**To cite this article:** LV G H, PENG Z H, WANG D, et al. Target assignment in formation reconfiguration for swarms of unmanned ships[J/OL]. Chinese Journal of Ship Research, 2018, 13(6). http://www.ship-research.com/EN/Y2018/V13/I6/101.

**DOI:** 10.19693/j.issn.1673-3185.01362

# Target assignment in formation reconfiguration for swarms of unmanned ships

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**Abstract:** [**Objectives**] To study the target assignment in the formation reconfiguration of unmanned ships, a target assignment method is proposed. [**Methods**] Firstly, a distance-based cost function is generated by the current positions of the unmanned ships and the fixed target points. Secondly, based on the auction theory and according to the rapidity requirement of the target assignment in the formation reconfiguration of the unmanned ship, an auction termination mechanism is proposed based on the maximum number of iterations for possible non-feasible solution in the assignment of the traditional auction algorithm, which disperses part of the simulations, thus shortening the assignment time. [**Results**] Finally, the simulation results show that this proposed method can quickly give an optimized target assignment scheme for the formation reconfiguration of swarms of the unmanned ships when compared with the classical Hungarian method. [**Conclusions**] The proposed method herein can provide an effective reference for the target assignment in the formation reconfiguration of swarms of the unmanned ships and for the study on the autonomous decision-making of the unmanned ships.

**Key words:** unmanned ships; formation reconfiguration; task allocation; auction algorithm

**CLC number:** U674.91

## 0 Introduction

With the proposal of the concept of "industry 4.0", artificial intelligence and unmanned navigation technology have developed rapidly, and unmanned ship has become the trend of intelligent ship. Because of its advantages of high autonomy, simple assembly, flexible use and low cost [1], unmanned ships have been widely used in military and civil fields, such as using unmanned ships for military reconnaissance, search and rescue, hydrological survey, marine environmental monitoring and other tasks. In order to expand the scope of tasks and improve the efficiency of task execution, swarms of unmanned ships usually work together to complete a task in formation. When swarms of unmanned ships carry out their tasks in the form of formation, because of the complexity of waters and the temporary change of tasks, the formation reconfiguration of swarms of unmanned ships is inevitable. In the formation reconfiguration, the target assignment points which constitute the preset formation need to be assigned to the unmanned ships in the swarm. The assignment efficiency of target points has an important impact on formation reconfiguration and cooperative task execution efficiency of a swarm of unmanned ships.

**Received:** 2018-07-22

**Supported by:** National Natural Science Foundation of China (61673081, 51579023); Fundamental Research Funds for the Central Universities of Ministry of Education of China (3132016313, 3132018306); Key Special Funds of National Key R&D Program (2016YFC0301500); High-level Talents Innovation and Entrepreneurship Project of Dalian, Liaoning Province, China (2016RQ036); University Innovative Talents Subsidy Project of Liaoning Province, China (LR2017014)

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For the target assignment, Mcgrew et al. [2] used approximate dynamic programming technology to solve the one-to-one combat maneuver problem with specified speed; Sujit et al.[3] solved the cooperative search problem of unknown regions of dual intelligent agents through game theory; Manathara et al.[4] used heuristic algorithm to design the allocation strategy for resources of multiple heterogeneous UAV; Kim et al.[5] proposed a regional search task assignment method based on the response threshold model; Wei et al.[6] designed a two-stage task assignment method based on particle swarm optimization, which improved the accuracy and reliability of task completion; Xie and Zhu et al.[7-8] respectively used mutation series method and genetic algorithm to analyze the deployment and operational capability of warship formation, so as to achieve the optimal allocation of resources. In order to solve the problem that the classical Hungarian method cannot deal with the task assignment of large-scale swarms, Chopra et al.[9] improved the Hungarian method into a parallel operation allocation method. In addition to the task assignment methods mentioned above, in recent years, a resource allocation method based on auction mechanism[10-11] has attracted extensive attention of scholars all over the world because of its small computation and flexible operation. Although there are some related studies on target task assignment of multi-UAV system, there are few studies and applications on autonomous decision-making task assignment of swarms of unmanned ships and unmanned ship formation reconfiguration.

In this paper, we mainly study the assignment of target task points in formation reconfiguration for swarms of unmanned ships. Based on auction theory, a target assignment method in formation reconfiguration for swarms of unmanned ship was designed, in which each unmanned ship independently selects interested targets for auction. At the same time, aiming at the non-feasible solution problem that the traditional auction algorithm may have in the target assignment of formation reconfiguration, an auction termination mechanism based on the maximum number of iterations was proposed. Then, it was simulated and compared with Hungarian method.

## 1 Description of task assignment for unmanned ship formation reconfiguration

As shown in Fig. 1, in this section we will study the assignment of $n$ unmanned ships (yellow circle) in the swarm of unmanned ships to $n$ targets (blue circle) in the formation, and maximize the benefit $z$ and minimize the stroke after assignment, as shown in Formula (1).

$$z = \max_{1 \leqslant j \leqslant n}\left\{\boldsymbol{a}_{ij} \times x_{ij}\right\} \tag{1}$$

Where $\boldsymbol{a}_{ij}$ is the benefit matrix of this mission, and the shorter distance between unmanned ship $i$ and target $j$ leads to the greater benefit; $x_{ij}$ is the result of task assignment, and when $x_{ij}=1$, target $j$ is assigned to unmanned ship $i$. After task assignment is completed, the unmanned ship will form a one-to-one relationship with the target, as shown in Formula (2).

$$\begin{cases}\sum_{\{j|(i,j)\in A\}} x_{ij}=1,\ \forall i=1,2,\cdots,n \\ \sum_{\{i|(i,j)\in A\}} x_{ij}=1,\ \forall j=1,2,\cdots,n \\ x_{ij}=0,1, \qquad \forall (i,j)\in A\end{cases} \tag{2}$$

Where $A$ is the set of all possible pairs in an assignment.

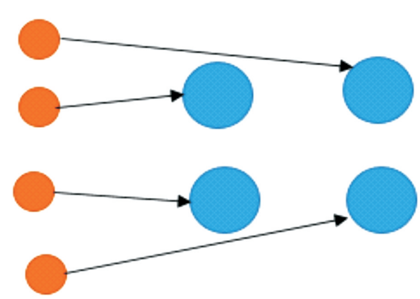


Fig.1 Visualization of a swarm reconfiguration

Assuming that the bidding price of target $j$ is $p_j$, and then the net value of the target obtained by the unmanned ship $i$ bidding is $a_{ij}-p_j$. Every unmanned ship wants to bid for the target $j_i$ with the maximum net worth, namely

$$a_{ij}-p_j=\max_{j\in A(i)}\left\{a_{ij}-p_j\right\} \tag{3}$$

In the formula, $A(i)=\{j|(i,j)\in A\}$ which are the set of targets that unmanned ship $i$ can bid on. When all unmanned ships satisfy this condition, it can be considered that the price vector $\boldsymbol{p}=(p_1,p_2,\ \ldots,p_n)$ is within the complementary relaxation [12].

For a given assignment $S$, if there exists a binary pair $(i,j)\in S$, then the unmanned ship $i$ or the target $j$ is assigned; otherwise, the unmanned ship $i$ or the target $j$ is not assigned. If this assignment $S$ includes $n$ binary pairs and each unmanned ship and target have been assigned one-to-one, then this assignment can be called feasible assignment or complete assignment; otherwise, this assignment is called partial assignment. For all binary pairs $(i,j)\in S$, if the target $j$ is the optimal assignment of unmanned ship $i$ in the range of $\varepsilon$, i.e. $a_{ij}-p_j \geqslant \max_{j\in A(i)}\{a_{ij}-p_j\}-\varepsilon$, $\forall(i,j)\in S$ then the assignment $S$ and the price vector $\boldsymbol{p}$ satisfy the complementary relaxation ($\varepsilon$—$CS$) condition.

# 2 Unmanned ship task assignment based on auction method

## 2.1 Description of the auction process

The bidding process is executed through an iteration cycle of the auction algorithm until the final assignment is the optimal one. Before each iteration begins, a price vector $\boldsymbol{p}$ that meets the conditions of $\varepsilon$—$CS$ is needed. The assignment satisfying the degree of $\varepsilon$—$CS$ and the corresponding price $p_j$ is used as the input of the initial selection to select the attractive targets for the unmanned ship, and the auction bidding is used to make the two satisfy the condition of $\varepsilon$—$CS$ all the time. The whole auction process consists of two stages: bidding stage and assignment stage.

1) Bidding stage.

It is supposed that the set of unassigned unmanned ships in allocation $S$ is $I$. For any unmanned ship, $i\in I$:

(1) We find the target $j_i$ of maximum benefit, so that

$$j_i = \arg\max\{a_{ij}-p_j\} \tag{4}$$

And we calculate the corresponding maximum benefit value $v_i$, i.e.,

$$v_i = \max_{j\in A(i)}\{a_{ij}-p_j\} \tag{5}$$

Then, we find the best value $\omega_i$ provided by other targets besides $j_i$, i.e.,

$$\omega_i = \max_{j\in A(i), j\neq j_i}\{a_{ij}-p_j\} \tag{6}$$

If $j_i$ is the only target, namely that there is only one point in $A(i)$, and then we define that $\omega_i=-\infty$. For ease of calculation, a value much smaller than $v_i$ is assigned to $\omega_i$.

(2) The $p_{j_i}$ of unmanned ship $i$ bidding for target $j_i$ and the price $p_{ij}$ of unmanned ship $i$ that target $j_i$ receives are computed as below:

$$p_{ij} = p_{j_i} + v_i - \omega_i + \varepsilon \tag{7}$$

2) Assignment stage.

For each target $j$, it is possible to receive bids from several unmanned ships at the bidding stage, and the aggregation of these unmanned ships is written as $\boldsymbol{P}(j)$. If $\boldsymbol{P}(j)$ is not empty, the highest bid price $p_j$ is recorded, i.e.,

$$p_j = \max_{i\in \boldsymbol{P}(j)} p_{ij} \tag{8}$$

If target $j$ is assigned to unmanned ship $i$, all binary pairs related to unmanned ship $i$ and target $j$ are removed from assignment $S$, and a new binary pair $(i_j, j)$ is added to assignment $S$, where $i_j$ is the unmanned ship in $\boldsymbol{P}(j)$ with the highest bid.

In the process of auction, the price of the target will rise only when it is auctioned, and in each bidding, the price will increase by at least $\varepsilon$. The price of the target that has not been auctioned remains at the initial value. For example, if unmanned ship $i$ is bidding for target $j$, then the bidding cost $p_{ij_i}$ is

$$p_{ij_i} = a_{ij_i} - \omega_i + \varepsilon = p_{j_i} + \varepsilon \tag{9}$$

After the auction, there will be a new assignment. In this new assignment, the previously assigned targets and unmanned ship numbers are removed, so the designated unmanned ship and targets are no longer involved in the subsequent auction process.

3) Auction termination mechanism without feasible solution.

The above auction algorithm will terminate when a feasible assignment is generated. If there is no feasible solution to the assignment problem, the auction process will be infinitely circular. In order to break this cycle, an auction termination mechanism must be added to the above auction algorithm. Assuming that there is a feasible solution, the number of iterations in auction is limited, as shown in Formula (10), namely that there is an upper limit $D$ of the maximum number of iterations. If there is no feasible solution, that is, because the targets satisfying the complementary relaxation conditions cannot be assigned one by one in the end, the auction will continue and the number of iterations will exceed the maximum number of iterations. When the maximum number of iterations is reached, in order to take into account the running time of the auction, the auction of the target is stopped, and the target is assigned to the unmanned ship with small subscription.

$$D = n \max_{i=1,\cdots,n}\left(\left\lceil \frac{\max_{j=1,\cdots,n} a_{ij} - \min_{j=1,\cdots,n} a_{ij}}{\varepsilon} \right\rceil\right) \tag{10}$$

## 2.2 Design of task assignment mechanism based on auction method

As shown in Fig. 2, the dynamic system network composed of $n$ unmanned ships has integrated network communication capabilities, in which the role of unmanned ships can be divided into two categories: task management and task execution. The main function of the task management ship is to send the task requirements and assignments to the execution ships. Task execution ship is a unit that can perform tasks, which is usually unmanned ships with various loads, and its main function is to execute various task requests sent by task management ship. In this paper, the task management ship sends the information of the target in the preset formation to the task execution ship in the swarm, and each task execution ship makes decision independently according to the information of the target, chooses the target of interest for bidding, and sends the bidding to the task management ship. Then, the task management ship assigns the target task point through the bidding level. Finally the target task point can be assigned to each task execution ship, and the task execution ships go to their assigned targets to form a preset formation.

Fig.2 Communications network of unmanned ships

### 2.3 Unmanned ship task assignment process based on auction method

The proposed algorithm runs in the task execution ship, and the bidding information will be sent and stored in the task management ship during the auction process. Each task execution ship can receive the current bidding information of the target. The target task point $\chi_f$ is set up to form the preset formation, and the task management ship sends the information of the target to the task execution ship. Each execution ship calculates its own distance to each target locally according to the information of the target, and generates the benefit $a_{ij}$. The bidding price is initialized to zero, and then the auction process is started. The algorithm flow chart is shown in Fig. 3, which is divided into the following five steps:

1) The number $N$ of unmanned ships that are not currently assigned is updated. Each unmanned ship calculates the net benefit $b^i(j)$ for all targets locally, independently finds the maximum net benefit $v^i$ and records its corresponding target $j^i$, and then finds out the second largest net benefit $w^i$ of unmanned ships. At this point, an increment $\varepsilon$ is introduced to ensure that the bidding is always increasing. Bids are made according to Formula (7) and the bidding information is sent to the task management ship.

2) Task management ships begin to record the number of ships bidding for task $s$ and the highest bidding price as the next bidding price for task $s$ for all current execution ships.

3) If the number of bids for task $s$ is unique, it means that only one execution ship is bidding and satisfies the complementary relaxation conditions. Therefore, task $s$ is assigned to the execution ship that bids. If the number of bids for task $s$ is duplicated, we add 1 to $count_i$.

4) If $count_i$ exceeds the set maximum number of iterations $D$, it means that several unmanned ships have been bidding repeatedly and have the same interest in task $s$, and the bids have been the same. In this case, task $s$ is assigned to the execution ship with small subscript. At the same time, the task s and the corresponding execution ship are deleted to improve the computing speed.

5) The number $l_j$ of ships that have not been as-

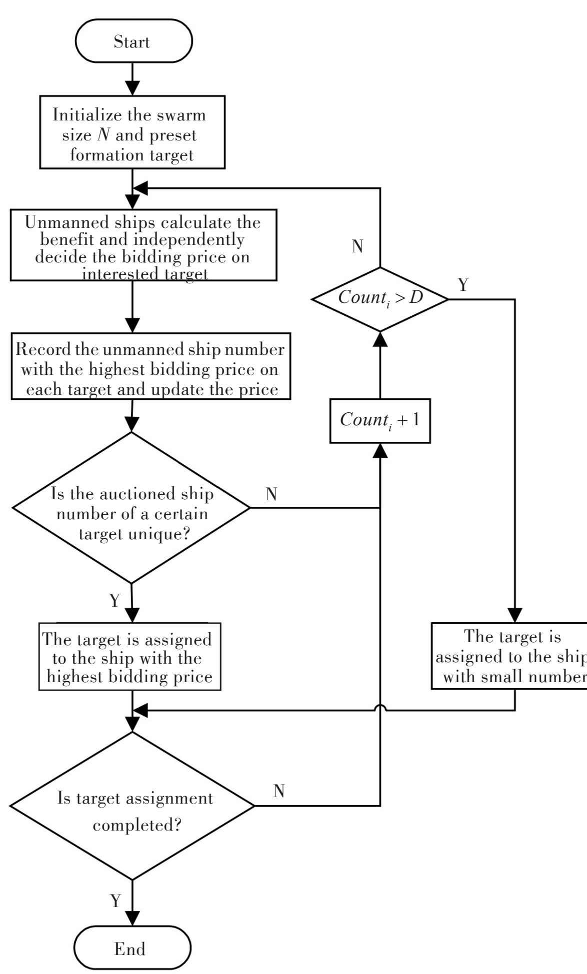



Fig.3 Flow chart of algorithm

signed tasks are judged. If $l_j = 0$, it means that all tasks have been assigned. Then it jumps out of the cycle and the assignment ends. If $l_j = 1$, it means that there is still an execution ship and a target not assigned. At this time, there is no need to bid, and it can directly assign. It jumps out of the cycle and the assignment ends. In this algorithm, the task execution ship does not need to know its initial location information, and the task management ship sends the information of the target to each task execution ship. Each task execution ship calculates its own benefit locally, and independently decides and selects the interested target for bidding, so as to disperse the calculation amount and finally complete the task assignment.

In this process, there will be the following two problems:

1) When the unmanned ship $i$ changes, the subscript set $j^i$ corresponding to its maximum net benefit will change accordingly, namely that the dimension of $j^i$ will change during the iteration process of the algorithm. Therefore, when actually writing programs, we should pay special attention to declaring the size of $j^i$ arrays.

2) In order to fit the auction process in the real market and reduce the assignment time, in this algorithm, whenever a pair of unmanned ship $i$ matches the target $j$, all data related to unmanned ship $i$ and task $j$ are deleted and no longer participate in the subsequent auction process. In recording the task assignment in steps 3) and 5), the first element in $x_i$ corresponds not to the first unmanned ship, but to the unmanned ship with the smallest subscript in the unassigned ships. Similarly, the first element stored in $\chi_{\mathrm{f}}$ is the target with the smallest subscript in the unassigned targets.

## 3 Task assignment simulation analysis of unmanned ship

In this paper, we assume that there is a swarm of 39 unmanned ships in a certain water area which needs formation reconstruction, and simulate the assignment of 39 target task points which constitute the preset formation. As shown in Fig. 4, 39 unmanned ships randomly distributed in the water are assigned to 39 target task points which constitute the DMU formation to form the DMU formation.

The incremental parameter $\varepsilon$ in the above assignment scheme has an important influence on the assignment benefit. Therefore, firstly, the simulation

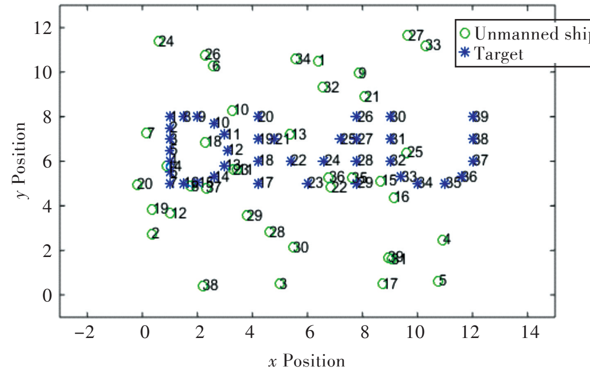



Fig.4 Scatter chart of unmanned ships and targets

analysis of the assignment benefit with different $\varepsilon$ values was carried out. Fig. 5 shows the effect of the incremental parameter $\varepsilon$ on the post-assignment benefits. Generally, the assigned benefit tends to decrease with the increase in the incremental parameter $\varepsilon$. Especially when the incremental parameter $\varepsilon$ is 0.02~0.03, the assignment benefit decreases greatly. When $\varepsilon > 0.1$, the decline of assignment benefit tends to be gentle, and at this time, the value of distribution benefit reaches about 93% of the optimal value of assignment benefit.

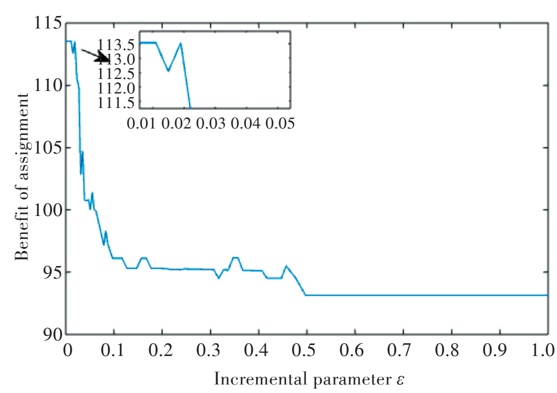
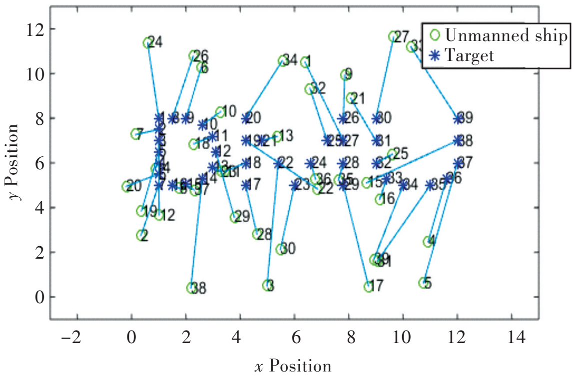


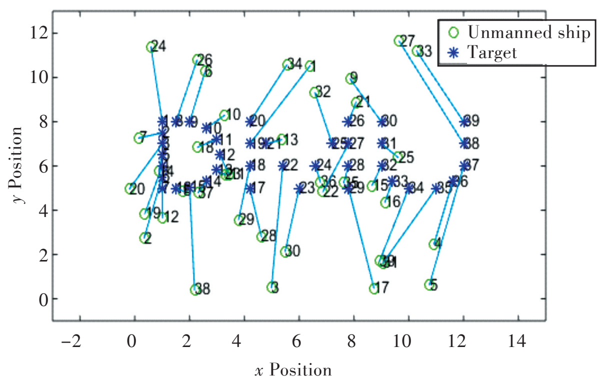

Fig.5 Influence of $\varepsilon$ on benefit of target assignment in reconfiguration

Secondly, the distribution results of the selected $\varepsilon = 1/39$ were compared with the optimal assignment results of the Hungarian method in this paper. And the assignment results are shown in Fig. 6. The 39 target task points in DMU formation are assigned, and the targets assigned for unmanned ships are basically in the vicinity. The assignment results obtained by the two methods are similar, which verifies the rationality of the assignment scheme described in this paper.

Finally, in order to further compare the algorithm mentioned in this paper with the classical Hungarian method, the task points of formation are assigned for swarms of unmanned ships with different sizes. At this time, the value of $\varepsilon$ is $1/n$, and the setting of the maximum number of iterations $D$ is shown in Formu-




(a) Target assignment results of unmanned ship using Hungarian method




(b) Target assignment results of unmanned ship using the auction method

Fig.6 Result of target assignment in reconfiguration

la (10). From Table 1, we can see that the maximum difference of benefit between the proposed assignment method and Hungarian method is about 2%. However with the increase in swarm size, the solution time of auction assignment is shorter than that of Hungarian method, namely that the assignment benefit of target by Hungarian method is larger than that of target by auction assignment, but the calculation amount of auction assignment is scattered and the assignment time is shortened.

**Table 1 Comparisons of the results of two assignment algorithms**

| Swarm size $n$ | Benefit of assignment | | Assignment time/s | |
|---|---|---|---|---|
| | The proposed auction method | Classical Hungarian method | The proposed auction method | Classical Hungarian method |
| 10 | 35.4 | 35.4 | 0 | 0 |
| 30 | 80.3 | 82.0 | 0.005 | 0.007 |
| 60 | 159.3 | 159.0 | 0.021 | 0.063 |
| 90 | 190.8 | 192.2 | 0.053 | 0.112 |
| 110 | 230.4 | 233.9 | 0.104 | 0.251 |

## 4 Conclusion

Based on the auction theory, an algorithm for assigning the target task points in unmanned ship formation reconfiguration was proposed in this paper. The unmanned ship in the swarm calculates locally, and decides independently to select the interested targets for bidding, so as to complete the assignment of the targets in the preset formation. The results compared with those of Hungarian method show that the method proposed in this paper can quickly obtain a relatively optimal assignment scheme when the value of supplementary increment $\varepsilon$ is near $1/n$. The assignment method in this paper can also be further studied for the multi-node communication problem of swarms of unmanned ships, which can not only reduce the dependence on processors, but also solve the problem of insufficient communication bandwidth of swarms of unmanned ships, so as to improve the robustness of dynamic formation reconfiguration of large-scale swarms of unmanned ships.

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# 无人船集群队形重构的目标任务分配

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**摘　要:**[**目的**]针对无人船编队队形重构中的目标分配问题,提出一种队形重构目标分配方法。[**方法**]首先,在目标点固定的情况下,通过各无人船的当前位置,生成基于距离的收益函数。其次,以拍卖理论为基础,根据无人船队形重构中目标分配的快速性要求,针对传统拍卖算法在重构分配中可能存在的无可行解问题,提出基于最大迭代次数的拍卖终止机制,分散部分计算量,从而缩短分配时间。[**结果**]仿真结果表明,与匈牙利法相比,所提方法针对大规模无人船集群队形重构能够快速给出目标任务分配方案。[**结论**]所提方法能为无人船集群队形重构中目标分配问题以及无人船自主决策研究提供一定的参考。

**关键词:** 无人船; 队形重构; 任务分配; 拍卖算法