Coalition Formation for Multiple UAVs Cooperative Search and Attack with Communication Constraints in Unknown Environment

Liu Zhong, *Gao Xiaoguang* *, *Fu Xiaowei*

School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710129, P. R. China

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Abstract: A coalition formation algorithm is presented with limited communication ranges and delays in unknown environment, for the performance of multiple heterogeneous unmanned aerial vehicles (UAVs) in cooperative search and attack missions. The mathematic model of coalition formation is built on basis of the minimum attacking time and the minimum coalition size with satisfying resources and simultaneous strikes requirements. A communication protocol based on maximum number of hops is developed to determine the potential coalition members in dynamic network. A multistage sub-optimal coalition formation algorithm (MSOCFA) with polynomial time is established. The performances of MSOCFA and particle swarm optimization (PSO) algorithms are compared in terms of complexity, mission performance and computational time. A complex scenario is deployed to illustrate how the coalitions are formed and validate the feasibility of the MSOCFA. The effect of communication constraints (hop delay and max-hops) on mission performance is studied. The results show that it is beneficial to determine potential coalition members in a wide and deep range over the network in the presence of less delay. However, when the delays are significant, it is more advantageous to determine coalitions from among the immediate neighbors.

Key words: multi-unmmaned aerial vehicles (UAVs); cooperative search and attack; coalition formation; communication constraints

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0 Introduction

The use of multi-unmmaned aerial vehicles (UAVs) for search and attack mission in unknown environment has received a growing attention[1-2]. To increase the mission performance, it is necessary to design algorithms that efficiently allocate tasks to UAVs[3]. We focus on the real-time task assignment problem of multi-UAVs in cooperative search and attack mission under unknown environment.

Task assignment refers to how to determine the task and timing sequences for each UAV that satisfies all the constraints and minimizes some objective functions of overall team[4-6]. In mathematic, task assignment could be modeled as a combinatorial optimization problem, such as dynamic network flow optimization[7], multiple traveling salesman problem[8], vehicle routing problem[9], mixed integer linear programming[10], multidimensional multiple choice of knapsack problem[11], contract net[12], satisfying decision theory[13], game theory[14], and intelligent optimization algorithms[15].

However, in most of the previous methods, ① The UAVs are homogeneous, and the resources of UAVs are unlimited, like in Ref. [7]; ②The task allocation algorithms have high computation cost, like in Refs. [8,10-11,15], while in real-time applications, the low computational

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* Corresponding author, E-mail address: 15829732829@163.com.

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complexity methods are more appropriate; ③The number, the location and the resources of targets are known a priori, but the UAVs only have limited or even non-existent priori information about the targets in unknown environment; ④The existing task allocation schemes are designed on perfect communication network, like in Refs. [12-14]. Therefore, the previous algorithms cannot be applied directly to the problem which is considered in this paper.

In multiple agents system (MAS), if an agent cannot complete tasks alone, a sub-group of agents will form a coalition to cooperatively complete the tasks. The coalitions are temporary. Once the task is accomplished, the coalition members can perform other tasks[16]. Forming a coalition to complete task allocation has been applied to both MAS[16] and multiple robots system (MRS)[17]. However, the resources cannot be transferred between UAVs, so the algorithms in MAS can not be applied to multiple UAVs system directly. Since UAVs can not stop in the air and move fast, the algorithms in MRS, which have high computation cost, also cannot be applied directly to multi-UAVs system.

The coalition formation algorithms of multi-UAVs system have been investigated[18-19]. Based on particle swarm optimization algorithm, Sujit[18] presented a task allocation algorithm that formed coalitions which included some UAVs to attack each target. However, the target locations were known a priori, so this method could not be used in unknown environment. To develop the coalition formation algorithms for the UAVs in unknown environment, Manathara[19] presented a two-stage algorithm that determines optimal coalitions.

Due to limited communication ranges and delays, the communication between UAVs is restricted. Team coordination requires UAVs to exchange their state information, observations of the world, and control decisions such as task allocation or motion planning; hence inadequate communications can significantly degrade team performance. Thus, coalition formation in dynamic network is very challenging. Sun[20] studied the network distributing cooperation observation and tracking of heterogeneous multi-UAV based on local communication and limited detection range, but he ignored the communication delay. In Ref. [21], an efficient task allocation scheme using negotiation between multi-UAVs was demonstrated, but the UAVs only had limited communication ranges. Thus, neither the realistic communication constraints nor the flexible and efficient communication protocol have been considered thoroughly in the previous approaches. Moreover, there was no literature related to the effect of communication constraints on coalition formation.

We present a novel mechanism to determine coalitions of multiple heterogeneous UAVs performing cooperative search and attack missions in unknown environment. The realistic constrains on UAVs are taken into account, such as limited sensing, limited communication ranges, communication delays, and limited consumable resources.

1 Problem Formulation

A search and attack mission using N heterogeneous UAVs is considered as shown in Fig. 1. The UAVs can carry n types of resources in limited numbers, so they are heterogeneous. These resources are consumable, that is, the resources deplete with use. The UAVs are identified by their unique identity numbers $A_i (i=1,2,\cdots,N)$. The unique identity numbers are assigned prior. The resources represented capability vector $\boldsymbol{R}_i^A$ of A_i is

$$\boldsymbol{R}_i^A = (R_{i1}^A, \cdots, R_{in}^A) \tag{1}$$

where R_{ip}^A $(p=1,\cdots,n)$ denotes the quantity of type-p resources of A_i.

There are M targets in the mission region. The resource requirements and locations of the targets are unknown a priori. The UAVs must

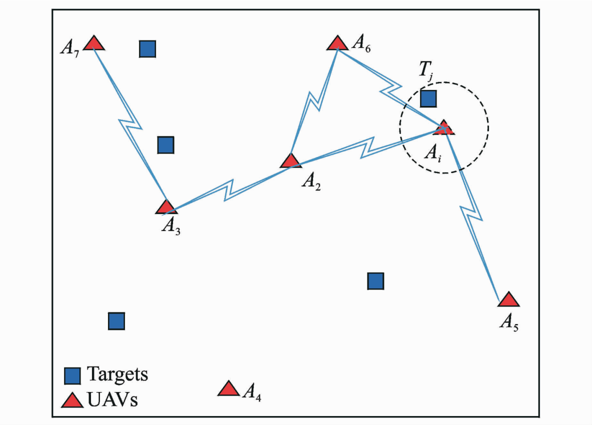

Fig. 1 Cooperative search and attack mission scenario

perform the search task to detect the targets. The sensor range of A_i is limited and denoted by r_s^i. When T_j is detected by A_i, the resources requirement of attacking T_j can be obtained and represented by the target resource requirement vector $\boldsymbol{R}_j^T$

$$\boldsymbol{R}_j^T = (R_{j1}^T, \cdots, R_{jm}^T) \tag{2}$$

where $R_{jq}^T (q=1,\cdots,m \text{ and } m \leqslant n)$ represents the quantity of type-q resources required to attack T_j.

A_i can directly communicate with other UAVs that in communication range r_c^i, while other UAVs who are outside the range can communicate indirectly through a sequence of communication links. It is assumed that $r_c^i > 2r_s^i$. This assumption ensures that multiple UAVs within the communication ranges of each other do not form multiple coalitions for the same target when they detect the same target.

The process of a coalition formation is described as follows. If a target T_j is detected by the UAV A_i, but A_i has insufficient resources to attack T_j, A_i becomes coalition leader (CL) and broadcasts resource requirement vector $\boldsymbol{R}_j^T$ and location of T_j to other UAVs. This process is called Request.

The UAVs, which directly or indirectly communicate with A_i, that having at least one type of the required resources to attack T_j will respond to A_i with their earliest time to arrive (ETA) at the target location and the resources represented capability vectors. The responding UAVs are called potential coalition members (PCMs). This process is called Bid.

The CL A_i receives the bids from PCMs and determines a coalition. The UAVs which form the final coalition are called coalition members (CMs). This process is called Formation.

The coalition should satisfy certain constraints: ① Attacking the target in minimum time, which ensures the total mission completion time is reduded; ② The final coalition formed must be minimum size, which allows more UAVs and resources to remain available for the early and quick detection of other potential targets, thus the total mission complete time can be redued; ③ To maximize damage of targets, the targets should be attacking simultaneously; ④ Satisfying resources requirement to ensure target could be destroyed.

A_i, a UAV, after detecting a target T_j, with the condition $\boldsymbol{R}_j^T > \boldsymbol{R}_i^A$, becomes a CL and determines the coalition $\boldsymbol{C}_j^i$ on the basis of above defined constraints. The total resources of coalition $\boldsymbol{C}_j^i$ is defined as the sum of resource capabilities of the coalition members

$$\boldsymbol{R}_j^{C^i} = \sum\nolimits_{A_k \in C_j^i} \boldsymbol{R}_k^A \tag{3}$$

Let Λ denotes the set of the CL and the PCMs that responded to the request of CL. λ_k denotes the ETA of UAV $A_k \in \Lambda$ at location of T_j. The coalition formation model can be represented mathematically as

$$\text{Objective: } \min\nolimits_{\hat{\Lambda}} \max\nolimits_{k:A_k \in \hat{\Lambda}} \lambda_k \tag{4}$$

$$\text{s.t.} \quad \sum\nolimits_{k:A_k \in \hat{\Lambda}} R_{kp}^A \geqslant R_{jp}^T \quad p=1,\cdots,n \tag{5}$$

where $\hat{\Lambda} \subseteq \Lambda$. The UAVs must arrive at the target at the same time. It means that the earliest attacking time of the coalition is the latest arrival time. A smallest size coalition with minimum attacking time is determined by Eq. (4). The constraint ④ is described by Eq. (5).

2 Discovery of Potential Coalition Members over Dynamic Network

CL selects a feasible coalition from PCMs and broadcasts their acceptance or rejection decisions. Thus, to form a feasible coalition, a key requirement is determining PCMs. It cannot ensure that every UAV can receive messages from CL due to limited communication ranges. Thus，a mechanism to find PCMs over a dynamic network is designed. The UAVs outside the communication range can communicate with others indirectly through a sequence of communication links. The UAVs can retransmit messages from one to another. These intermediate UAVs are called relay，and the communication protocol between UAVs is called "flooding". However，this communication protocol can not guarantee the successful delivery of the broadcast packets due to the lack of any collision detection. The notion of time-to-live (TTL) is used to avoid the messages floating in the network indefinitely. The TTL is the maximum number of hops ($H_{\max}$) that a message can be transmitted before it is abandon. The message has its own current hop counter，H_j^i，which is initially set to $H_{\max}$. As shown in Fig 2，if a UAV rebroadcasts this message，H_j^i is changed to H_j^i-1. The message is abandon until $H_j^i=0$.

Since $H_{\max}$ is the maximum allowed hops and each hop delay is δ，the coalition proposal，the response to this proposal，and the result message of coalition formation together will take at most $\zeta_j^i=3\delta H_{\max}+\Delta\omega+\Delta c$ seconds to propagate over the network，where $\Delta\omega$ is a given time window that allowing PCMs to respond to the request of CL，Δc a given time window that allowing CL to form a coalition.

The CL A_i broadcasts the following request

$$\boldsymbol{P}_j^i=\langle A_i,T_j,\boldsymbol{Z}_j^T,\boldsymbol{R}_j^T,H_j^i,H_{\max},\zeta_j^i,t\rangle \tag{6}$$

where $\boldsymbol{Z}_j^T=[x_j^T,\ y_j^T]$ is the location of the target T_j，$\boldsymbol{R}_j^T$ the resources requirement vector to attack target T_j，and H_j^i the current hop counter. The upper bound on the whole time of forming a coalition is ζ_j^i. At time t，T_j is detected.

Each UAV A_k in the network can be a relay or a PCM or both. Once A_k receives the request massage，it will check whether $H_j^i>0$ or not. If $H_j^i>0$，A_k will play the relay role to broadcast the request to the neighbors. If $H_j^i=0$，A_k will abandon this message. If A_k does not belong to any other coalitions and has any resource required to attack the target，A_k sends following biding message to A_i

$$\boldsymbol{Q}_k^i=\langle A_k,A_i,T_j,\boldsymbol{R}_k^A,\lambda_k\rangle \tag{7}$$

where the resources vector of A_k is $\boldsymbol{R}_k^A$，and λ_k is the ETA from the go-ahead location $\boldsymbol{G}_k^j$ to target. Using ζ_j^i and current position，A_k can estimate its go-ahead location where starts the attacking maneuver. If A_k receives the request for coalition formation at time τ，its go-ahead location $\boldsymbol{G}_k^j$ is

$$\boldsymbol{G}_k^j=[x_k^\tau+(t+\zeta_j^i-\tau)v_k\cos\varphi_k^\tau,\ y_k^\tau+(t+\zeta_j^i-\tau)v_k\sin\varphi_k^\tau] \tag{8}$$

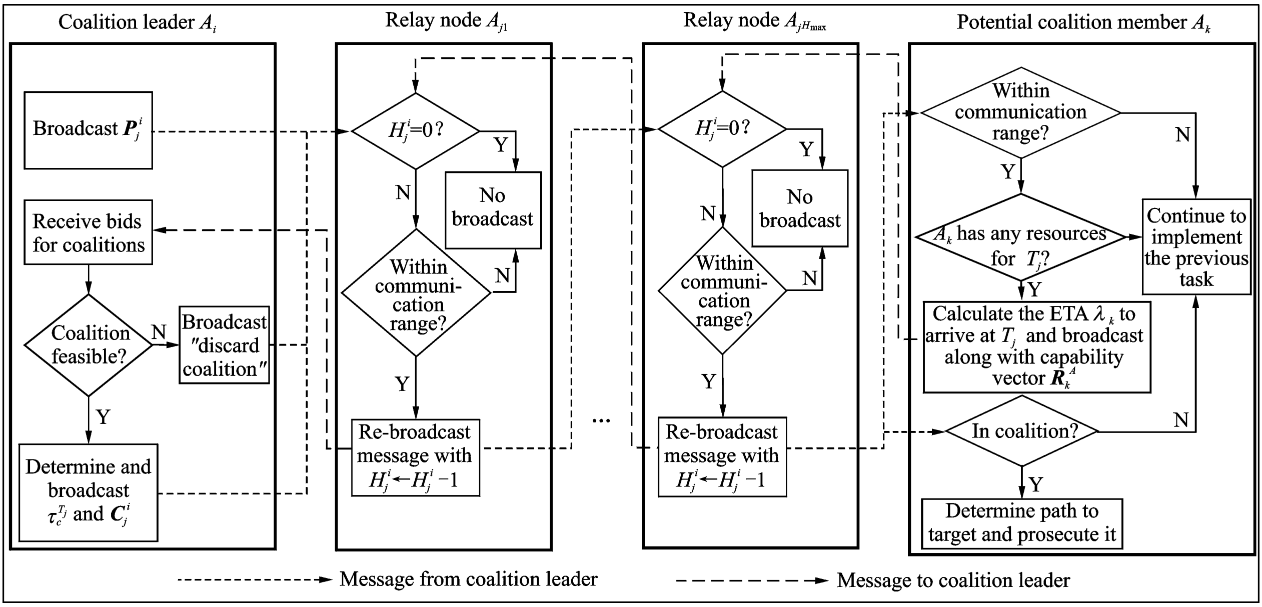

Fig. 2 Communication protocol for coalition formation

where $[x_k^\tau, y_k^\tau]$ is the location of A_k, φ_k^τ the heading angle, and v_k the ground speed.

3 Coalition Formation

The problem of determining an optimal coalition is combinatorial in nature (which is NP-hard), therefore the solutions are computationally intensive and complex. Therefore, coalition formation algorithms with less computational burden and complexity are required. For this, a multistage sub-optimal coalition formation algorithm (MSOCFA) that has sub-optimal and real time in nature is presented.

3.1 Multistage sub-optimal coalition formation algorithm

MSOCFA determines the smallest size and minimum time coalition that can destroy the target in two stages. Algorithm 1 determines a set of UAVs with required total resources that can achieve the minimum attacking time requirement in the first stage. In the second stage, the obtained set of UAVs is pruned to achieve the minimum size requirement in Algorithm 2.

In the beginning of Algorithm 1, the coalition is set to empty, and the coalition resources are set to zero (line 1). Firstly, the responses of the PCMs are sorted in the ascending order of their ETA to target (line 3). The algorithm takes one UAV (A_q) at a time (line 5) from the order list $\boldsymbol{\Lambda}_{\text{sort}}$, appends A_q to the coalition $\boldsymbol{C}_j^i$ (line 6), and updates the coalition resource vector (line 7) and the coalition time (line 8). Then it checks whether the required resource constraint is satisfied or not (line 9). If the constraint is unsatisfied, the next UAV is included and the resource constraint is checked one by one until the required resource is sufficient. If the total resources of all UAVs in the order list $\boldsymbol{\Lambda}_{\text{sort}}$ are insufficient, no feasible coalitions can be formed (line 18). Once the required resource is sufficient, Algorithm 1 returns the feasible coalition $\boldsymbol{C}_j^i$ and the coalition time (line 16). Ref. [22] has proved that Algorithm 1 will always return a coalition with minimum attacking time.

Algorithm 1 First stage of MSOCFA

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Input: Potential coalition members $\boldsymbol{\Lambda}=[A_1, A_2, \cdots, A_{N'}]$ and their ETAs $\boldsymbol{D}=[\lambda_1, \lambda_2, \cdots, \lambda_{N'}]$
Output: Coalition $\boldsymbol{C}_j^i$ and coalition time $\boldsymbol{\tau}_c^{T_j}$
1 $\boldsymbol{C}_j^i=\varnothing$ and $\boldsymbol{R}_j^{C^i}=0$
2 Stage 1:
3 $[\boldsymbol{D}_{\text{sort}}, \boldsymbol{\Lambda}_{\text{sort}}]$ = Sort($\boldsymbol{\Lambda}$, $\boldsymbol{D}$); % $\boldsymbol{D}_{\text{sort}}\leftarrow$sorted $\boldsymbol{D}$ in ascending order, $\boldsymbol{\Lambda}_{\text{sort}}\leftarrow$ corresponding UAV index of $\boldsymbol{D}_{\text{sort}}$
4 for $k=1$ to $|\boldsymbol{\Lambda}_{\text{sort}}|$ do
5     $A_q\leftarrow\boldsymbol{\Lambda}_{\text{sort}}(k)$
6     $\boldsymbol{C}_j^i\leftarrow$append $A_q$
7     $\boldsymbol{R}_j^{C^i}\leftarrow\boldsymbol{R}_j^{C^i}+\boldsymbol{R}_q^A$
8     $\boldsymbol{\tau}_c^{T_j}\leftarrow\boldsymbol{D}_{\text{sort}}(k)$
9     if $R_{jp}^{C^i}\geqslant R_{jp}^T$, for all $p$ then
10        break
11    else
12        continue
13    end if
14 end for
15 if $R_{jp}^{C^i}\geqslant R_{jp}^T$, for all $p$ then
16    return $\boldsymbol{C}_j^i$ and $\boldsymbol{\tau}_c^{T_j}$
17 else
18    return No feasible coalitions
19 end if
```

Algorithm 2 Second stage of MSOCFAInput: Minimum time coalition $\boldsymbol{C}_j^i$ from Algorithm 1

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Output: Pruned coalition $\boldsymbol{C}_j^i$
Stage 2:
for $k=1$ to $|\boldsymbol{C}_j^i|$ do
    $A_q\leftarrow\boldsymbol{C}_j^i(k)$
    $\hat{\boldsymbol{R}}_j^{C^i}=\boldsymbol{R}_j^{C^i}-\boldsymbol{R}_q^A$
    if $\hat{R}_{jp}^{C^i}\geqslant R_{jp}^T$, for all $p$ then
    $\boldsymbol{C}_j^i\leftarrow$remove $A_q$ from $\boldsymbol{C}_j^i$
    $\boldsymbol{R}_j^{C^i}=\hat{\boldsymbol{R}}_j^{C^i}$
    end if
end for
return $\boldsymbol{C}_j^i$
```

After the coalition that can achieve the minimum attacking time requirement is determined by Algorithm 1, those UAVs in the minimum time coalition who are not necessarily required must be pruned in order to form a smaller size coalition. The smaller size coalition is achieved by using Algorithm 2. By removing resources of A_q from $\boldsymbol{R}_j^{C^i}$, Algorithm 2 checks whether the resources of each UAV A_q in the coalition $\boldsymbol{C}_j^i$ determined in the first stage are necessarily required for the smaller size coalition or not (lines 4 and 5). If not necessarily required, A_q is removed from $\boldsymbol{C}_j^i$ (line 6) and its resources are deducted from $\boldsymbol{R}_j^{C^i}$ (line 7). This process is carried out for all UAVs in the coalition $\boldsymbol{C}_j^i$ determined in the first stage ($A_q \in \boldsymbol{C}_j^i$).

The Algorithms 1 and 2 together form MSOCFA. Ref. [22] has proved that the algorithm complexity of MSOCFA is $O(N(\log N + 2m))$.

3.2 Deadlock resolution

(1) Multiple UAVs detect the same target simultaneously

When multiple UAVs detect the same target at the same time, there can be situations causing deadlock where all the detecting UAVs want to form coalition for this target. We use a token mechanism to eliminate deadlock. Each UAV has a unique token number TN_i^A ($i=1,2,\cdots,N$). When a UAV receives multiple coalition formation requests, it will respond to the UAV who has the highest token number.

(2) A single UAV detects multiple targets simultaneously

When a single UAV detects multiple targets at the same time, there can be a deadlock where the coalition leader needs to form multiple coalitions for multiple targets at the same time. In order to eliminate deadlock, the target use unique token number, TN_j^T ($j=1,2,\cdots,M$), which are assigned to them to be attacked preferentially.

(3) Multi-UAVs detect multiple targets simultaneously

When multiple UAVs detect multiple targets at the same time, we need combine TN_i^A and TN_j^T to eliminate deadlock. For example, assume that the descending order of TN_i^A is $TN_1^A > TN_2^A > TN_3^A > TN_4^A$, A_1 and A_4 detect target T_2 and T_1, respectively, and need to form coalitions. With the highest token number, A_1 will broadcast the proposal for coalition formation firstly. Thus A_2 and A_3 (A_4 has been the coalition leader already with detecting T_1) will respond to A_1 firstly and a coalition $\boldsymbol{C}_2^1 = \{A_1, A_3\}$ is formed. After A_1 determines its coalition, A_4 broadcasts a request, and then A_2 will send its response to A_4. Then, A_4 determines a coalition $\boldsymbol{C}_1^4 = \{A_2, A_4\}$ to attack target T_2.

Consider a complex scenario where A_1 detect targets T_1 and T_2 simultaneously, at this moment, A_1 also detects targets T_1 and T_2. With the highest token number, A_1 will be the CL and broadcast the proposal for coalition formation firstly. But A_1 need select which one to be attacked from T_1 and T_2. Since T_1 has higher token number than T_2, A_1 determines the coalition $\boldsymbol{C}_1^1$ to attack T_1. After A_1 determines its coalition $\boldsymbol{C}_1^1$, A_4 determines the coalition $\boldsymbol{C}_2^4$ to attack T_2.

4 Simultaneous Strikes

4.1 UAV model

In general, UAV is equipped with an autopilot that holds a constant altitude and ground speed. Assuming that each UAV is located at different unique altitudes and hence there is no need for collision avoidance. Therefore, the two-dimension motion of UAV in a horizontal plane is analyzed and the inner loop dynamic of the UAV is modeled as a first-order model[23].

$$\dot{x} = V\cos\psi, \quad \dot{y} = V\sin\psi, \quad \dot{\psi} = W_\psi(\psi^c - \psi) \tag{9}$$

where x and y give the UAV location, $\psi \in [0, 2\pi)$ is the current heading, V the ground speed, W_ψ the autopilot gain, and ψ^c the desired (commanded) heading of the UAV, which is generated by path tracking algorithm[24] in the outer guidance loop.

4.2 Path generation based on Dubins curves

Given position and heading of UAVs, there are two Dubins paths to arrive at target T: The short path (D_{short}) and the long path (D_{long}). As shown in Fig. 3, A_1 and A_2 are members of the coalition. When the short path is selected, A_1 needs to continually increase its path length until

$D^1_{\mathrm{short}} = D^2_{\mathrm{short}}$. However, it is impossible to generate a Dubins path for A_1 if the circle encircles the target. If the short path is selected, the achievable ETA is discontinuous[19]. To eliminate this discontinuity, the long Dubins curve is always used as a tracking path to target for the coalition members in this paper. When the long path is selected, A_1 can continually increase its radius until $D^1_{\mathrm{long}} = D^2_{\mathrm{long}}$.

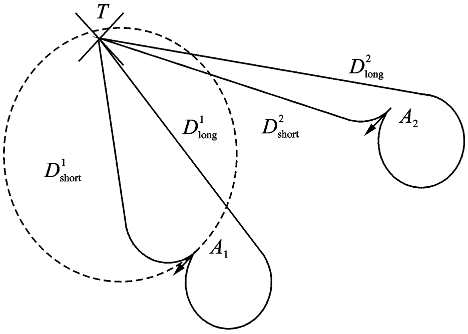

Fig. 3 Path generation based on Dubins curves

5 Simulation Results

5.1 Performance of MSOCFA in a complex scenario

A complex scenario experiment was presented to illustrate how the coalitions are formed and validate the feasibility of MSOCFA. In Scenario 1, 6 UAVs and 3 targets were distributed in a region (2 km×2 km). Tables 1, 2 list the initial settings of the UAVs and targets, respectively. The corresponding parameters of UAVs are listed in Table 3.

Table 1 The initial settings of 6 UAVs in Scenario 1

UAV A_i	Token number TN^A_i	Position (x_i, y_i)/m	Heading ψ_i/(°)	Capability vector $\boldsymbol{R}^A_i$
A_1	6	(10,10)	160	(1,2,3)
A_2	5	(150,150)	0	(2,0,1)
A_3	4	(900,700)	225	(1,3,1)
A_4	3	(800,−800)	270	(1,2,1)
A_5	2	(−900,−600)	60	(1,0,0)
A_6	1	(600,−900)	100	(1,2,3)

Table 2 The initial settings of 3 targets in Scenario 1

Target T_j	Token number TN^T_j	Position (x_j, y_j)/m	Requirement vector $\boldsymbol{R}^T_j$
T_1	3	(300,0)	(3,2,2)
T_2	2	(−500,0)	(2,1,1)
T_3	1	(0,300)	(0,0,1)

Table 3 The parameters of UAVs in Scenario 1

Parameter	Value
Ground speed V/(m · s^{-1})	50
Minimum turning radius $R_{\min}$/m	100
Communication range r_s/m	500
Maximum number of allowed hops $H_{\max}$	3
Estimated maximum possible hop delay δ/s	1
Time window $\Delta\omega$/s	0.2
Time window Δc/s	0.3

As shown in Fig. 4, at time $t=0$, A_1 detected targets T_1 and T_3 simultaneously, at this moment, A_1 also detected targets T_1 and T_3. With the highest token number, A_1 became CL and formed coalition first. Then, A_1 need determine which one to be attacked from T_1 and T_3. Since T_1 had higher token number than T_3, A_1 determined the coalition $\boldsymbol{C}^1_1$ to attack T_1 by sending the information of T_1 to the potential coalition members A_3, A_4, A_5 and A_6. The formed coalition $\boldsymbol{C}^1_1$ included A_1, A_3 and A_6, the total resources vector of $\boldsymbol{C}^1_1$ is (3, 7, 7) and the latest arrival time of $\boldsymbol{C}^1_1$ is 30.3 s. The resources requirement vector of T_1 was $\boldsymbol{R}^T_1 = (3, 2, 2)$, thus the total resources of coalition satisfied resources requirement of T_1.

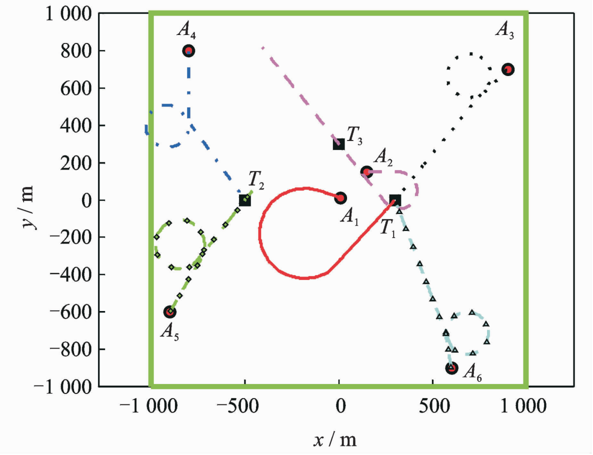

Fig. 4 Coalition formation and UAVs' trajectories (Scenario 1)

After $\boldsymbol{C}^1_1$ has been formed, A_2 performed the attack task for T_3. Its resources satisfied the condition $\boldsymbol{R}^A_2 > \boldsymbol{R}^T_3$, hence A_2 attacked T_3 without sending a coalition proposal.

At time $t = 4.7$ s, A_5 detected T_2 and broadcasts for a coalition. Only A_4 performed the search task and becomes PCM after it had received the proposal from A_5. The coalition $\boldsymbol{C}_2^5 = \{A_4, A_5\}$ was formed, the total resources vector of $\boldsymbol{C}_2^5$ was (2, 2, 1) and the latest arrival time of $\boldsymbol{C}_2^5$ is 24.6 s. The mission was accomplished at 32.9 s.

5.2 Performance of MSOCFA for pop-up targets

In order to demonstrate feasibility of MSOCFA in pop-up targets scenario, Scenario 2 was carried out. Table 4, 5 list the initial settings of the UAVs and targets, respectively. The appearance of time with target T_1 is unknown a priori and random, as shown in Fig 5.

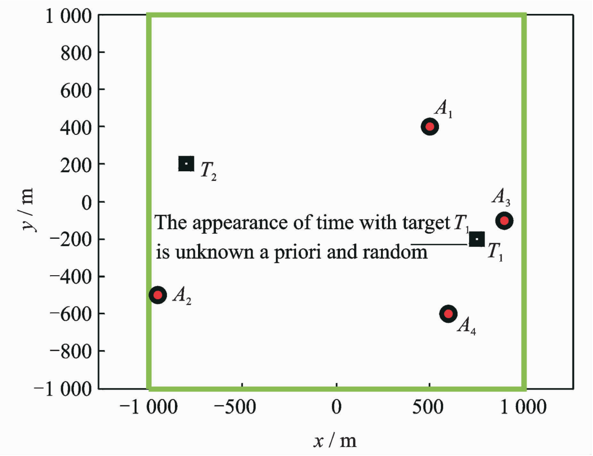

Fig. 5 Initial positions of UAVs and targets in Scenario 2

As shown in Fig 6, at $t = 21.7$ s, A_1 detected T_2. The resources requirement vector of target T_2 was $\boldsymbol{R}_2^T = (2, 2, 2)$, but the available resources of A_1 was $\boldsymbol{R}_1^A = (1, 0, 3)$, so A_1 became CL and broadcasted request message to form coalition $\boldsymbol{C}_2^1$ for T_2. The coalition $\boldsymbol{C}_2^1$ with A_1 and A_3 was formed, the total resources vector of $\boldsymbol{C}_2^1$ was (2, 2, 4) and the latest arrival time of $\boldsymbol{C}_2^1$ was 26.2 s. As T_2 was destroyed, the available resources of A_1 would deplete and became $\boldsymbol{R}_1^A = (0,0,1)$, the available resources of A_3 became $\boldsymbol{R}_3^A = (0,0,1)$. As shown in Fig. 7, at $t = 51.6$ s, T_1 appeared. As shown in Fig. 8, at $t = 51.8$ s, A_2 detected T_1. The resources requirement vector of target T_1 was $\boldsymbol{R}_1^T = (2,3,2)$, but the available resources of A_2 was $\boldsymbol{R}_2^A = (1, 1, 1)$, so A_2 became the CL and formed coalition $\boldsymbol{C}_1^2$ for T_1. The total resources vector of $\boldsymbol{C}_1^2$ was (2, 3, 2) and the latest arrival time is 43.3 s. The mission was accomplished at $t = 95.1$ s, as shown in Fig. 9.

Table 4 The initial settings of four UAVs in Scenario 2

UAV A_i	Token number TN_i^A	Position (x_i, y_i)/m	Heading $\psi_i/(°)$	Capability vector $\boldsymbol{R}_i^A$
A_1	4	(500,400)	180	(1,0,3)
A_2	3	(−950,−500)	8	(1,1,1)
A_3	2	(900,−100)	160	(1,2,1)
A_4	1	(600,−600)	190	(1,2,0)

Table 5 The initial settings of two targets in Scenario 2

Target T_j	Token number TN_j^T	Position (x_j, y_j)/m	Requirement vector $\boldsymbol{R}_j^T$
T_1	3	(300,0)	(3,2,2)
T_2	2	(−500,0)	(2,1,1)
T_3	1	(0,300)	(0,0,1)

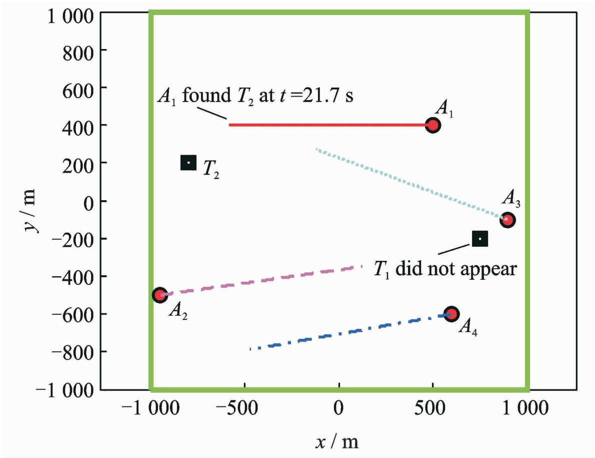

Fig. 6 Situation at $t = 21.7$ s

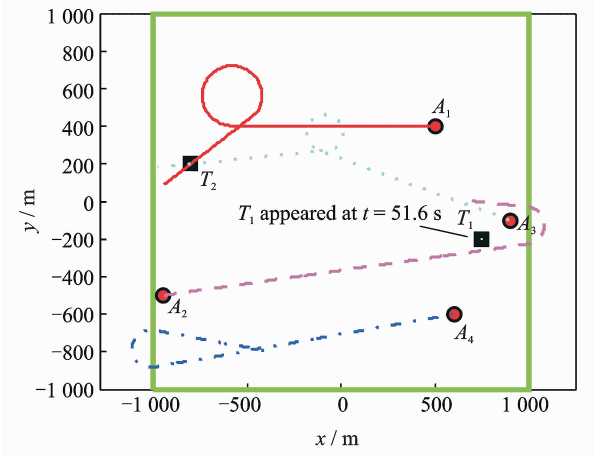

Fig. 7 Situation at $t = 51.6$ s

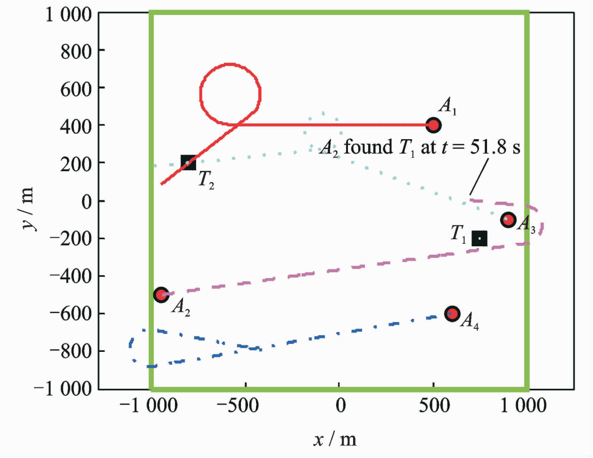

Fig. 8 Situation at $t=51.8$ s

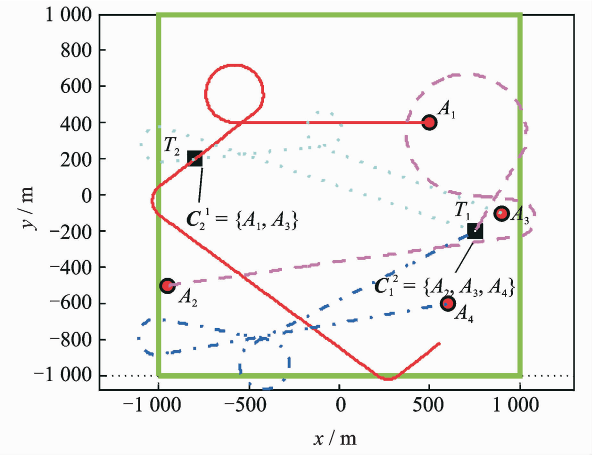

Fig. 9 Coalition formation and UAVs' trajectories (Scenario 2)

5.3 Validation of MSOCFA with low computational complexity

The combinatorial coalition formation problem can be solved by PSO algorithm when the resources requirement and locations of the all targets are known a priori[18]. To validate the MSOCFA with low computational complexity, we considered Scenario 3 with 4 UAVs and 4 targets and analyzed the effect in terms of the time taken to accomplish the mission, and the computational time taken to form the coalitions using MSOCFA and PSO algorithms in Microsoft Visual C++ 6.0 on 2.4 GHz, 2 GB RAM machine. Tables 6, 7 list the initial settings of the UAVs and targets, respectively.

Table 6 The initial settings of 4 UAVs in Scenario 3

UAV A_i	Token Number TN_i^A	Position (x_i, y_i)/m	Heading ψ_i/(°)	Capability vector $\boldsymbol{R}_i^A$
A_1	4	(400,100)	0	(2,3,4)
A_2	3	(−700,600)	0	(2,1,3)
A_3	2	(700,500)	135	(3,2,4)
A_4	1	(−500,−800)	0	(2,2,0)

Table 7 The initial settings of 4 targets in Scenario 3

Target T_j	Token Number TN_j^T	Position (x_j, y_j)/m	Requirement vector $\boldsymbol{R}_j^T$
T_1	4	(600,−100)	(1,2,2)
T_2	3	(−200,−400)	(3,2,4)
T_3	2	(−600,210)	(2,1,2)
T_4	1	(400,700)	(3,4,1)

As shown in Fig. 10, at time $t=0$, A_1 detected T_1. The available resources of A_1 was $\boldsymbol{R}_1^A=(2,3,4)$ and the resources requirement of T_1 was $\boldsymbol{R}_1^T=(1,1,2)$, hence A_1 attacked T_1 without sending a coalition proposal. At time $t=0.4$ s, A_3 detected T_4 and formed $\boldsymbol{C}_4^3$ to attack T_4 by sending the information of T_4 to the PCMs A_2 and A_4. The formed coalition $\boldsymbol{C}_4^3$ included A_3 and A_4. The total resources vector was of $\boldsymbol{C}_4^3(5,4,4)$ and the latest arrival time of $\boldsymbol{C}_4^3$ is 47.2 s. The resources requirement vector of T_4 was $\boldsymbol{R}_4^T=(3,4,1)$, which satisfied resources requirement of T_4.

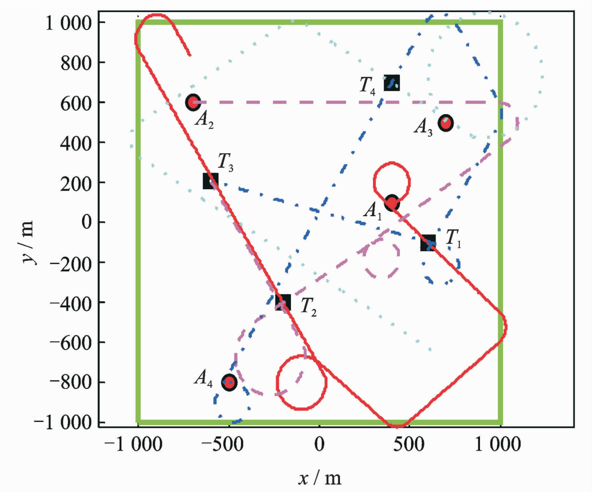

Fig. 10 Coalition formation and UAVs' trajectories achieved using MSOCFA (Scenario 3)

At time $t=57.5$ s, A_1 detected T_2 and determined the coalition $\boldsymbol{C}_2^1$ to attack T_2 by sending the information of T_2 to the PCMs A_2, A_3 and A_4. The formed coalition $\boldsymbol{C}_4^3$ included A_3 and A_4. The latest arrival time of $\boldsymbol{C}_4^3$ was 24.2 s. At time $t=85.6$ s, A_3 detected T_3 and determined the coalition $\boldsymbol{C}_3^3$ to attack T_3 by sending the information of T_3 to the PCMs A_1, A_2 and A_4. The formed coalition $\boldsymbol{C}_3^3$ included A_2 and A_4. The latest arrival time of $\boldsymbol{C}_3^3$ was 3.9 s. The total mission was accomplished in 122.4 s.

The details of the coalitions formed in the whole process using MSOCFA are listed in Table 8.

Table 8 The coalitions formed using MSOCFA

Time/s	CL	Target	Coalition	Latest arrival time/s
0	A_1	T_1	—	—
0.4	A_3	T_4	$\{A_3, A_4\}$	47.2
57.5	A_1	T_2	$\{A_1, A_2\}$	24.2
85.6	A_3	T_3	$\{A_2, A_4\}$	36.9

Fig. 11 shows the coalition formation results using PSO and the trajectories that the UAVs took to accomplish the attacking mission. A_2 attacked T_3 alone. A_3 attacked T_2 alone. A_1 firstly attacked T_1 and then attacked T_4, with A_4 together. The Dubins path length for A_4 attacking T_4 was equal to the Dubins path length for A_1 attacking T_1 plus the Dubins path length from T_1 to T_4. The mission was accomplished in 47.2 s. The details of the coalitions formed using PSO are listed in Table 9.

Table 10 summarizes the time taken to accomplish the mission and the computational time spent on forming the coalitions using MSOCFA and PSO algorithms. It can be concluded that the mission is accomplished earlier when using PSO than using MSOCFA, because locations of all targets are known a priori. The UAVs do not need to search targets, when we use PSO algorithm. However, the computational time spent on the coalition formation using MSOCFA is much lower than using PSO.

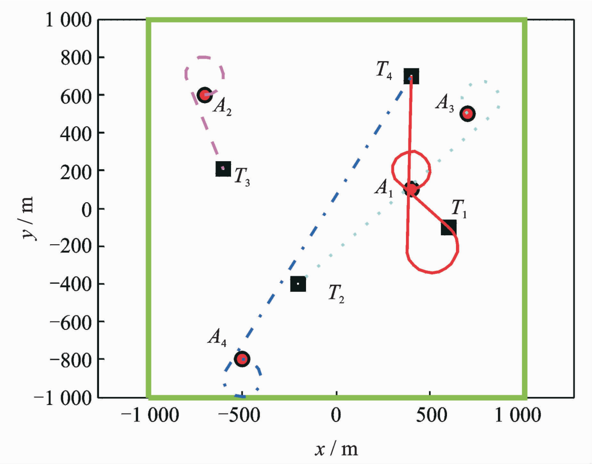

Fig. 11 Coalition formation and UAVs′ trajectories achieved using PSO (Scenario 3)

Table 9 The coalitions formed using PSO

Target	Coalition	Latest arrival time/s
T_1	$\{A_1\}$	18.1
T_2	$\{A_3\}$	37.0
T_3	$\{A_2\}$	20.3
T_4	$\{A_1, A_4\}$	47.2

Table 10 Comparison of MSOCFA and PSO (Scenario 3)

Time	MSOCFA	PSO
Taken to accomplish the mission/s	122.4	47.2
Spent on the coalition formation/s	0.064	17.3

5.4 Effect of hop delay and max-hops

The Monte-Carlo experiments were used to study the effect of max-hops ($H_{\max}$) and hop delay (δ) on mission performance. The metric of comparison was the average mission completion time. Fig. 12 shows the variation of average mission completion time (averaged over 100 runs) taken by 10 UAVs and 5 targets in 2 km×2 km area with combined effect of $H_{\max}$ and δ. In these simulations, δ were 1 s, 2 s and 3 s, while $H_{\max}$ were 1, 2 and 3.

(1) The effect of varied $H_{\max}$ for a given δ on mission performance

When $\delta=1$ s, with the increase in $H_{\max}$, the mission time will decrease. This is because as the network depth is more, the CL can get more PCMs, and hence the CL will be able to make more reasonable coalitions to attack the target more quickly. However, when the delays are significant (for example, $\delta=2$ or 3 s), further increasing $H_{\max}$ will result in a slight degradation of performance. The reason is that if the values of delay are large, the cumulative delays of reaching $H_{\max}$ depth in the network are significant, leading to further increases in the ETA and effect on the performance.

(2) The effect of varied δ for a given $H_{\max}$ on mission performance

With the increase in communication delay, the mission completion time will increase.

It can be concluded that if the delay is low, finding PCMs over a wide and deep range in the network is beneficial. However, it is advantageous to determine coalitions among the immediate neighbors in the presence of significant delays.

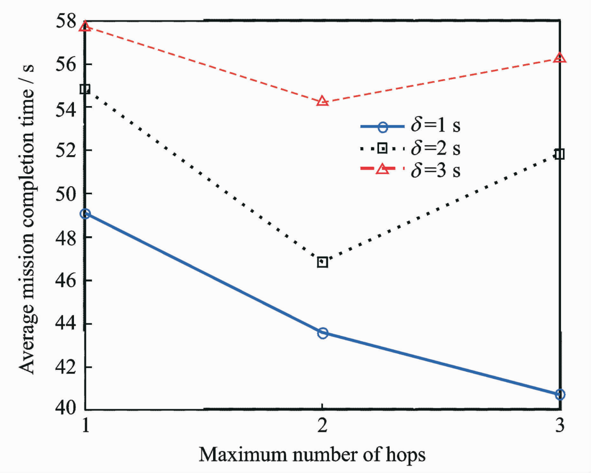

Fig. 12 Effect of increase in each δ and $H_{\max}$ on mission performance

6 Conclusions

In this paper, a coalition formation algorithm (called MSOCFA) for multiple heterogeneous UAVs performing search and attack mission in unknown environment is presented. Some conclusions can be obtained as follows:

(1) The performance of MSOCFA and PSO are compared in terms of the mission completion time and the computational time. The mission is accomplished earlier using PSO than using MSOCFA because locations of all targets are known a priori. However, the computational time taken to form the coalitions using MSOCFA is much lower than using PSO.

(2) The effect of max-hops and hop delay on the average mission completion time is studied. It can be concluded that if the delay is low, finding PCMs over a wide and deep range in the network is beneficial. However, it is advantageous to determine coalitions among the immediate neighbors in the presence of significant delays.

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Mr. **Liu Zhong** is a Ph. D. candidate in College of Electronics and Information at Northwestern Polytechnical University. His area of research is unmanned systems cooperative control and optimization.

Prof. **Gao Xiaoguang** is Ph. D. advisor in College of Electronics and Information at Northwestern Polytechnical University. Her area of research is aerial systems engineering and effectiveness evaluation.

Dr. **Fu Xiaowei** is an associate professor and master tutor in College of Electronics and Information at Northwestern Polytechnical University. His area of research is unmanned systems cooperative control and optimization.

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