm heterogeneity. At present, the research focus on coalition formation in the field of artificial intelligence is mainly on the formation of homogeneous agent coalitions. The research on the dynamic coalition formation of heterogeneous UAV swarms has started, but it is still in its infancy. The existing coalition methods are mostly simple task cooperation of homogeneous UAVs, distributed coalition formation of heterogeneous UAV swarms in the form of fixed teams, and centralized coalition formation of heterogeneous UAV swarms aiming at complex tasks. However, the problem of dynamic coalition formation of

distributed heterogeneous UAV swarm in complex networks has received less attention and research, and there is no flexible and effective solution yet.

4. Less consideration is given to task allocation with inadequate resources. Currently, the main purpose of task allocation is to minimize the total cost, mostly assuming that UAV swarms have the autonomy to finish tasks and possess sufficient capacity to complete all tasks. However, in reality, UAV swarms may not always have adequate resources and capabilities to complete every task, not to mention tasks are constantly changing. In the task execution process, if the number of UAVs is insufficient, the existing methods may not be able to form a coalition under the condition that the resources do not fully meet the task conditions, resulting in the inability to carry out the current task.
5. The coalition formation methods are not practical enough. Firstly, most of the existing coalition formation methods adopt the “single-target coalition” model, which is high in coalition formation cost but low in task efficiency. Secondly, in order to adapt to the needs of the dynamic environment, the formation of coalitions usually adopts the step-by-step solution, which increases the intermediate links, and the results are often far from the optimal solution set. Thirdly, most of the existing coalition formation methods are deployed centrally, which makes it difficult to real-time process complex coalition formation problems.

In view of the deficiencies of current research, the methods to solve such problems can be researched in the following aspects:

1. Comprehensively consider relevant constraints and enhance the feasibility of allocation results. First, comprehensively consider the complex practical constraints such as task timing, communication within the swarm, swarm resources, and execution time window, based on the reality of the tasks. Second, it is necessary to carefully analyze the result standard constraints in the process of task execution, for example, the balance of task execution, the efficiency of task completion, and the cost of task execution.
2. Fully consider the heterogeneity of swarms and design a suitable coalition formation method. Increase the research on the task cooperation of heterogeneous UAVs and distributed coalition formation of heterogeneous UAV swarms in the form of flexible teams; focus on designing parallel and multi-task complex coalition formation methods around the requirements of high dynamic complex tasks, to ensure the efficient completion of diversified tasks.
3. Improve the optimization performance of the algorithm and enhance the fast and accurate decision-making ability of the swarms. First, improve the optimization speed of centralized algorithms to ensure the speed of solutions and meet the needs of dynamic tasks. Second, improve the optimization accuracy of distributed algorithms in order to guarantee the accuracy of the results and avoid the waste of resources. Third, make clear the mapping relationship between the algorithm and the problem, give full play to the performance of the algorithm, and enhance the ability of independent decision-making of the system.

6. CONCLUSION

This paper starts with the related work of UAV swarm coalition task allocation and introduces the basic concept, general model, and constraint index of task allocation for UAV swarm coalition. Then, from the perspective of the number of tasks performed by the same coalition, the coalition formation methods are divided into single-task coalition formation method and multi-task coalition formation method, and their specific content, research status, advantages, and disadvantages of these two methods are analyzed, respectively. Thirdly, from the two aspects of the centralized solution method and distributed solution method, the commonly used solution algorithms and current research on

coalition task allocation are introduced, and the advantages and disadvantages of existing coalition formation solution algorithms are compared and analyzed. Finally, the specific problems existing in the current task allocation method of UAV swarm coalitions are summarized and analyzed, and future directions for research are suggested. This paper is of great significance for reference to fully understand the research of coalition task allocation of UAV swarm.

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CONFLICT OF INTEREST

The authors of this publication declare there is no conflict of interest.

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