IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 7, 2019, accepted March 23, 2019, date of publication March 26, 2019, date of current version April 11, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2907544

Swarm UAVs Task and Resource Dynamic Assignment Algorithm Based on Task Sequence Mechanism

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This work was supported by the Foundation of Shaanxi Key Laboratory of Integrated and Intelligent Navigation under Grant SKLIIN-20180104.

ABSTRACT This paper proposed an unmanned air vehicle (UAV) swarm task and resource dynamic assignment algorithm based on task sequence mechanism. By establishing a task sequence, each UAV strictly separates the necessary task time and synchronization waiting time. For the found new targets, each UAV quickly determines its available time period. According to the available time and task resources, an auction algorithm and consensus algorithm are used to decompose the task assignment into initial distributed assignment phase and swarm consensus phase to develop real-time conflict-free task solutions for UAV swarm. The simulation experiment verified that the algorithm could assign different tasks to UAVs in a real-time distributed manner with the limited resources of each UAV.

INDEX TERMS Task and resource assignment, task sequence mechanism, unmanned air vehicle, UAV swarm.

I. INTRODUCTION

Swarm UAVs consist of a large number of small drones which have limited task resources, and operate in a more autonomous, distributed and adaptable manner. UAV swarm cooperative task and resource assignment is to real-time assign targets according to their locations and values to UAVs reasonably [1]. However, in dynamic environment, the previously task assignment solutions are need to be revised according to changed situation [2]–[5].

A discrete invasive weed optimization algorithm is proposed to improve the efficiency of task assignment in [6]. The task assignment problem of multi-UAV is modeled as an integer programming problem for the heterogeneous type of UAV in [7]. The single task assignment algorithm CBAA (Consensus-Based Auction Algorithm) and the multi-tasks assignment algorithm CBBA (Consensus-Based Bundle Algorithm) are improved in [8], and these two algorithms are applied to many scenarios [9]. The tasks order is considered as an important constraint for UAV task planning in [10], and an improved particle swarm optimization is used to solve the problem. An online task assignment algorithm based on task alliance is proposed in [11], which requests the neighboring UAVs to form a task alliance to deal with pop-up tasks.

A modified genetic algorithm with multi-type genes is designed for cooperative task assignment of multiple UAVs with limited resources and kinematic constraints for multiple consecutive tasks cooperatively on multiple ground targets [12], An iterative strategy is proposed to enhance the performance of task assignment and path planning in applications of distributed multiple UAVs [13], and the strategy overcomes difficulties caused by the information coupling between task assignment and path planning.

A scalable and flexible architecture for real-time mission planning and dynamic agent-to-task assignment for UAV swarm is presented [14]. In this architecture, Global Mission Planner (GMP) is responsible for assigning and monitoring different high-level missions, and a local coordinator called Agent Mission Planner (AMP) is in charge of executing these tasks with an asynchronous communication with the GMP. Two different genetic fuzzy clustering algorithms are developed to the task assignment for cooperating UAVs classified as the Polygon Visiting Multiple Traveling Salesman Problem, and they are more efficient compared to k-means

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The associate editor coordinating the review of this manuscript and approving it for publication was Omar Khadeer Hussain.

and c-means clustering. One evaluates the distance covered by each UAV to cluster the search-space and the other uses a cost function that approximates the distance covered thus resulting in a reduced computational time [15]. By partitioning a group of robots in parallel clusters, Cluster-Formed Consensus-Based Bundle Algorithm is designed to reduce the amount of communication required to complete a distributed task allocation process [16]. A hierarchical task assignment method is designed to address multiple UAVs task assignment problem [17], and it breaks the original problem to three levels of sub-problems: target clustering, cluster allocation and target assignment. The first two sub-problems are centrally solved by using clustering algorithms and integer linear programming, respectively, and the third sub-problem is solved in a distributed and parallel manner, using a mixed integer linear programming model and an improved ant colony algorithm. A simple and efficient distributed control algorithm is proposed to implement dynamic task allocation in a robotic swarm [18]. In this algorithm, each robot that integrates the swarm runs the algorithm whenever it senses a change in the environment. A dynamic ant colony's labor division method is proposed for UAV task allocation, which has the characteristic of distributed framework, multi-tasks with execution order, multi-state, adaptive response threshold and multi-individual response [19]. And the method is applied to UAV swarm dynamic task allocation with a certain number of enemy targets and task re-allocation due to unexpected threats.

Most of these studies have not conducted in-depth exploration of the characteristics of UAV swarm, which has the real-time requirements of task assignment in dynamic environment and each individual UAV has limited task resources. The characteristics require that the task assignment of UAV swarm in a distributed and real time manner with full use of task resources and available time. And available time is equivalent to available energy to some extent.

This paper proposed a UAV swarm task and resource dynamic assignment algorithm based on task sequence mechanism. Each UAV can quickly calculate its available task time period based on task sequence mechanism in a distributed and real time manner. If a UAV has available time and resources for task assignment, it will bid for new targets based on the available task time period, task reward, and available resources. All UAVs available for new targets will negotiate to a conflict-free task assignment solution.

II. COOPERATIVE TASK ASSIGNMENT IN DYNAMIC ENVIRONMENT

A. TASK RESOURCE MODEL

Given a swarm of N heterogeneous UAVs $U = \{U_1, U_2, \ldots, U_N\}$ and set of M targets $T = \{T_1, T_2, \ldots, T_M\}$, the UAV swarm performs two kind of tasks for each target, and the task set is $S = \{I, A\}$. I represents the electronic interference task, and A represents the attack task, the goal of the task assignment algorithm is to find a matching of tasks to UAVs that maximizes some global reward.

These UAVs are heterogeneous, and each UAV carries different types and amounts of resources. The UAV swarm can be divided into two subsets $U = \{U_I, U_A\}$ according to the task type, U_I is the collection of electronic interfering UAVs and U_A is the collection of attack UAVs. Each UAV belongs to only one of collection. At the same time, each UAV carries n kinds of task resources. The attack UAVs carry the weapon resources, and the task resources vector is represented by $\mathbf{resSu}_i^A, i = 1, \ldots, N$; the electronic interfering UAVs carry the interference payload, and the task resources vector is represented by $\mathbf{resSu}_i^I, i = 1, \ldots, N$.

There are corresponding task resource requirements for attack and electronic interfering tasks. $\mathbf{resRe}_j^A, j = 1, \ldots, M$ indicates the type and quantity of weapons required to perform attack task on one target; $\mathbf{resRe}_j^I, j = 1, \ldots, M$ indicates the type and quantity of interference payload required to perform electronic interference task on one target [20].

In addition to known targets, there are some unknown targets in the mission area. During the performing of the scheduled task of the UAV swarm, some UAVs may discover some new targets, and then broadcast the status information of the new targets to the entire swarm. All available UAVs autonomously bid for new targets, and through the tasks and resource distributed assignment and swarm consensus process, form task squads for new targets.

Due to the limited task resources of each UAV, it may be not sufficient to complete all tasks of target T_x independently. Therefore, it is necessary to request other UAVs to form a task squad I_A. Ultimately, the total amount of task resources carried by the task squad must meet the tasks requirements.

$$\begin{array}{l} \sum\limits_{U_i \in I_A} x_{i,k}^A \cdot resSu_{i,k}^A \geq resRe_{x,k}^A, \forall k \in \{1, 2, \ldots, n\} \\ \sum\limits_{U_i \in I_A} x_{i,k}^I \cdot resSu_{i,k}^I \geq resRe_{x,k}^I, \forall k \in \{1, 2, \ldots, n\} \end{array} \tag{1}$$

where, $x_{i,k}^A$ and $x_{i,k}^I$ respectively indicate whether the k-th weapon resource or interference payload of the U_i is used to perform the task on the target; $resSu_{i,k}^A$ and $resSu_{i,k}^I$ indicate the number of the k-th weapon resources or interference payload of U_i respectively.

B. TASK REWARD MODEL

Definition 1 (The Initial Reward of Attack Task): Suppose the damage probability of U_i to one target is $p_{i,a}$, the initial reward of attack task is defined as

$$G_{i,j}^A = V_j p_{i,a} - D_j \tag{2}$$

where V_j and D_j are the value and threat of target T_j.

The task of attack reduces the threat level of the target, therefore the threat of target T_j that has been attacked is

$$D_j^* = \left(1 - p_{i,a}\right) D_j \tag{3}$$

Definition 2 (The Initial Reward of Electronic Interference Task): As shown in Figure 1, the electronic interference task

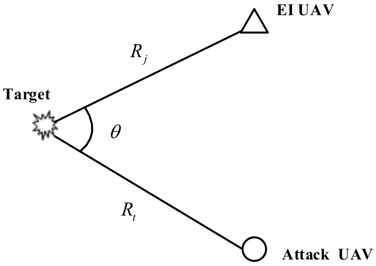

FIGURE 1. Schematic diagram of electronic interference process.

is related to the attack task, and it should be performed before attack task a certain period of time. UAV swarm assigns an attack task to a target at first, and then estimates the start time of electronic interference task according to the time of the attack task [21].

Radar interference equation

$$\frac{P_jG_j}{P_tG_t}\cdot\frac{4\pi\gamma_j}{\sigma}\cdot\frac{R_t^4}{R_j^2}\cdot\frac{G_t'}{G_t}\ge K_j \tag{4}$$

where, P_j, G_j and γ_j represent transmit power, gain and loss coefficient of the main lobe of electronic interference UAV respectively; R_j represents the distance between the electronic interference UAV and the target; G_t' represents the gain of the radar antenna in the direction of the UAV; P_t and represent the transmit power of the target radar and the gain on the main lobe respectively; K_j represents the compression coefficient of the radar; σ represents the reflective area of the attack UAV. Therefore

$$R_t\ge\sqrt[4]{\frac{P_tG_t\sigma R_j^2G_t}{P_jG_j4\pi\gamma_jG_t'}K_j} \tag{5}$$

where

$$G_t'(\theta)=\begin{cases}G_t & 0\le\theta\le\frac{\theta_{0.5}}{2}\\ K(\frac{\theta_{0.5}}{\theta})^2G_t & \frac{\theta_{0.5}}{2}<\theta<90\\ K(\frac{\theta_{0.5}}{90})^2G_t & \theta\ge 90\end{cases} \tag{6}$$

where, $\theta_{0.5}$ represents the lobe width of the target radar antenna; θ represents the angle between the target line of sight of the electronic interference UAV and the target line of sight of the attack UAV.

The maximum interference distance R_t is a function of R_j and the angle θ, which is

$$R_t=f(R_j,\theta) \tag{7}$$

The reward of the electronic interference task is defined as [22]

$$G_{i,j}^I=\begin{cases}0 & R^a<R_t\\ \delta G_{i,j}^I & R^a\ge R_t\end{cases} \tag{8}$$

where, R_t indicates the maximum interference distance of UAV U_i, R^a represents the distance between the UAV U_i and the target T_j.

C. TASK ASSIGNMENT MODEL

The task and resource assignment model of the UAV swarm is described as:

$$\max\left\{J=\sum_{i=1}^{N}\sum_{j=1}^{M}X_{i,j}\cdot C_{i,j}(p_i)/\sum_{i=1}^{N}X_{i,j}\cdot Len_i(p_i)\right\} \tag{9}$$

$$\begin{aligned}\text{s.t. }&\sum_{j=1}^{M}X_{i,j}\le L,\forall U_i\in U\\ &X_{i,j}^k\cdot resSu_{i,j}^k\le resSu_i^k\\ &\sum_{i=1}^{N}X_{i,j}^k\cdot resSu_{i,j}^k\ge resRe_j^k\\ &X_{i,j}\in\{0,1\},\forall(i,j)\in U\times T\end{aligned} \tag{10}$$

where $X_{i,j}$ denotes whether UAV U_i is assigned to target j. L represents the maximum number of tasks of each UAV. Vector $p_i\in(T\cup\{\emptyset\})^L$ represents an ordered sequence of tasks path of U_i. $Len_i(p_i)$ indicates the length of the path that the UAV performs the current task sequence. The fractional function $C_{i,j}(p_i)$ represents the total tasks reward that is calculated as described in equation (2) and (8). $X_{i,j}^k$ denotes whether UAV U_i with *k-th* resource is assigned to target j. $resSu_{i,j}^k$ indicates the number of the *k-th* resources of U_i that is assigned to target j, and $resSu_i^k$ indicates the number of the *k-th* resources of U_i. $resRe_j^k$ indicates the number of the *k-th* resources acting on target j.

III. TASK AND RESOURCE DYNAMIC ASSIGNMENT ALGORITHM BASED ON TASK SEQUENCE MECHANISM

A. TASK SEQUENCE MECHANISM

Due to limited task resources of each UAV, UAV swarm needs to build task squads to each target. Each UAV should arrive at the task destination at specified time. Since the position status and flight path of each UAV are different, the distances to the task destination are different, and the times to reach the destination are inconsistent. In this case, the task start time of each squad is determined by the UAV which arrives at the latest.

The synchronous time for each UAV to wait for the other members of the task squad is called the task idle period. So the flight time of each UAV can be decomposed into the necessary task time and the synchronization waiting time. Figure 2 shows the task sequence of a UAV, where (t_{j-1}^1, t_j^0) is the necessary flight time for the UAV to fly from target T_{j-1} to target T_j; (t_j^1, t_j^2) is the necessary task time for the UAV to perform a task on target T_j. (t_j^0, t_j^1) is the synchronization waiting time between the earliest time that the UAV theoretically reaches the target and the task start time, that is, the task idle period.

When a new target is found, the UAV swarm can utilize the task sequence to assign the tasks of the new target in real time, and insert the new task into the appropriate task idle period, and quickly assign the new tasks without affecting the established task assignment plan.

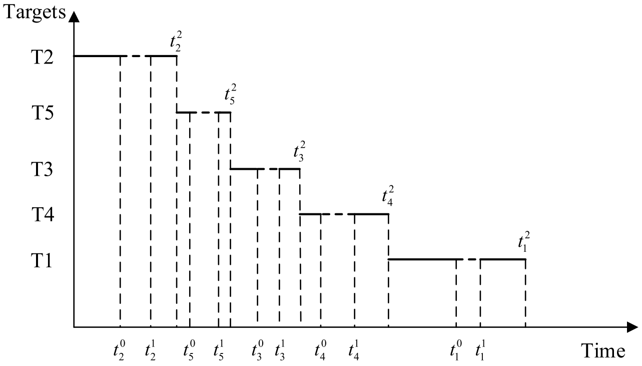

FIGURE 2. The task sequence of a UAV.

In order to utilize the task idle period under the task sequence mechanism, it is necessary to clarify the start time and the end time of the task idle period. For the new target T_j, the start time of the task idle period refers to the earliest moment $t_{i,j}^a$ when the UAV U_i can reach the position of the new target T_j without affecting the assigned task.

For different scenarios, the start time $t_{i,j}^a$ of the task idle period is discussed in three cases.

(1) The UAV is searching new target, and there is no task in the established task assignment plan. In this case, the UAV can fly directly to the target, and the start time of the task idle period is

$$t_{i,j}^a = t_{c,j}^a + t^c \tag{11}$$

where, t^c represents the current time, $t_{c,j}^a$ represents the flight time of the UAV U_i from the current position to the position of new target T_j.

(2) The UAV has a longer synchronization waiting time for the target T_o in the established task assignment plan, and the tasks for the new target T_j can be performed by the UAV firstly. In this case, the calculation method of $t_{i,j}^a$ is the same as above, and the time for the UAV to perform the task for the intended target T_o is:

$$t_{i,o}^a = t_{i,j}^w + t_{j,o}^a + t_{i,j}^a \tag{12}$$

where, $t_{i,j}^w$ represents the synchronization waiting time before, $t_{j,o}^a$ represents the necessary flight time from T_o to T_j.

(3) The UAV has a shorter synchronization waiting time for the target T_o in the established task assignment plan, and can only perform tasks on the new target T_j after performing the task on the target T_o. In this case, the start time of the task idle period is

$$t_{i,j}^a = t_{i,o}^l + t_{o,j}^a \tag{13}$$

where, $t_{i,o}^l$ is the time the UAV U_i leaves the target T_o in the established task assignment plan; $t_{o,j}^a$ is the necessary flight time from T_o to T_j.

For the new target T_j, the end time of the task idle period $t_{i,j}^l$ refers to the latest moment that UAV U_i leaves the new target and flies to the next target without affecting the established task assignment plan. The UAV must complete the task of the target T_j before this moment. The end time of the task idle period is:

$$t_{i,j}^l = t_{i,o}^a - t_{j,o}^a \tag{14}$$

where, $t_{i,o}^a$ is the time at which the task is started for the next target in the established task assignment; $t_{j,o}^a$ is the necessary flight time from T_j, to T_o.

According to the start time and the end time of the task idle period, the task sequence mechanism determines whether target T_j can be inserted into the task sequence of the UAV according to the rules expressed by equation (15) and (16). Assuming that target T_j is inserted in the k-th position of the task sequence, the arrival time of the previous task and the next task in the established task assignment plan must be met:

$$t_{i,k-1}^a + t_{i,k-1}^p + t_{k-1,j}^a \leq t_{i,j}^a \leq t_{i,j}^l + t_{i,j}^p \tag{15}$$

$$t_{i,j}^a + t_{i,j}^p \leq t_{i,j}^l \leq t_{i,k+1}^a - t_{j,k+1}^a \tag{16}$$

where, equations (15) and (16) respectively ensure that the start and end time of new task satisfies the timing relationship with the preceding and succeeding tasks in the established scheme. According to the task sequence mechanism, after each UAV gets the task idle period with respect to new target, only the UAVs with overlapping idle period have the opportunity to bid new tasks to form a task squad for the new target. Assume that w_i is the task idle period of the UAV, the task squad's task idle segment is:

$$w_A = \bigcap_{i=1}^{n} w_i \neq \emptyset, \forall U_i \in I_A \tag{17}$$

B. TASK AND RESOURCE ASSIGNMENT

We extend CBBA algorithm to the problem of UAV swarm task and resource dynamic assignment. In the bundle building phase of CBBA algorithm, each UAV independently calculates the reward of each task, and continuously updates its task bundle. There are two types of task sequences, which $\mathbf{b}_i$ is the task bundle based on the order of each task is added to the assignment plan and $\mathbf{p}_i$ is the path bundle based on the sequence of task performed path.

In addition, the extended algorithm also needs to determine how much task resources are allocated to the target. Therefore, when a UAV bids on a target, it should also bid on the task resources involved in the target. The UAV not only calculates the task reward, but also calculates how many task resources can be contributed.

In order to represent the task resource allocation status of UAV U_i to target T_j, besides task bundle $\mathbf{b}_i$ and path bundle $\mathbf{p}_i$, resource bundle $\mathbf{r}_i$ is added to the algorithm. $r_i^{q,j}$ indicates the number of q-th task resources provided to T_j by U_i.

CBBA algorithm must meet the marginal diminishing characteristics of the task reward during the bundle construction phase. That is, as the length of task bundle increases, the calculated task reward must be successively decremented. Therefore, the first task added to the task bundle has the greatest task reward, and each task has the current maximum reward when it added to the task bundle. This is in line with the principle of maximizing resource utilization, that is, assigning the most resources to tasks with the greatest rewards.

Based on the above principles, when UAV U_i assigns task and resource to target T_j, the number of q-th resource assigned to the target is:

$$r_i^{q,j} = \min\{resSu_{i,q}, resRe_{j,q}\} \tag{18}$$

where, $resSu_{i,q}$ indicates the number of q-th resources of U_i, and $resRe_{j,q}$ indicates the number of q-th resources required by the target T_j.

After completing the resource assignment, UAV U_i updates its own resource supply vector:

$$resSu_{i,q} = resSu_{i,q} - r_i^{q,j} \tag{19}$$

If $resSu_{i,q} = 0, \forall q = 1, 2, \ldots, m$, it indicates that the UAV has no redundant resources to bid new tasks any more.

C. TASK AND RESOURCE CONSENSUS

Once each UAV has built local task bundle $\mathbf{b}_i$, path bundle $\mathbf{p}_i$, and resource bundle $\mathbf{r}_i$, they communicate with each other to resolve conflicting assignments amongst every task squad.

Each UAV will obtain the bidding of neighboring UAVs for each task through communication, and compare it with the task reward bid of the local task bundle. If another UAV has a higher reward of a task, the task should be immediately removed from the local task bundle.

The reward of a task is related to all tasks that added to the task bundle earlier than it. Once a task is removed from the task bundle, all subsequent tasks after this task should also be removed from the task bundle.

Each UAV compares the task assignment and resource assignment of local and other UAVs, and makes the assigning decisions according to certain rules. This is the consensus process. The consensus process requires information transfer between UAVs, mainly using three information vectors, which are the list of winning bids $\mathbf{y}_i$ and the corresponding list of winning task resources $\mathbf{z}_i$ and communication time lists $\mathbf{t}_i$.

The winning bids list and the communication time list are two-dimensional vectors, and the winning task resources list is a three-dimensional vector. $y_i^{l,j}$ indicates the winning reward of the local assignment in the U_i to the target T_j, and $z_i^{l,j,m}$ represents the quantity of the m-th task resource that U_l can provide to the target T_j. $t_i^{i,l}$ indicates the latest communication time between U_i and U_l. Similarly, $y_k^{l,j}$, $z_k^{l,j,m}$ and $t_k^{l,j}$ represent the same information in the local assignment result of the U_k.

A collection of UAVs that perform same tasks on the target T_j is called I_j, where $I_j \subseteq U$. In the consensus phase, all the candidate UAVs that perform the task for the target T_j are selected and finally form the task squad. The criteria for selecting includes:

1) The task is performed in the shortest time. This criterion is set to eliminate the target threat as quickly as possible and ensure the survival safety of the UAV swarm. 2) The scale of task squad is the smallest which occupy less UAVs resources. This criterion is set to improve the utilization of task resources and ensure that tasks are completed in an efficient manner. 3) Each squad member arrives at target position at the same time. This criterion is set to let each member perform tasks on the target at the same time and ensure that the tasks are completed effectively. 4) The sum of resources of each squad member satisfies the task requirement. This criterion is set to ensure the success rate of tasks.

In the consensus phase, each UAV receives information from neighboring UAVs and compares them. When U_i receives message from the U_k, it compares $\mathbf{y}_i$ and $\mathbf{y}_k$, $\mathbf{z}_i$ and $\mathbf{z}_k$, $\mathbf{t}_i$ and $\mathbf{t}_k$, to determine the final task assignment solution for each target. For the task assignment of target T_j, the process of consensus decision is as follows:

(1) The Selection Process: Comparing $\mathbf{y}_i$ and $\mathbf{y}_k$, and selecting the bidding reward Bid_j of each UAV to target T_j and the corresponding resource assignment result Res_j according to the decision rule of Table 1. $Bid_j(x)$ and $\mathrm{Res}_j(x)$ represent the outbid reward and resource assignment result of UAV U_x to target T_j respectively.

TABLE 1. **Rules for UAVs to Decide the Bidding Reward.**

UAV	Results of Bidding Reward	Results of Resource Assignment
U_i	$Bid_j = y_i^{i,j}$	$\mathrm{Res}_j = z_i^{i,j}$
U_k	$Bid_j = y_k^{k,j}$	$\mathrm{Res}_j = z_k^{k,j}$
$U_m, m \neq i,k$	If $t_i^{i,m} \geq t_k^{k,m}$,Then $Bid_j = y_i^{m,j}$	If $t_i^{i,m} \geq t_k^{k,m}$,,Then $\mathrm{Res}_j = z_i^{m,j}$
	If $t_i^{i,m} < t_k^{k,m}$,Then $Bid_j = y_k^{m,j}$	If $t_i^{i,m} < t_k^{k,m}$,,Then $\mathrm{Res}_j = z_k^{m,j}$

(2) The Adding Process: $Bid_j(x)$ calculated by Step 1 is the latest outbid reward for each UAV to the target T_j. The UAV with the largest bid reward is selected to enter the task squad in turn, and calculate the resources of the task squad, ie

$$\mathrm{Res}(I_j) = \sum \mathrm{Res}_j(\arg\max Bid_j(x)) \tag{20}$$

When the total resources of the task squad meet the resource requirements for the target, the adding process is stopped. That is, the stop condition is:

$$\mathrm{Res}(I_j) \geq \mathrm{resRe}_j \tag{21}$$

At this point, the initial task squad is formed.

(3) The Elimination Process: The task squad formed in step 2 may not be refined, and there may be redundancy of resources. Therefore, the task squad will be refined using the concept of resource contribution.

Resource contribution $resCo_x$ measures the contribution of a UAV in a task squad to a task's resources.

$$resCo_x = \sum_{j=0}^{n} w^j \frac{D_x^j}{(R_x^j - R_A^j)^2} \tag{22}$$

where, w^j indicates the weight of the j-th task resource; R_A^j indicates the quantity of j-th resources that the task squad still requires; $D_x^j = \min\{R_x^j, R_A^j\}$ indicates the contribution of existing j-th resource of U_i to the task squad; R_x^j indicates the quantity of j-th task resources of U_i.

According to $resCo_x$, the UAV with the smallest resource contribution is eliminated in turn, and the total resources of the task squad are reduced accordingly:

$$\mathrm{Res}(I_j)' = \mathrm{Res}(I_j) - \mathrm{Res}_j(x) \tag{23}$$

If the total task resources of the task squad still meet the resource requirements for the target T_j, ie

$$\mathrm{Res}(I_j)' \geq \mathrm{resRe}_j \tag{24}$$

The U_x can be successfully removed from the task squad, which further reduces the size of the squad. If the total task resource of the task squad does not meet the resource requirements after U_x is removed, the elimination process is stopped. The current I_j is the set of task squad that ultimately perform the task on the target.

(4) The Update Process: According to the final task squad collection I_j, the winning list of the UAV and the corresponding winning resource list and communication time list are updated, and the updated information is transmitted to other UAVs.

IV. SIMULATION

In the simulation experiment, UAV swarm search targets in mission area by default, when new targets are found, electronic interference or attack tasks on targets will be assigned to UAV swarm.

The mission area is set to a rectangular area of 10km∗10km, and there are 4 known targets and 2 unknown targets in the area. UAV swarm consists of 14 UAVs, including 7 attack UAVs and 7 electronic interference UAVs. The speed of the UAV is 50m/s and the maximum detection distance is 300m.

The simulation experiment firstly assigns tasks and resources to UAVs based on the known targets to form the initial UAV swarm task sequence. When the unknown targets are found, the task and resource dynamic assignment process are triggered. The duration time of attack task is set to 10s; the electronic interference UAV must reach target position 5s before the start of the attack task to perform electronic interference until the end of the attack task to leave, so the duration time of the electronic interference task is set to 15s.

A. TASK AND RESOURCE ASSIGNMENT FOR KNOWN TARGETS

Among the 14 UAVs, U_1–U_7 are attack UAVs, U_8–U_{14} are electronic interference UAVs. The initial position and resource vectors for all UAVs and targets are generated in a random manner. Each UAV has three kinds of resources, that is, the attack UAVs has three kinds of weapons, and the electronic interference UAVs has three kinds of interference payloads. Correspondingly, each target's attack task and electronic interference task also require three kinds of resources.

The initial states of attack UAVs and electronic interference UAVs are shown in Table 2 and Table 3. The initial state of the target is shown in Table 4.

TABLE 2. **The Initial State of Attack UAVs.**

U_i	Initial Position	Vector of Weapons
U_1	(5313, 4085)	(0, 2, 3)
U_2	(9085, 3371)	(2, 1, 0)
U_3	(6441, 6490)	(4, 0, 1)
U_4	(1191, 2594)	(3, 3, 0)
U_5	(3568, 7959)	(0, 2, 4)
U_6	(2644, 1174)	(2, 0, 4)
U_7	(9321, 9148)	(2, 3, 0)

TABLE 3. **The Initial State of Interference UAVs.**

U_i	Initial Position	Vector of Interference
U_8	(6069, 1642)	(4, 0, 3)
U_9	(3990, 5324)	(2, 3, 0)
U_{10}	(1435, 8812)	(2, 0, 2)
U_{11}	(8752, 6590)	(3, 4, 0)
U_{12}	(7876, 1260)	(0, 1, 3)
U_{13}	(7248, 7995)	(4, 0, 2)
U_{14}	(1091, 6346)	(2, 0, 3)

TABLE 4. **The Initial State of Targets.**

T_j	Initial Position	Requirement for Attack Resources	Requirement for Interfering Resources
T_1	(2446, 5429)	(1, 3, 2)	(1, 1, 1)
T_2	(7809, 5219)	(1, 0, 2)	(1, 1, 2)
T_3	(9319, 1471)	(1, 2, 2)	(1, 2, 1)
T_4	(4168, 2802)	(2, 1, 1)	(2, 1, 0)
T_5	(4627, 2718)	(2, 1, 1)	(1, 1, 2)
T_6	(8510, 3261)	(1, 1, 1)	(1, 2, 1)

In summary, the initial situation of this simulation experiment is shown in Figure 3. The attack UAVs, the electronic interference UAVs and the known targets are respectively represented by labels of different shapes. Each UAV is represented by a different color. Target T_5 and T_6 are targets to be discovered in the initial situation.

For the known targets, the task sequence mechanism and the task and resource distributed assignment algorithm proposed in this paper are used to assign these four targets in turn. The task time and task squad results are shown in Table 5. The UAV task resource assignment result is shown in Table 6. The approximate trajectory map and task sequence of the UAV swarm are shown in Figure 4 and Figure 5, respectively. As can be seen from the task assignment results, a single UAV can be assigned up to two tasks, such as U_1 and U_3; some UAVs are not assigned any task, such as U_7 and U_{10}; most UAVs are only assigned one task, such as U_{12}.

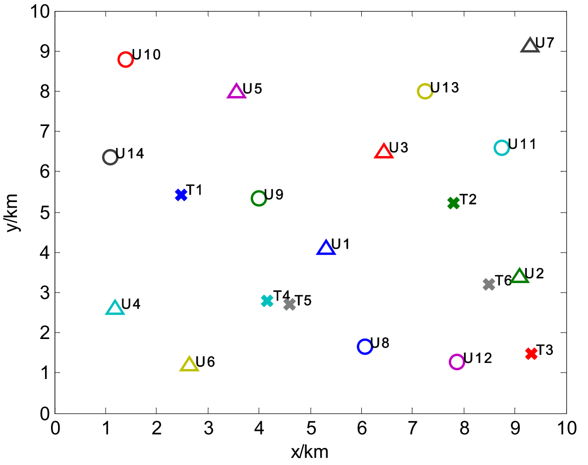

FIGURE 3. **The initial situation of task assignment scenario.**

TABLE 5. **The Result of Task Assignment.**

T_j	Critical Time of Task (Interfering, Attack, Ending)	Task Squad
T_1	(169, 174, 184)	$\lvert U_3,U_4,U_5,U_9,U_{14}\rvert$
T_2	(47, 52, 62)	$\lvert U_1,U_3,U_{11},U_{13}\rvert$
T_3	(162, 167, 177)	$\lvert U_1,U_2,U_6,U_{11},U_{12}\rvert$
T_4	(56, 61, 71)	$\lvert U_4,U_6,U_8,U_9\rvert$

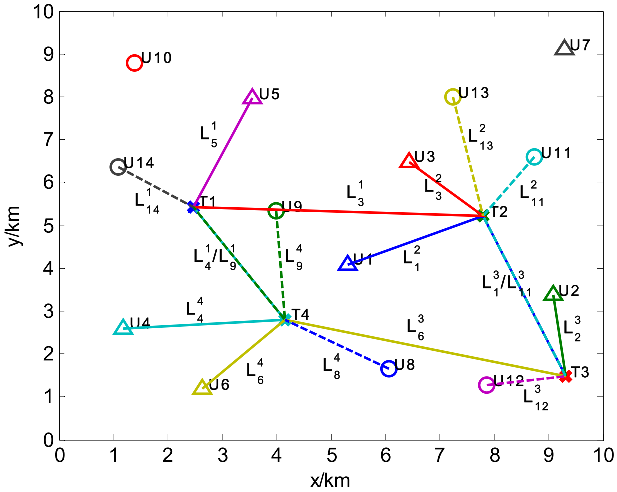

FIGURE 4. **The approximate trajectory of UAVs.**

Figure 4 shows an approximate trajectory in the task sequence of each UAV. L_i^j indicates the route of U_i to perform the task on the target T_j. Figure 5 shows the task sequence of the UAV swarm. The flight time of each UAV is divided into synchronous waiting time, necessary flight time and necessary task time. The synchronization waiting time is to ensure that the task squad launches the task at the same time. This part of the time can be used to search for targets or handle new targets.

As can be seen from Figure 5, (1) Time-sequence constraints between the electronic inference task and the attack task. Electronic interference must start before the attack UAV on the same target. For example, U_1 and U_3 will reach the position of target T_2 early, and then wait for U_{11} and U_{13}, and they will interfere target T_2 for 5 seconds before U_{11} and U_{13} attack target T_2.

(2) U_1 is farthest from target T_2 and will arrive at the task position at last, so U_3, U_9, and U_{11} have to wait synchronously. The waiting time of each UAV is different, and

TABLE 6. **The Result of Resource Assignment.**

U_i	First Task		Second Task		Remained Resource
	Target	Resource	Target	Resource	
U_1	T_2	(0, 0, 2)	T_3	(0, 2, 0)	(0, 0, 1)
U_2	T_3	(1, 0, 0)	None		(1, 1, 0)
U_3	T_2	(1, 0, 0)	T_1	(1, 0, 0)	(2, 0, 1)
U_4	T_4	(0, 1, 0)	T_1	(0, 1, 0)	(3, 1, 0)
U_5	T_1	(0, 2, 2)	None		(0, 0, 2)
U_6	T_4	(2, 0, 1)	T_3	(0, 0, 2)	(0, 0, 1)
U_7	None		None		(2, 3, 0)
U_8	T_4	(2, 0, 0)	None		(2, 0, 3)
U_9	T_4	(0, 1, 0)	T_1	(0, 1, 0)	(2, 1, 0)
U_{10}	None		None		(2, 0, 2)
U_{11}	T_2	(1, 0, 0)	T_3	(1, 1, 0)	(1, 2, 0)
U_{12}	T_3	(0, 1, 1)	None		(0, 0, 2)
U_{13}	T_2	(0, 0, 2)	None		(4, 0, 0)
U_{14}	T_1	(1, 0, 1)	None		(1, 0, 2)

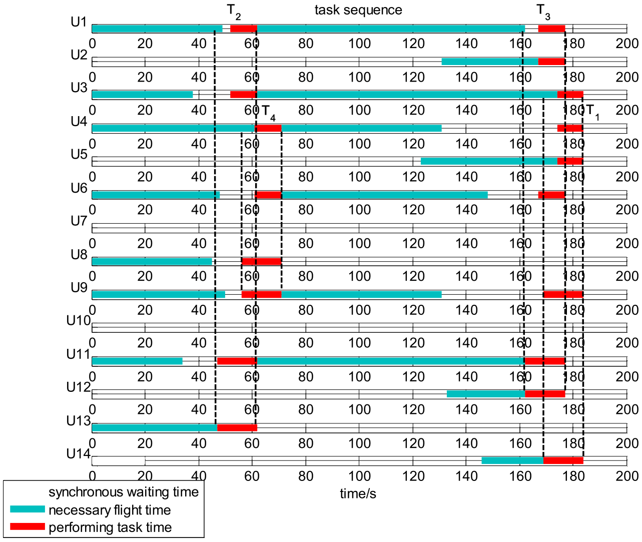

FIGURE 5. The task sequences of UAV swarm.

TABLE 7. The Result of Task and Resource Assignment for New Targets.

T_j	Requirement for Attack Resources	Requirement for Interfering Resources	Critical Task Time	Task Squad
T_1	(2, 0, 1)	(1, 1, 2)	(78, 83 93)	$\lvert U_4,U_6,U_8,U_9\rvert$
T_6	(1, 1, 1)	(1, 0, 2)	(101, 106, 116)	$\lvert U_1,U_2,U_{11},U_{12}\rvert$

it depends on the distance between each UAV and the target. Similarly, for target T_4, U_6, U_7, and U_8 need to wait for U_4; for target T_3, U_2, U_6, and U_9 must wait for U_1 and U_{10}.

This example can demonstrate the effectiveness of the UAV swarm tasks and resource assignment algorithm. The algorithm can reasonably plan the task order and resource ratio based on the task time-sequence constraint. At the same time, the established task sequence mechanism can also work effectively. Through this task sequence, the time status of each UAV can be clearly clarified, and the synchronization waiting time of each UAV is counted to provide support for the next dynamic task assignment.

B. DYNAMIC ASSIGNMENT FOR NEW FOUND TARGETS

When UAV swarm fly along the aforementioned task and resource assignment solution, the unknown targets may be found. For example, U_8 finds target T_5 during the flight to target T_4, and U_2 finds target T_6 in the synchronous waiting time. For new found targets in a dynamic environment, the UAV swarm immediately allocates tasks and resource based on the initial assignment results. After the unknown targets are found and UAV swarm reassignment, the approximate task trajectory of the UAV swarm is shown in Figure 6. L_i^j indicates the route of U_i to target T_j.

The task time and task squad results of the UAV swarm for target T_5 and target T_6 are shown in Table 7.

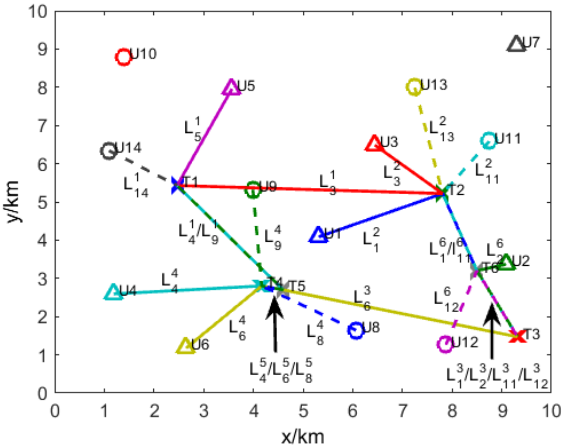

FIGURE 6. The approximate trajectory of UAV swarm after find new targets.

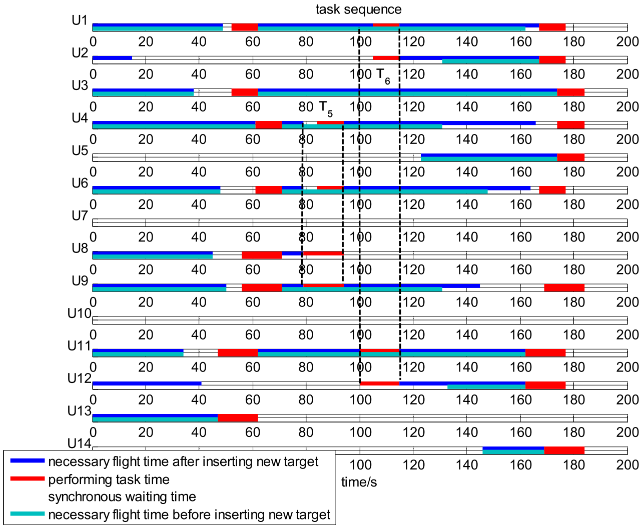

FIGURE 7. The comparison of task sequences of UAV swarm before and after inserting targets.

TABLE 8. The Bidding Information of Each UAV.

U_j	Target Reward	Task Idle Period	Remained Resource
U_4	47.10	(74, 106)	(3, 1, 0)
U_6	52.14	(74, 85)	(0, 0, 1)
U_8	47.51	(74, +)	(2, 0, 3)
U_9	49.64	(74, 106)	(2, 1, 0)
U_{12}	28.35	(85, 96)	(0, 0, 2)

For comparative analysis, Figure 7 places the task sequence of each UAV for new targets under the same timeline. On the timeline of each UAV, the lower layer shows the task sequence before finding new targets, which is consistent with Figure 5; the upper layer shows the task sequence updated after finding new targets. Figure 7 shows the time and task squad members on target T_5 and target T_6.

TABLE 9. The Initial State of Targets.

T_j	Initial Position	Requirement for Attack Resources	Requirement for Interfering Resources
T_7	(7531, 3924)	(2, 1, 1)	(1, 1, 2)

After the UAV swarm finds new targets, each UAV immediately checks the local task sequence and the resource vector, and obtains the synchronization waiting time available locally under current task assignment plan. If the idle time and resources meet the target requirements, the UAV bids for the new target, and determines the time period for corresponding task, and assigns its resources, and then calculates the task rewards, and then broadcasts this information to other UAVs. After receiving the bids from other UAVs, each UAV does conflict resolution as described in Section 2.3, and updates the tasks and resource assignment results. This process does not require the central node for cooperative control, and each UAV is completely autonomous, and the swarm completes distributed tasks and resource assignment.

Let's take target T_5 as an example to illustrate the process. When U_8 detects target T_5 and obtains its status information, each UAV checks the local task sequence and the resource vector. U_4, U_6, U_8, U_9 and U_{12} find themselves can use the original synchronization waiting time to bid tasks of target T_5. These UAVs independently calculate its own task reward for the target, the task idle period under the current task sequence, and the remaining task resources. The detailed bidding information for each UAV is shown in Table 8.

After the consensus process, U_{12} is kicked out of the task squad due to the lowest reward, the smallest resources contribution, and the remaining UAVs can meet the target resource requirements.

According to the task sequences, it can be found that U_4 and U_6 could firstly perform the task on target T_5 by using the 40s synchronization waiting time before the task is performed on target T_1. This does not affect subsequent tasks on target T_1.

C. DYNAMIC ASSIGNMENT AFTER TARGETS LOST

In a dynamic environment, some targets may be lost due to strategic transfer. When a target is lost, the UAV swarm must quickly adjust the task sequence of all the UAVs.

As the previous experiments, the UAV swarm performs tasks according to the initial task assignment scheme shown in Figures 4 and 5. Target T_2 will disappear before UAVs arriving at its position. And target T_7 will be found as a new target. The initial state of the prior unknown target T_7 is shown in Table 9.

When U_{11} reached the target T_2 position (37s) and found that target T_2 was lost, the UAV swarm immediately adjusted the task sequence. After target T_2 is moved out of the task sequence, the idle period of U_1, U_3, U_{11} and U_{13} also increase accordingly. After the idle period of this four UAVs has increased, it is possible to make a second bid for other targets. These four UAVs calculate bidding information for target T_1 and T_4, Details are shown in Table 10.

As can be seen from Table 10, the necessary flight time of U_1 and U_{11} is too long for target T_1 or target T_4, and there is no feasible idle period to insert a new task before the start of the next task. U_3 cannot perform the task on target T_4 due to start time of next task, and it has highest reward for target T_1. Due to the low task reward, U_{13} will fail to bid the task on target T_1,

U_1 and U_{11} are waited by U_2 and U_{12} when performing tasks on target T_3. After target T_2 disappear, U_1 and U_{11} will arrive at the target T_3 in advance, so task squad of target T_3 will also start task in advance accordingly.

When U_1 flies toward target T_3, target T_7 is found at 58s. The remaining weapon resources of U_1 are (0, 0, 3), which cannot meet the requirements of target T_7. Other UAVs have to be assigned the new target.

After calculation, U_2, U_3, U_8, U_{11} and U_{12} can use the original synchronization waiting time to perform the task on the new target. The task reward, the task idle period and the assignment of weapon resources are independently calculated by attack UAVs U_2 and U_3, as shown in Table 11.

Table 12 shows the task reward, the task idle period and the interference payload assignments of U_8, U_{11} and U_{12}.

As can be seen from Table 12, although U_8 has more resources available, the task reward is the smallest. Due to it is farther away from the new target, the start time of task idle period is later. As can be seen from Table 11, the task idle period of U_3 ends at 115s, so if U_8 is selected, the task squad does not have enough time (10s) to interfere and attack the new target cooperatively. As a result, U_8 was removed from task squad, and U_{11} and U_{12} became the ultimate winning bidder.

TABLE 10. The Bidding Information for Potential Targets of Four UAVs.

U_i	Start Time of Next Task/s	Remained Resource	Reward for T1	Time Flying To T1/s	Reward for T4	Time Flying To T4/s
U_1	163	(0, 0, 3)	13.20	261	26.51	172
U_3	168	(3, 0, 1)	51.26	91	33.48	148
U_{11}	163	(2, 2, 0)	12.65	284	25.48	189
U_{13}	NONE	(4, 0, 2)	25.21	105	30.48	96

TABLE 11. The Bidding Information of Candidate Attack UAVs.

U_j	Target Reward	Task Idle Period	Available Resource
U_2	40.24	(89, +)	(1, 1, 0)
U_3	47.84	(85, 115)	(3, 0, 1)

TABLE 12. The Bidding Information of Candidate Electronic Interference UAVs.

U_j	Target Reward	Task Idle Period	Available Resource
U_8	35.41	(112, +)	(2, 0, 3)
U_{11}	54.17	(81, +)	(2, 2, 0)
U_{12}	43.48	(101, +)	(0, 0, 2)

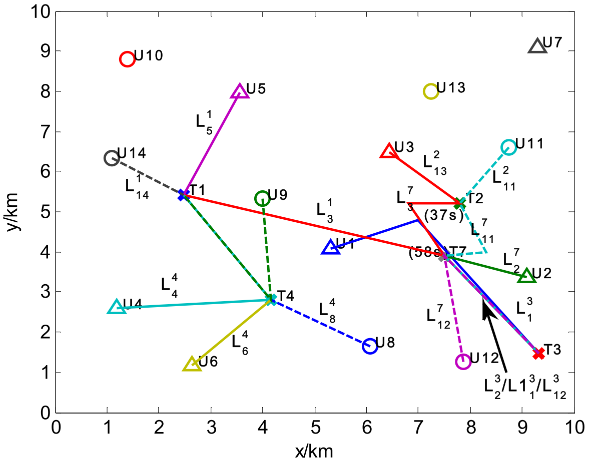

FIGURE 8. The approximate trajectory of UAV swarm after targets lost.

Finally, the task squad of the new target is $|U_2, U_3, U_{11}, U_{12}|$ and the task time duration is 96s–111s. The approximate trajectory of the UAVs is shown in Fig. 8, where L_i^j represents the trajectory route of the U_i to the T_j. For comparative analysis, Figure 9 places the task sequence of each UAV.

It can be seen from these simulation experiments that the proposed algorithm can achieve the coordinated assignment of tasks and resources. When a new target is found by a UAV swarm in a dynamic environment, the algorithm can quickly acquire the available time of the UAV using the task sequence mechanism. Since the algorithm does not affect the original task and resource assignment scheme when inserting a new target, there is no need to completely redistribute all unexecuted tasks (including known targets), so real-time performance is guaranteed.

D. ADVANTAGES ANALYSIS

Comparing with the baseline CBBA, the proposed algorithm can make full use of the UAV's available task time and task resources due to task sequence mechanism. When a new target is found, the UAV swarm can reassign the tasks in real time, and insert the new tasks into the appropriate task idle segments without reassigning the established task allocation results. This mechanism enables the algorithm to assign tasks in real time.

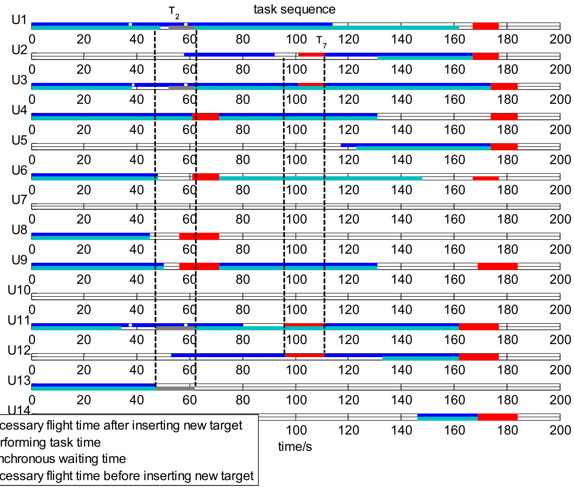

FIGURE 9. The comparison of task sequences of UAV swarm before and after targets lost.

Since there is no need to redistribute the existing allocation results, the algorithm computation time and the amount of communications are greatly reduced.

V. CONCLUSION

In this paper, based on the real-time requirements of task assignment in dynamic environment and the limited resources of each individual in UAV swarm, a task and resource dynamic assignment algorithm based on task sequence mechanism is proposed. The algorithm assigns all prior known tasks and new found tasks for UAV swarm in a distributed and real time manner, and it is very suitable for dynamic task allocation in large-scale UAV swarm. It can make full use of the available time and resources of each UAV in the swarm and improve the efficiency of UAV swarm.

The simulation results show that the proposed algorithm can effectively solve the real-time assignment of UAV swarm tasks and resources when new target is found or some target is lost in the dynamic environment.

One next research direction is the real-time assignment of tasks and resources when some UAVs are added to the swarm or destroyed in a dynamic environment. Based on the task sequence mechanism, under the premise of not changing the original order and time of the task, the task team is dynamically adjusted according to the bid information of the newly added UAV or surviving UAV to improve the reward of the task and resource utilization. The other research direction is the real-time assignment of tasks and resources with limited communication conditions among UAV swarm.

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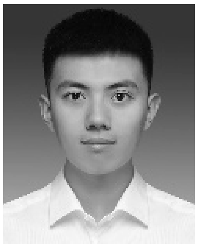

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