An Algorithm for Coalition Formation of Swarm Aerial Vehicles Considering Communication Constraints

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Abstract. To realize efficient coalition formation of swarm aerial vehicles to attack static and dynamic targets on future battlefields, this study proposes a real-time dynamic network model that takes into consideration constraints in communication range and communication delay. Moreover, by using the improved particle swarm optimization algorithm for decision-making of coalition formation, the SAV resources are made best use of and the size of the coalition is minimized. The simulation result shows that in a dynamic network on the battlefield, the proposed model can realize communication and form coalitions, and the optimized algorithm shows higher efficiency than other algorithms in finding solutions. Monte-Carlo simulation result shows that when the communication delay is small, expanding the communication network to find potential coalition members can effectively reduce the time for task completion and improve the system’s overall performance, but when the communication delay is large, it is better to select coalition members from neighboring SAVs.

1. Introduction
Swarm aerial vehicles (SAVs) have been widely used to perform multi-target searching, surveillance and attacks on the battlefield because they are intelligent, flexible and can reduce casualties. As the battlefield becomes more complex and networked, it is difficult to fulfill a series of tasks using single SAVs. Coordinated operations of SAVs can give full play to their advantages, improve the operational efficiency, and accomplish missions that single SAVs cannot fulfill, such as strategic camouflage, coordinated attacks and electromagnetic interference [1-4]. Communication problems, however, are bound to occur in coordinated operations of SAVs. These problems are major challenges in coordinated operations of SAVs and also a hot research topic in recent years. Only when the communication between SAVs are ensured can a coalition be formed in military operations and give full play to the advantages of coordinated operations of SAVs on the battlefield. Most current methods of coordinated operations of SAVs, including centralized [5-8] and distributed [9-13] methods, are based on thorough communication between vehicle-mounted data chains and on the assumption that the control center or each operations unit has obtained all information about both parties involved in the war, which underestimates the actual communication constraints on the battlefield [14-16]. In actual military operations, limited by the communication distance, members...
involved a war cannot acquire all information of the battlefield. Moreover, because both the SAVs and targets are moving objects, the communication network is usually very unstable on the battlefield. Nevertheless, few studies considered the fact that the agents and targets are both dynamic. They assumed that all agents and targets were static while the communication would not be interrupted.

In actual military operations, SAVs fly at a high speed and hence the communication network among the member SAVs in a swarm is highly dynamic. Thus, by taking into account the influence of communication constraints, we built a multi-node dynamic network model for modern aerial combat based on the concept of “time to live” (TTL) to identify the potential coalition members in a dynamic network, and realized coalition formation using the improved PSO algorithm with the goal of minimizing the resource cost and the size of the coalition.

2. Problem Description
we assume that there are $M$ unknown targets in a bounded area $\partial$, and the targets are dynamic. Each target is associated with at least one task, and the tasks may be different as the target’s location and the required resources differ. Therefore, to form coalitions that have different types and different numbers of heterogeneous SAVs flying at different speeds will realize coordinated operations and allow each coalition to complete all tasks the detected target is associated with.

We assume that a SAV is mounted with devices for search and communication, and the range of communication $rc$ is at least two times larger than the range of search $rs$ ($rc \leq 2rs$). By using the method proposed by Mengyuan Z, et al. [17], when a SAV is in the same grid as a target, it is considered that the SAV has found the target, and can obtain all information about resources required to destroy this target. When a SAV finds a target, it will first judge whether it can destroy this target alone with the resources it carries; if it cannot destroy the target alone, it will send out a request for coalition formation, and other SAVs within its range of communication will compare the resources required to destroy the target with the resources they carry, and respond to the request if they have any of the resources required to complete the task of destroying the target. The SAV that finds the target will then make a decision for coalition formation and send out notifications to the coalition members that have responded. SAVs that receive the notification will cooperate to destroy the target, and other SAVs will continue searching in the area until all targets are found and destroyed.

3. Research Problem Modelling

3.1. Definition of element attributes
By using the geometric method, we rasterized the bounded task area $\partial$ for coordinated operations of SAVs to overcome the intrinsic problem of lack of air routes in unknown airspace. Through rasterization, the bounded area $\partial$ was divided into $\partial x \times \partial y$ grids. Each SAV ($N$) in the swarm is numbered $Vi (i = 1, 2, 3, \ldots, N)$. Each target ($M$) is associated with task $Tj (j = 1, 2, 3 \ldots, M)$. Each SAV carries multiple types of resources, and different SAVs may achieve different results when assigned to a same task. $Vi$ has $n$ types of task resources (the resources will be consumed as $Vi$ performs tasks), and the resource vector is represented as $R_i^v = (R_i^r_1, R_i^r_2, \ldots, R_i^r_n)$. The resource information means the type and number of resources required to destroy the target, which is represented by the resource demand vector $R_j^v = (R_j^r_1, R_j^r_2, \ldots, R_j^r_m)$.

3.2. Coalition Formation Modelling
When building the coalition formation model, the goal of optimization is to make the fullest of the available resources and minimize the size of the coalition. It is better to minimize the size of the coalition because more SAVs can keep searching targets and thus cut the time to detect all targets and complete all related tasks. To destroy the targets, it is necessary to ensure all resources in the coalition are enough to complete the task and are made the best use of.
When the SAV $V_i$ detects a target $T_j$, the coalition formed at last is marked as $C'_i$. $\Phi$ represents a coalition consisting of coalition members $V_k$ and a coalition leader $V_i$, and $\varphi$ is the number of all members in the coalition. Therefore, the coalition formation is described as:

$$\text{min}\text{.Remaine} = \sum_{i=0} R^i_j - R^j_i$$

(1)

$$\text{min} \varphi$$

(2)

$$st: \sum_{i=0} R^i_p \geq R^j_p, p = 1, 2, \ldots, n$$

(3)

4. Network Model for Identification of Potential Coalition Members

4.1 Dynamic Network Model

![Diagram of coalition formation decision-making process and communication protocol in bounded communication area](image)

The constantly moving SAVs and the limited range of communication generates a time-varying dynamic network among SAVs, and formation of a coalition in this network depends much on a communication protocol. The SAV that finds the target is the coalition leader (CL), SAVs that receive the leader’s request for coalition formation are potential coalition members (PCMs), and the PCMs decides whether to become a coalition member (CM) for the task through negotiation with the CL.

It is necessary to find a solution to ensure stable communication and avoid such problems. In a network of SAVs, SAVs deliver messages through relay nodes. As shown in Figure 2 (b), when the member $V_7$ receives information about the target $T_j$ that $V_i$ detects, the information transmission route is $V_2 \rightarrow V_3 \rightarrow V_5$, and in this case, $V_2$ and $V_3$ are relay nodes of $V_i$. This type of communication among wireless nodes is called flooding. To avoid infinite circulation of information in the network and cut unnecessary bandwidth, the concept of “time to live” (TTL) is adopted. TTL originally refers to the maximum hops of a data packet in a computer or a network. The maximum hops $H_{max}$ is used to define TTL to represent the maximum hops of message of communication in this example of dynamic...
network. Within each piece of message, there is a hop counter \( H_i \) (the depth of \( V_i \) in communication of information about \( T_j \)). Each time a relay node transmits a message, the hop counter is reset as \( H_i - 1 \), and when \( H_i = 0 \), the message will no longer be transmitted by the relay nodes.

![Figure 2](image-url)

**Figure 2.** (a) Targets and SAVs in coordinated operations (b) \( V_i \) delivers message \( T_j \) to \( V_7 \)

When a message is transmitted from one SAV to another, there will be communication delay \( \sigma \) which is caused by queuing, processing and broadcasting of information among the relay nodes. Therefore, the IEEE802.11MAC protocol is used to consider \( \sigma \) as a constant the value of the largest delay in the network.

### 4.2 Selection of Potential Coalition Members

In the complex environment of war, there are usually many dynamic targets. When a SAV detects a target, it can obtain all information about the target and predict the location of the target when the coalition is formed. As the target escapes at a speed far slower than the SAV’s flying speed, we assume that the target is relatively static within the time period when the coalition is attacking the target.

The research shows that when the coalition members attack the target, the operational efficiency is maximized, so before the coalition leader decides to form a coalition, it needs to obtain the following information from the potential coalition members: (a) the latest estimated time of arrival at the target (LTAT) which determines the target-attacking time of the coalition members; (b) the type and number of resources needed to destroy the target. This study aims to make the best use of resources of the coalition members to save resources and ensure successful completion of multiple tasks of the swarm of SAVs. By setting the deadline time (DT), we can estimate the location of the SAVs when the decision of coalition formation is made, and identify a relatively accurate parameter of LTAT according to the Dubins path.

When information is transmitted among nodes in a communication network, there is communication delay \( \sigma \), and according to the concept of “time to live” (TTL). Therefore, we can use \( \sigma \times H_{\text{max}} \) to define the deadline time for PCMs to bid, the deadline time for the CL to send the decision message and to implement the decision. The deadline time for PCMs to bid is \( 2\sigma H_{\text{max}} + \Delta \omega \), where \( \Delta \omega \) is the time window that allows the PCM to accept other requests of coalition formation, so that the PCM can decide which coalition to join according to the information it collects within the time window. The CL that receives bidding messages needs to make the coalition formation decision within \( \Delta c \) units of time, and sends the decision to the last member within \( \sigma H_{\text{max}} \) units of time. Therefore, the maximum time that a PCM waits the CL to make a decision after responding to it is \( \xi_i = 3\sigma H_{\text{max}} + \Delta \omega + \Delta c \) units of time. A PCM decides whether to bid according to the value of \( \xi_i \), and decides whether to serve as a relay node according to its estimated location \( G_i \).

### 5. Improved PSO algorithm for coalition formation decision-making

When a CL forms a coalition, it will seek to make the best use of resources and minimize the size of
the coalition. This is a multi-target optimization problem, so the improved PSO algorithm is used to find solutions.

**Algorithm 1 Dynamic coalition formation algorithm**

1: Initialize: $S, \Delta \epsilon, D, s, stime = cputime + \Delta \epsilon, stime0 = stime, \ blength = \infty, P = 1, R_{c}$
2: While $stime \geq 0$ do
3:     for $s = 1: S$ do
4:         $[R_{s}, time] \leftarrow$ determine coalition$(X_{s}, L_{s}, T_{j})$
5:             if $time \leq btime$ and $\sum X_{s} \leq P$ and $R_{s} \leq R_{c}$ then
6:                 $btime = time$
7:             $P = X_{s}$
8:             $R_{c} = R_{s}$
9:         end if
10:     end for
11:     update location and speed
12:     $stime = stime0 - cputime$
13: end while

The CL will perform iteration of Algorithm 1 until $stime = 0$. Each particle $X_{s}$ that belongs to $S$ will be evaluated by the “determine coalition” function during each time of iteration.

**Algorithm 2 Optimum Coalition Update Iteration Algorithm**

1: Function $\text{determinecoalition}(X_{s}, L_{s}, T_{j})$
2: Initialize: $R_{s} = [0, \ldots, |R_{s}^{T}|], \Phi = \emptyset, L_{s}$
3:     for $d = 1: D$ do
4:         if $X_{ad} = 1$ then
5:             $R_{s} = R_{s} + R_{d}, V_{d} \in \Phi$
6:             $\Phi \leftarrow \text{append}V_{d}, V_{d} \in \Phi$
7:         if $L_{d} < L_{s}$ then
8:             $L_{s} = L_{d}$
9:         end if
10:     end if
11: end for
12: if $R_{m} \geq R_{n}^{T}, \forall n$ where
13:     $R_{m} \in R_{s}, R_{n}^{T} \in R_{s}^{T}$ then
14: end if
15: return $[R_{s}, time]$

6. Simulation and Analysis
To prove that the proposed method is feasible and effective, we used Matlab R2013b as the simulation platform to perform comparative experiments.

Experiment 1: for the ease of analysis, we set a 60km×60 km simulation area. At a given time point $K$, there are four SAVs flying at different velocities: $V_1 = 150m/s$, $V_2 = 200m/s$, $V_3 = 220m/s$, and $V_4 = 260m/s$. The locations of these four SAVs are shown in Figure 3. The resources these four SAVs
carry are represented as \( R^V_1 = (1,2,0.3) \), \( R^V_2 = (2,1,1,0) \), \( R^V_3 = (0,0,2,1) \), and \( R^V_4 = (2,3,2,1) \). The resources needed to attack the detected targets are \( R^T_2 = (2,3,1,0) \) and \( R^T_1 = (1,1,1,2) \). The SAVs’ search range is 5000 m, and their communication range is 10000 m. The communication delay between SAVs \( \sigma = 0.1 \) s, the maximum hop \( H_{\text{max}} = 3 \), \( \Delta \omega = 2 \sigma \), and \( \Delta c = 3 \sigma \).

Figure 3. Locations of SAVs and targets at time point \( K \) and \( K + \xi^i \).

As Figure 3 shows, at the time point \( K \), \( V1 \) finds \( T2 \), and \( V4 \) finds \( T1 \), at the time point \( K + \xi^i \) that is, after a time span of \( 3 \sigma H_{\text{max}} + \Delta \omega + \Delta c \) (1.4 seconds), \( V1 \) and \( V2 \) form a coalition to attack \( T2 \), and \( V4 \) implement the task to attack \( T1 \). \( V3 \) has not joined any coalition and will continue searching.

Experiment 2: In a 60km×60km simulation area, we performed experiments on 15 SAVs and 5 random dynamic targets. The initial locations of the SAVs are randomly set; with regard to the locations of the targets, each target conforms to two-dimensional normal distribution with 9 as the mean and the variance; the moving directions of SAVs and targets are randomly generated. The flying velocity of any SAV is a random number between 150 m/s and 300 m/s, and the moving velocity of any target is a random number between 15 m/s and 20 m/s. There are five threats of different radii in the area. The SAVs’ search range is 5000 m, and their communication range is 10000 m, and \( D = 4 \), \( S = 20 \), \( \Delta \omega = 0.2 \) s, and \( \Delta c = 0.3 \) s. In case that one simulation test may incur errors, 100 simulation tests were performed, and the average time for completion of the tasks was identified as the time for task completion. The upper time limit to form coalitions for the five targets during each simulation test was 1000 s, that is, formation of coalitions for all the targets must be completed within 1000 s. The communication delay \( \sigma \) among SAVs was 0.1 s, 0.2 s and 0.5 s, and the maximum hops \( H_{\text{max}} \) was 1, 2 and 3.

Figure 4 shows the correlation between the average time for task completion, the value of \( H_{\text{max}} \) and \( \sigma \). First, we studied the influence of the increase in \( H_{\text{max}} \) with the value of \( \sigma \) fixed. As Figure 5 shows, when \( \sigma = 0.1 \), the average time for task completion reduces as \( H_{\text{max}} \) increases from 1 to 2. This is because in this case, the coalition leader can select quality CMs from more PCMs to complete the task more quickly. When \( H_{\text{max}} \) increases to 3, the average time for task completion is longer than that in the case when \( H_{\text{max}} = 2 \), so when \( \sigma = 0.1 \), the communication delay has little influence on the whole system’s efficiency.
Figure 4. Correlation between average task completion time, $\sigma$ and $H_{\text{max}}$

When $\sigma = 0.2$ s, increasing the $H_{\text{max}}$ will allow the coalition leader to find better PCMs so that the system can complete the tasks more quickly and improve its efficiency. Compared with the case when $\sigma = 0.1$ s, the system spent more time in completing the tasks when $\sigma = 0.2$ s, and hence showed less efficiency, which was because of accumulation of communication delay.

When $\sigma$ was increased to 0.5 s, the influence of communication delay on the task completion time grew. By the same token, when the $H_{\text{max}}$ was fixed, the task completion time increased and the system’s efficiency declined as $\sigma$ increased. 100 simulation tests showed similar results.

As the experiment result shows, the maximum hops and the communication delay has influence on the coalition’s task completion efficiency, so it is necessary to probe into the influence of communication constraints on coalition formation.

Experiment 3: To research on the advantages of the PSO coalition formation decision-making algorithm proposed in this paper, we adopted three algorithms – the algorithm proposed in this paper, the PSO algorithm without considering the communication constraints, and the centralized exhaustive search algorithm without considering the dynamic network. In the experiment, we compared the time to form five random coalitions by using these three algorithms and performed 50 simulation tests. As the simulation results in Figure 5 show, the algorithm proposed in this paper consumes less time on coalition formation than the other two algorithms.

Figure 5. Comparison of time for coalition formation by three algorithms

7. Conclusion
Considering the influence of communication constraints on coalition formation of SAVs, we proposed...
a network model to select coalition members from a time-varying network to complete tasks of attacking dynamic or static targets. This model identifies potential coalition members from a time-varying and dynamic network within the communication range, and we studied the influence of the maximum hops and communication delay on the time of task completion. By using the concepts of “time to live” and “deadline time”, we identified the latest time of arrival at the target (LTAT) in the dynamic network, and provided the optimum solution for the improved PSO coalition formation decision-making algorithm. The research result shows that the proposed model can form coalitions efficiently, and the proposed algorithm consumes less time on to form a coalition than other algorithms do. Moreover, by using Monte-Carlo simulation, we studied the influence of the increase of hops and communication delay on the time of task completion. The simulation result shows that when the communication delay is small, increasing the maximum hops can reduce the task completion time and improve the system’s efficiency; however, when the communication delay is large, it is better to select coalition members from neighboring SAVs to form a coalition.

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