

Collaborative Task Planning Method for Heterogeneous UAVs Based on Resource Constrained Project Scheduling

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Abstract: In this paper, the heterogeneous UAVs collaborative task planning problem is studied based on the resource constrained project scheduling. The main contributions and conclusions are as follows. First, the precedence constrains and resource constrains of heterogeneous UAVs collaborative task planning is analyzed, and the relevant mathematical model is established. Second, the planning method based on the resource constrained project scheduling is proposed, which is divided into the AON network establishment stage and the scheduling plan generation stage. The parallel and serial scheduling generation mechanism is presented, which are used to produce a feasible scheduling plan. Third, the proposed planning method is used to solve a mission case. The experiment result shows that the parallel scheduling generation scheme outperforms the serial one in our heterogeneous UAVs collaborative task planning problem. By conducting experiments in the case study section, the correctness of the mathematical model and the planning framework are verified.

1. Introduction

Unmanned aerial vehicle (UAV) has the characteristics of good stealth performance, strong autonomy, and repeatable recycling, playing an important role in some fields such as target reconnaissance and material delivery^[1]. Faced with increasingly complex and diverse mission requirements, the resources carried by a single UAV and its ability to perform tasks are limited, making it difficult to complete complex mission alone. Therefore, heterogeneous UAVs are often required to collaborate to complete tasks. In a complex environment with multiple constraints, reasonable allocation of heterogeneous UAVs tasks is the key to achieving collaboration^[2-3].

The heterogeneous UAVs collaborative task planning is a complex combinatorial optimization problem, where UAV resources, task sequence, and task categories need to be considered. Some classic combinatorial optimization algorithms have been used to solve the heterogeneous UAVs tasks planning problem. In order to obtain rational task allocation solutions, it is imperative to establish mathematical models for collaborative UAV planning and employ algorithms for solving^[4-6]. Zhang et al. proposed an improved GA-based scheduling method for solving multiple UAVs collaborative reconnaissance task planning problems^[7]. Zhu et al. addressed the multiple UAVs task allocation problem using a GA with dual-chromosome encoding, which obtains better

experiment results [8]. Yan et al. proposed a multi-UAVs collaborative task allocation scheme for maritime targets based on the PSO algorithm. In response to the problem of premature convergence in traditional PSO algorithms, the iterative process of PSO is improved by introducing matching exchange and transposition mutation in genetic algorithms [9]. Ye et al. proposed an improved GA based on a multi type gene chromosome encoding strategy in order to solve the cooperative multiple task assignment of heterogeneous UAVs [10].

The resource constrained project scheduling problem is a theoretical model that describes complex combinatorial optimization problems. It has wide applications in industrial process optimization problems. We are trying to use the resource constrained project scheduling method to solve the heterogeneous UAVs collaborative task planning in this paper.

The remainder of this paper is organized as follows. Section 2 presents the heterogeneous UAVs collaborative task planning model. The planning method based on the resource constrained project scheduling is proposed in section 3. Section 4 reports and discusses the results of the experiments. Finally, this paper is concluded in section 5.

2. Heterogeneous UAVs Collaborative Task Planning Model

2.1. Relevant Notations

There are a total of w types of UAVs, and the number of k -th type UAV is Q_k . The UAV continuous working duration of the type k is C_k . There are n tasks that need to be completed in total, and the duration of j -th task is d_j . P_j is denoted as the immediate predecessors set of task j , and S_j and E_j is denoted as the starting time and ending time of task j respectively. T is denoted as the overall planning duration. A_t is the set of all executing tasks at time t . R_{jk} is denoted as the quantity of UAV of the type k required to execute task j . The decision variable x_{ijkt} is defined as follows:

$$x_{ijkt} = \begin{cases} 1, & \text{if the } i\text{-th UAV of the type } k \text{ executes task } j \text{ at time } t \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Considering that the flight speed of UAVs is relatively fast and the round-trip time between different areas is much shorter than the time required to perform the task, the round-trip time is not considered in our paper.

2.2. Precedence constrains

The precedence constrains represents task order constraint of collaborative task planning for heterogeneous UAVs. The tasks that UAVs need to execute include reconnaissance, material delivery, and effectiveness evaluation, which need to be completed in a certain order. In actual missions, it is necessary to execute different operation in a certain order to achieve the best effect. The precedence constrains can be denoted as an Activity on Node (AON) network, which is shown in Figure1. In Figure1, a task is represented by a node, the precedence constraints between tasks are represented by solid arrows.

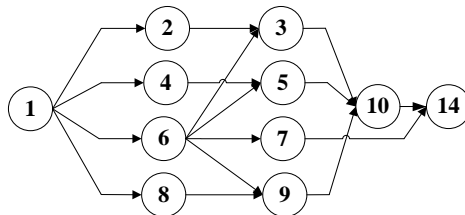


Figure 1: The AON network of collaborative task planning for heterogeneous UAVs.

The precedence constraints between tasks can be divided into end-to-start constraint and start-to-start constraint. For end-to-start constraint, task j can only begin after all tasks in P_j have been completed, which can be formulated as precedence constrains:

$$S_j \geq E_h, \forall h \in P_j, j = 1, 2, \dots, n \quad (2)$$

For start-to-start constraint, task j can be executed when all tasks in P_j begins, which can be formulated as precedence constrains:

$$S_j \geq S_h, \forall h \in P_j, j = 1, 2, \dots, n \quad (3)$$

For each task j , it can be executed once at most in overall planning duration:

$$\sum_{t=1}^T x_{ijkt} \leq 1, j = 1, 2, \dots, n \quad (4)$$

The relationship between the starting time and ending time of each task j can be expressed as follows:

$$E_j = S_j + d_j, j = 1, 2, \dots, n \quad (5)$$

2.3. Resource Constrains

In collaborative task planning for heterogeneous UAVs, the relationship between UAV resources and task requirements is an important aspect to be considered. A_t each time t , the number of UAVs used to execute tasks cannot exceed the total number of UAVs of that type, which can be concluded as follows:

$$\sum_{i=1}^{Q_k} \sum_{j \in A_t} x_{ijkt} \leq Q_k, k = 1, 2, \dots, w, t = 1, 2, \dots, T \quad (6)$$

The prerequisite for starting task j is that all types of UAVs required to execute the task can perform task j at that moment:

$$S_j = \sum_{t=1}^T t \cdot \left[1 - \text{sgn} \left(\max \left\{ \left| \sum_{i=1}^{Q_k} x_{ijkt} - R_{jk} \right|, 0 \right\} \right) \right], j = 1, 2, \dots, n \quad (7)$$

Where $\text{sgn}()$ is the symbol function:

For each type of UAV, limited by its total distance traveled, it must return to the base for refueling or charging after a certain period of continuous operation, which can be denoted as follows:

$$\sum_{t=t_0}^{t_0+c_k} x_{ijkt} \leq c_k, k = 1, 2, \dots, w \quad (8)$$

The purpose of collaborative task planning for heterogeneous UAVs is to find an allocation scheme that can complete collaborative missions while satisfying the above constraints (1)-(8).

3. Heterogeneous UAVs Collaborative Task Planning Model

3.1. AON Network Establishment

Based on the intelligence obtained, we have to clarify the number of tasks and the constraint relationships between different tasks (e.g., the order of investigation between different targets). Besides, the type and quantity for UAVs required and duration of each task also need to be mastered. Then, we have to establish the AON network, as shown in Figure 1.

3.2. Scheduling Generation Mechanism

In this section, we describe 2 scheduling generation mechanism, namely parallel scheduling generation mechanism (PSGS) and serial scheduling generation mechanism (SSGS), in order to produce a feasible UAV task plan.

3.2.1. Parallel Scheduling Generation Mechanism

In this section, the PSGS is used to generate a feasible plan for the AON network. The PSGS is a scheduling mechanism with time as the scheduling stage. At each time t , The PSGS set the starting time for all tasks which satisfy resource and precedence constraints. The procedure is shown in Figure 2.

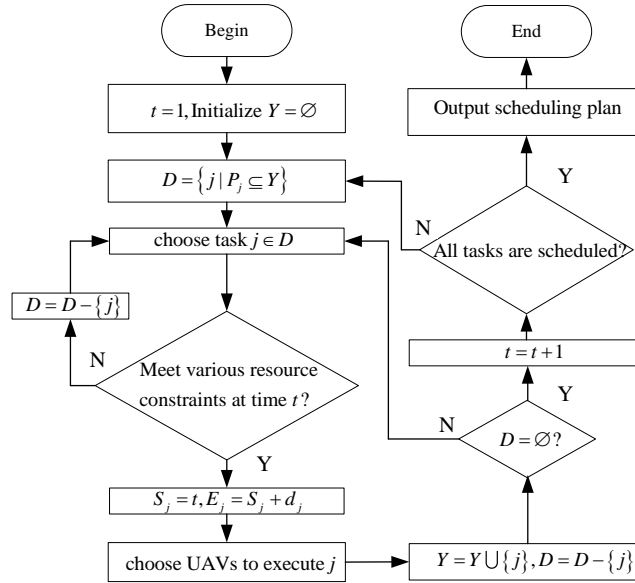


Figure 2: The procedure of PSGS.

Step1: Initialize $t=1$ and $Y = \emptyset$, where Y is the set of task which has been scheduled.

Step2: Calculate the set of task which can be scheduled D at time t . In each task j in D , its all precedence tasks have been scheduled.

Step3: Choose a task j to be scheduled in D according to task number, i.e., select the task in ascending order of task number.

Step4: If the UAV resources at this moment can meet the task j requirements, we set the starting and ending time of the task j , and choose the UAV to execute the task j . Otherwise, back to Step3. In this step, we need to determine whether each type of UAV required to execute the task is idle and whether its remaining distance traveled meets the task duration. Besides, we select UAVs to execute the task in ascending order of UAV number.

Step5: Move j from D to Y , add j to the set of task which has been scheduled.

Step6: If all the tasks in D are scheduled, we set $t=t+1$. Otherwise, back to Step3.

Step7: If all the tasks are scheduled, output the scheduling plan. Otherwise, back to Step2.

3.2.2. Serial scheduling generation mechanism

The SSGS is a scheduling mechanism with task (or node in AON network) as the scheduling stage. The procedure of the SSGS is shown in Figure 3.

The difference between SSGS and PSGS is described as follows. In the SSGS, we only select one task to be scheduled in ascending order of task number from the set of task which can be scheduled D in each scheduled stage. We set an earlier starting time as soon as possible for each task in each scheduled stage. It should be noted that the SSGS find a feasible starting time from the maximum ending time of immediate predecessors of the selected task. If the current time cannot meet the resource requirement, then the time is recursively pushed back until a time that can meet the resource requirement is found.

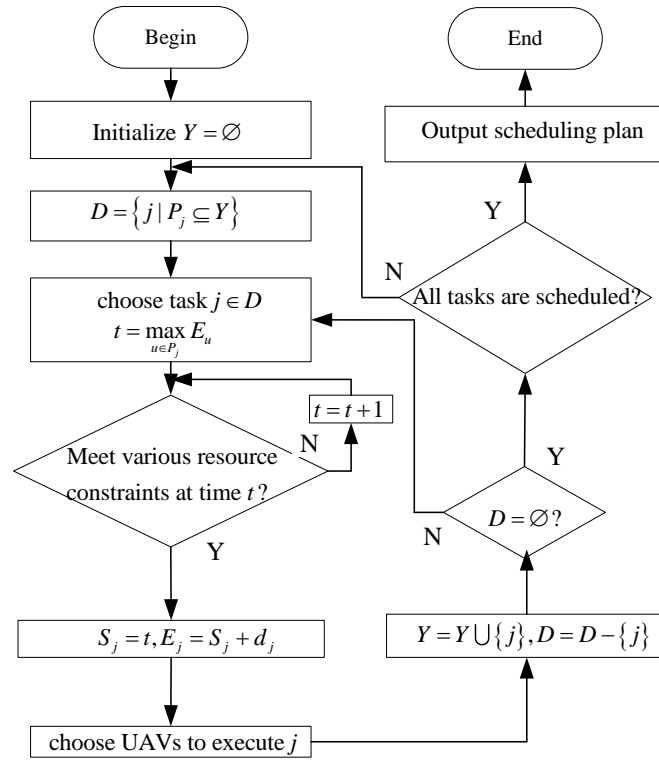


Figure 3: The procedure of SSGS.

4. Case Study

4.1. The description of mission case

In a material delivery mission, the UAV swarm at the base needs to carry out material delivery missions for 5 targets (denoted as M1-M5), as shown in Figure 4.

There are five types of UAVs, namely investigation UAVs (UAV1), material delivery UAVs (UAV2), investigation and material delivery integrated UAVs (UAV3), assistant UAVs (UAV4), and communication UAVs (UAV4). The maximum continuous working duration of each type of UAV is 3 hours, and if the operation exceeds 3 hours, it needs to return to the base for refueling. The duration of refueling is 1h for every type of UAV. If the UAV does not perform tasks continuously, it returns to the base and its continuous working duration can be refreshed. According

to comprehensive intelligence analysis, it is necessary to delivery material for targets M1 and M2 before delivering material for target M3, and to delivery material for target M4 before delivering material for target M5. Target M3 located far from the base and requires a communication relay UAV to establish a communication node in zone G to complete the measurement, control, and command of the UAVs which serve target M3. To ensure the effectiveness, it is necessary to complete the tasks of each target in the order of investigation, delivery material, and effectiveness evaluation. The types and quantities of UAVs available at the base, as well as the types and durations of UAVs required to execute each task, are shown in Table 1.

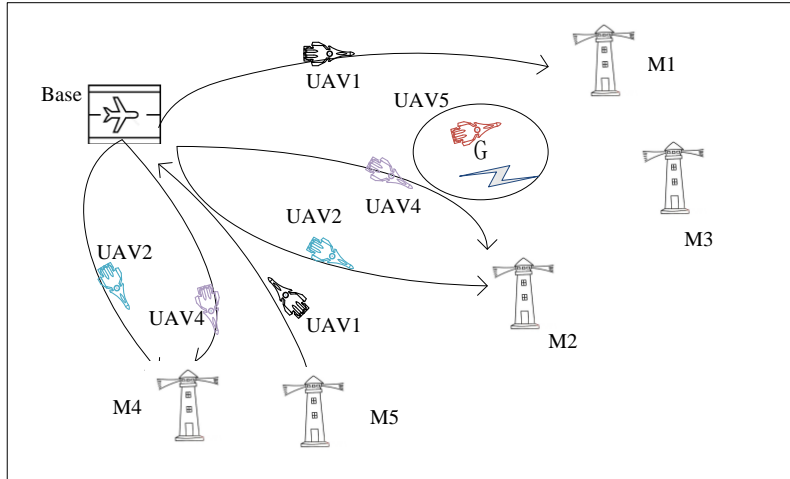


Figure 4: Distribution map of targets.

Table 1 UAV types and task duration table

Types and quantities of UAVs available in the base							
		UAV1	UAV2	UAV3	UAV4	UAV5	
		3	2	1	2	1	
Types and durations of UAVs required to execute each task							
Target	Task	Number of UAVs required					Duration
		UAV1	UAV2	UAV3	UAV4	UAV5	
M1	Investigation	1	-	-	-	-	2h
	Material delivery	-	2	-	1	-	2h
	Effectiveness evaluation	1	-	-	-	-	1h
M2	Investigation	1	-	-	-	-	1h
	Material delivery	-	1	-	1	-	1h
	Effectiveness evaluation	1	-	-	-	-	1h
M3	Investigation	2	-	-	-	-	2h
	Material delivery	-	2	-	1	-	3h
	Effectiveness evaluation	1	-	-	-	-	1h
M4	Investigation	2	-	-	-	-	2h
	Material delivery	-	2	-	-	-	2h
	Effectiveness evaluation	1	-	-	-	-	1h
M5	Investigation	1	-	-	-	-	2h
	Material delivery	-	1	-	1	-	1h
	Effectiveness evaluation	1	-	-	-	-	1h
G	Communication	-	-	-	-	1	-

Note: UAV3 can perform investigation and material delivery tasks, but UAV1 and UAV2 should be given priority.

4.2. The AON network of mission case

Based on the precedence constraints of the task described in section 4.1, we can construct the AON network as shown in Figure 5. In Figure 5, the numbers of each node represent the task number. The relationship between task 4 and task 11 belongs to the start-to-start constraint, which means that after the communication UAV arrives in zone G to carry out communication transmission, it can start investigation and delivery material for target M3. The precedence constraints between other tasks belong to the end-to-start constraint.

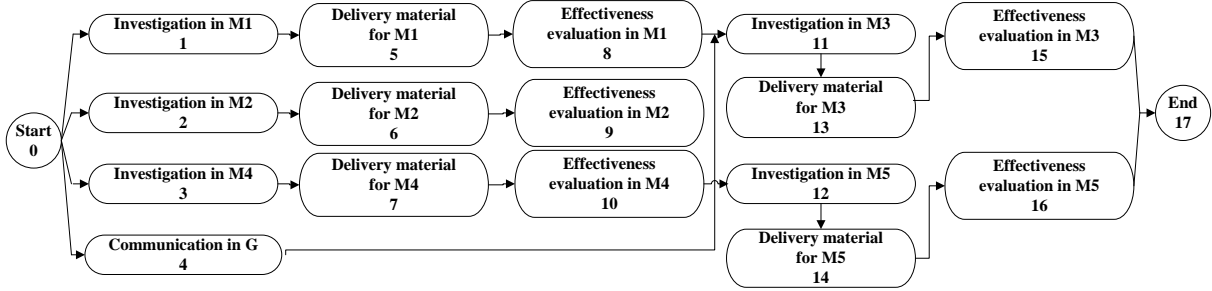


Figure 5: The AON network of mission case.

4.3. The scheduling plan of mission case

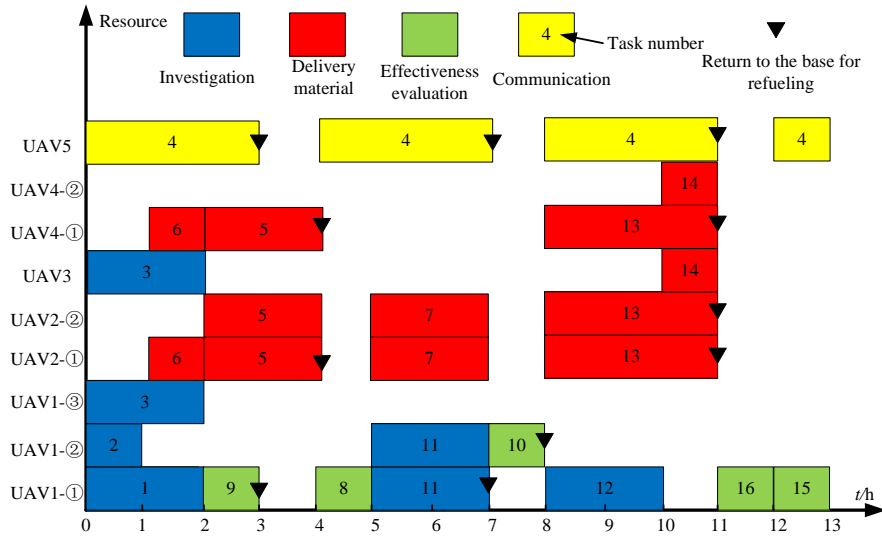


Figure 6: The scheduling plan of mission case (PSGS).

Based on the parallel scheduling generation mechanism proposed in section 3.2.1, we generate a scheduling plan that satisfies precedence constraints and resource constraints, which is shown in Figure 6. In Figure 6, the total duration of task planning is 13h, and all UAVs are used to execute tasks, although the UAV allocation is not balanced enough. The number and continuous working duration of UAVs have a significant impact on the results of mission planning. For example, when $t=2$, the task numbered 5, 7, and 9 can be scheduled. According to the task selection strategy proposed, we should prioritize executing task 7 and then execute task 9 (step 3 in section 3.2.1). However, the UAV2 and UAV3 required for executing task 7 is insufficient quantity, so the task 7 cannot be executed in this time. When $t=4$, although the UAV2 has completed the execution of task 5, it has reached its maximum continuous working duration and needs to return to the base for refueling, so this time cannot be used to execute mission 7. Through the visual display of Figure 6, it can be found that the generated scheduling plan meets various constraints, which verifies the

correctness of the model and parallel scheduling generation mechanism.

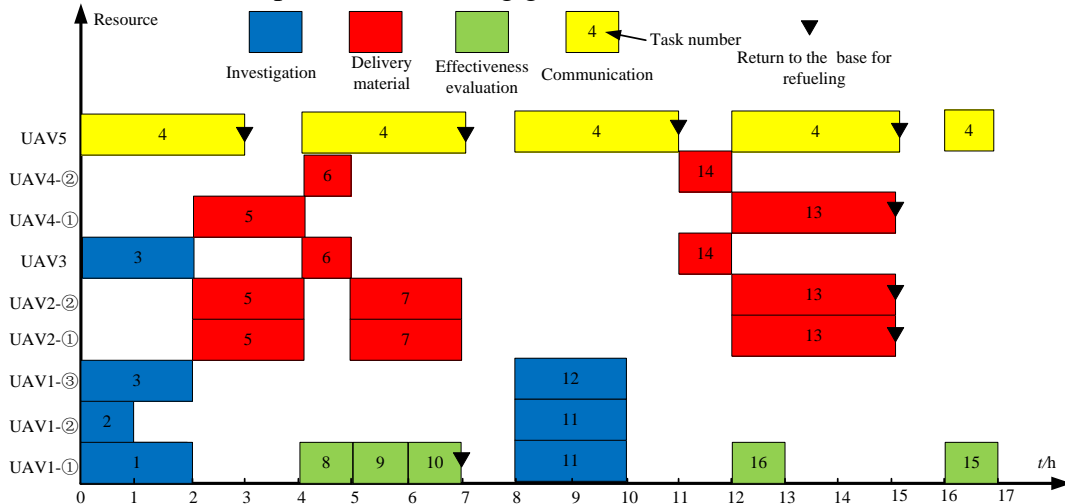


Figure 7: The scheduling plan of mission case (SSGS).

Based on the serial scheduling generation mechanism proposed in section 3.2.2, another scheduling plan is produced, which is shown in Figure 7. The total duration of task planning is 17h. By comparing Figure 6 and Figure 7, we can conclude that the total planning makespan given by PSGS is shorter than that given by serial one, which shows that the PSGS outperforms serial one in our heterogeneous UAVs collaborative task planning problem. This is because resource constraints are more restrictive than precedence constraints in heterogeneous UAVs collaborative task planning problem. The SSGS starts searching a feasible time for the selected task from the maximum ending time of immediate predecessors. However, due to more restrictive resource constraints, there may be no available resources in the short term, so the starting time of the selected task needs to be postponed. After inspection, the scheduling plan in Figure 7 meets various constraints, which verifies the correctness of the model and serial scheduling generation mechanism.

5. Conclusion and future work

In this paper, the heterogeneous UAVs collaborative task planning is studied based on the resource constrained project scheduling. The parallel and serial scheduling generation scheme is used to solve the mission case with 9 UAVs and 16 tasks. The experiment result shows that the parallel outperforms the serial one in our heterogeneous UAVs collaborative task planning problem. By conducting experiments in the case study section, the correctness of the model and the planning framework are verified.

In the future, there are some aspects that require more in-depth research. (1) The multi-optimization objectives, such as considering the load balance of UAV utilization efficiency and planning makespan, need to be considered. (2) More efficient algorithms, such as evolutionary algorithms, for the planning task need to be studied. (3) The influence of flight time and trajectory planning of UAVs needs to be considered.

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