A Group Maintenance Method of Drone Swarm Considering System Mission Reliability

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Abstract: Based on the characteristics of drone swarm such as low cost, strong integrity, and frequent information exchange, as well as the high cost of timely maintenance of traditional units. This paper proposes a swarm maintenance method based on the reliability assessment of multi-layer complex network missions, which combines the multi-layer complex network system evaluation method with the group maintenance method. On the basis of considering the problem of maintenance grouping cost, the failure mechanism of drones in different modes and the impact of drone maintenance on the system are studied. According to the failure model of single node, the complex network method is used to establish the swarm system’s topology model and evaluate the system mission reliability. The maintenance grouping strategy is optimized by using the multi-objective planning of cost and system mission reliability. Compared with the existing just in time maintenance methods, this method can greatly reduce the total maintenance cost of the swarm system maintenance under the condition of ensuring the high mission robustness of the swarm. In addition, a universal drone swarm mission scenario is used to illustrate the method, and the results verify the feasibility and effectiveness of the method.

Keywords: swarm maintenance; drone swarm; complex network; system reliability; multi-objective optimization

1. Introduction

The drone swarm has the characteristics of many nodes and complex interactions. The completion of the internal missions of the system mainly depends on the control structure and information exchange, which is dependent on mission networking. Drone swarm is widely used in various fields to perform public security [1], military [2], and industry due to its high flexibility, strong adaptability, and controllable economic cost. With the improvement of swarm usage requirements, swarm maintenance has become the focus of attention, and many maintenance theories and optimization design methods are applied to this [3,4]. The research on the failure mode of the drone system in the swarm [5] has been relatively mature. However, the concept of low-cost unmanned aerial vehicles has been born in recent years. Under the swarm system, the problem of the drone maintenance is no longer the primary factor limiting the ability of swarm missions. At the same time, performing single-point maintenance on many units in the swarm according to the timely maintenance method of traditional unit equipment will face problems such as large maintenance magnitude and difficulty in taking into account the mission networking connection. How to gradually transition from unit system maintenance to swarm system maintenance has become the focus of researchers [6].

To solve the problem of swarm system maintenance, researchers first introduced group maintenance into swarm systems based on the similarity of multi-level systems. The group maintenance method is of great significance for ensuring system safety and restoring the ability of multi-level systems [7]. The existing research’s maintenance models generally conduct many analyses at the unit and system levels [8–10], group the maintenance information at the unit level, and make system-level maintenance decisions. The general research
method of unit maintenance [11] uses the unit-level failure rate to propose a grouping strategy and combine the system maintenance cost to model the unit maintenance model. In addition, there is a degradation model [12] used to describe intuitively the health and working conditions of the unit level, and then combined with the system-level maintenance cost to carry out maintenance planning for the system. However, unlike other unit systems, drone swarm communicate more frequently at the unit level and in the system. The swarm network that relies on information transmission is likely to affect the reliability of missions due to the maintenance of the unit level. The performance parameters are also closer to the topology parameters of complex networks. It is difficult to guarantee the execution of actual swarm missions based only on unit-level degradation parameters and system-level cost functions. Therefore, in this study, we consider introducing complex network-related methods to evaluate system-level reliability. As another optimization indicator for swarm maintenance, the mission capability of the swarm is fully taken into account.

The complex network method constructs a network model of mutual information interaction in the form of nodes and edges. According to this model, the system's topology structure and evolution law is studied from the perspective of the nodes, edges, and their network evolution. Then the critical points of the system can be targeted. The system is analyzed by vulnerability cascading effect, mission reliability, and other vital issues [13]. With the development trend of complex systems and unmanned cooperative systems in recent years, complex network methods are widely used in swarm-like systems such as transportation systems [14] and circuit systems [15]. At present, the complex network methods mainly apply to cascade failure [16], seepage, phase transition [17], propagation dynamics [18], and other mechanisms to evaluate network vulnerability [19], elasticity [20], mission reliability and other characteristics.

To solve the optimization problem under multi-parameter constraints, the currently recognized method in the academic circles is the multi-objective optimization theory [21]. Whether it is based on the traditional linear weighting method or the particle swarm optimization algorithm based on the evolutionary algorithm, it has been widely and standardized in various fields.

Therefore, because of the combination of mission capability and maintenance planning of swarm systems, this paper proposes a maintenance method for drone swarm, which adopts multi-objective optimization theory and a swarm system-level mission reliability evaluation model to solve. This method provides a cognitive basis for the drone swarm research of related projects, and also provides technical support for the follow-up more complex cluster maintenance model research.

The remainder of this paper is as follows: Section 2 describes the mission characteristics of drone swarm and the theoretical basis for evaluating the reliability of swarm systems using complex network methods. Section 3 puts forward the basic assumptions of the application scenarios for the swarm maintenance method proposed in this paper and gives specific practical methods. Section 4 uses the drone swarm network model to verify the feasibility and superiority of the method by comparing it with the traditional method of timely maintenance of single aircraft. Section 5 illustrates the effectiveness of the application of this method with a general case model as an example. In Section 6, we summarize this paper and propose future work.

2. Preliminaries

2.1. Mission Characteristics of Drone Swarm

A drone swarm is a system unit composed of multiple drones with system mission capabilities. However, the drone swarm is not a simple combination of numerous drones. It also includes many structures such as data links between drones, mission network, ground control platform, etc., as shown in Figure 1.
2. Preliminaries

2.1. Mission Characteristics of Drone Swarm

A drone swarm is a system unit composed of multiple drones. The ground control system or the drone of the overall mission independently assigns the swarm mission. The submissions are transmitted through the data link to form the mission execution. Links form an internal mission network, and each drone performs the corresponding sub-missions according to the assigned instructions and comprehensively completes the final mission of the swarm.

2.2. Complex Network Model of Swarm

In the theory of complex network topology, the network is composed of nodes and edges, where edge represents the attribute parameters of edges in the form of weights. When modeling drone swarm systems with complex networks, a drone is usually regarded as a node, and the data link connection between drones is considered an edge. Both nodes and edges are given corresponding attributes according to the actual swarm capability values. Finally, transform the complex drone swarm system into a hierarchical network model composed of interacting nodes for analysis.

Considering there are factors at different levels in the drone’s mission execution process, such as communication interference, structural attack, mission system failure, etc., all of which are related to the degradation and unexpected collapse of the corresponding system level of the drone. Therefore, multi-node network is introduced, considering the changes in the capability indicators of different types of drones and thoroughly combining the follow-up corresponding maintenance strategies. According to the characteristics of drone and swarm interaction, the drone node is divided into three nodes of communication, structure, and mission, corresponding to the three-layer system of communication data link, drone carrier, and mission load in the network. Then, the relationship between the layers is described on this basis, and the process of establishing a multi-layer complex network is shown in Figure 2.

![Figure 1. Composition of drone swarm.](image-url)
2.3. Relationship between Swarm Maintenance and Network

Swarm maintenance is based on stand-alone maintenance. The premise of stand-alone maintenance is that the reliability of a certain level of single-machine structure cannot meet the requirements of subsequent missions. Therefore, it is necessary to recall the drone to be repaired during the mission execution process. At this time, the remaining swarm continue to perform the predetermined mission. That is, the maintenance of a drone is equivalent to the disappearance of the corresponding node in the swarm network. No matter what level (communication, structure, and mission) fails for a drone, the entire drone needs to be recalled for maintenance. The failure of a single-level node is equivalent to the disappearance of the corresponding nodes at the three levels, As shown in Figure 3.

2.4. Swarm Mission Reliability Evaluation Method

Network reliability refers to the ability of the network to maintain functional and structural integrity when nodes and edges in the network are attacked. In the actual maintenance scenario, the maintenance of a drone can also be regarded as removing the mission node in the corresponding network model, and the corresponding connection edges disappear. Based on this, the network reliability can be used to evaluate the reliability of swarm missions.

The concepts of basic network parameters: node degree, average path length, and swarm coefficient are introduced first. to establish network reliability evaluation indicators.
The node degree \( k_i \) is defined as the number of edges that node \( i \) is directly connected to other nodes, and the average of the degrees of all nodes in the network is called the average network degree, denoted as \( \langle k \rangle \).

The shortest path between two nodes \( i \) and \( j \) in the network refers to the way with the least number of edges connecting these two nodes, and the distance \( d_{ij} \) between node \( i \) and \( j \) are defined as the edge of the shortest path connecting these two nodes. Calculating the average path length \( L \) of the network is defined as the average of the distances between any two nodes.

\[
L = \frac{1}{2N(N-1)} \sum_{i,j} d_{ij}
\]

where \( N \) is the number of network nodes.

The swarm coefficient \( C \) of the network is defined as the average of the swarm coefficients of all nodes in the network.

\[
C = \frac{1}{N} \sum_{i=1}^{N} C_i
\]

Among them, the swarm coefficient \( C_i \) of a node \( i \) with a degree \( k_i \) in the network is defined as:

\[
C_i = \frac{E_i}{k_i(k_i-1)/2}
\]

Here \( E_i \) and \( k_i(k_i-1)/2 \) are the actual number of edges and the possible maximum number of edges between node \( i \) and its \( k_i \) neighbor nodes, respectively.

Based on the above three fundamental indicators of a complex network, reference [22] proposes network reliability indicators:

Assuming that the swarm system consists of \( N \) drones, the swarm system is randomly removed by considering the network characteristics, and the reliability index value \( s_k (k = 1, 2, 3, \ldots, m) \) of the remaining network is calculated at the same time.

For each index, a set of changes of the index with successive removal of nodes \( \Delta s_{ki} (i = 1, 2, 3, \ldots, N) \) can be obtained. Then the variance of the change of the index can be calculated, which is expressed as follows:

\[
S_k^2 = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\Delta s_{ki} - \bar{\Delta s}_{ki}}{N} \right)^2, \quad k = 1, 2, 3, \ldots, m
\]

Furthermore, by repeating this process \( n \) times, the mean value of the variance of the variation of the indicator for \( n \) simulations can be obtained, which can be expressed as follows:

\[
\overline{S_k^2} = \frac{1}{n} S_k^2, \quad k = 1, 2, 3, \ldots, m
\]

By comprehensively comparing the network reliability index and network performance index after sensitivity analysis, the weight of each index in the comprehensive reliability evaluation index can be determined according to the mean value of the variance of the index variation. The relationship between the weight and the mean variance is expressed as follows:

\[
w_k = \frac{\overline{S_k^2}}{\sum_{k=1}^{m} \overline{S_k^2}}, \quad k = 1, 2, 3, \ldots, m
\]

Finally, the index processing method of the literature [23] is introduced, and the comprehensive evaluation index of network reliability can be obtained, which is expressed as follows:

\[
R = \sum_{k=1}^{m} w_k \frac{s_k - \min(s_k)}{\max(s_k) - \min(s_k)}
\]
Among them, \( s \) represents the structural topology parameters and network performance parameter indicators, such as the average degree of the entire network node, the network efficiency of the communication layer, etc. \( w_k \) Represents the weight of the indicator, and its value can be determined according to Equation (7); \( R \) represents the reliability of the network, and its value range is \([0, 1]\), and the closer the value is to 1, the better the network reliability.

3. Swarm Maintenance Method

Aiming at the problem of how to formulate a swarm maintenance plan considering both the reliability of swarm missions and the maintenance cost, this chapter proposes a swarm maintenance method based on the reliability assessment of multi-layer complex network missions. The framework of the method is shown in Figure 4. This method integrates the primary method of group maintenance and a complex network analysis method. Based on the existing group maintenance, the drone level uses the degradation prediction method to evaluate the reliability of the drone, and the system level introduces the mission network and mission reliability evaluation index, and finally uses the multi-level maintenance method. The objective optimization method optimizes for maintenance cost and mission reliability. The method includes four steps: unit reliability prediction based on prevention, maintenance grouping strategy and cost, mission reliability evaluation, and optimize grouping decision.

![Figure 4. Basic theoretical flow chart.](image)

3.1. Basic Assumptions

This paper makes the following assumptions about the mission scenarios and maintenance behaviors of drone swarm applying this method:

**Assumption 1.** The theoretical maintenance time considering the reliability of system components is based on a preventive strategy, allowing a lag in maintenance within a specific time frame.

**Assumption 2.** Failure maintenance includes preventive maintenance of two kinds of failures: accidental failure maintenance and degradation failure maintenance. This method does not consider other unknown failure maintenance caused by complex environmental stress during the mission.

**Assumption 3.** The drone in a maintenance state only affects the reliability of the swarm system in the next mission stage.
Assumption 4. After the maintenance is completed, the return swarm link remains unchanged. It is assumed that the state parameters after the maintenance are the same as the initial parameters.

Based on the above assumptions, this paper introduces the basic theory of the maintenance method decision in Sections 3.2–3.5.

3.2. Unit Reliability Prediction Based on Prevention

According to experience, for determining the drone reliability function distribution of the system, empirical distributions, such as exponential distribution, normal distribution, Weibull distribution, etc., can be used to represent the reliability function distribution under its degradation failure. For the accidental failure in the drone mission, it is clarified that based on the known empirical data, the drone with unexpected failure can also be obtained using the observed distribution.

According to the above distribution theoretical basis, combined with the observation data of the single machine, fit and estimate the reliability prediction, and obtain the single machine life. For example, if the single machine structure life distribution obeys an exponential distribution, according to the reliability function formula of the exponential distribution: \( R(t) = \exp(-\lambda t) \). Where \( \lambda \) is the failure rate constant, determined by empirical data.

From the above analysis, we can predict any single node’s life considering accidental and self-degradation failure. For drone stand-alone equipment, preventive maintenance is generally used. In the case of prevention, a small estimation of the lifespan can be obtained to obtain the stand-alone maintenance time \( T \) based on prevention.

Considering the maintenance time \( T \) of a single machine based on prevention, a single machine failure may occur before time \( T \) and after time \( T \). If a single machine failure occurs before time \( T \), the single machine will not be able to perform the mission immediately and enter the maintenance state. According to the reliability function, at time \( T \), the probability of failure before and after time \( T \) is respectively \( R(T) \) and \( F(T) = 1 - R(T) \). Next, the total maintenance cost is further calculated.

Because there is a demarcation point at time \( T \), the cost of preventive maintenance is different before and after time \( T \). \( C_p \) and \( C_{dp} \) are defined as the maintenance cost and downtime cost of maintenance before time \( T \), respectively, and \( C_f \) and \( C_{df} \) are defined as maintenance costs after time \( T \) respectively. Maintenance cost and downtime cost, \( t \) is the actual maintenance time. Therefore, the equivalent stand-alone maintenance cost at time \( t \) is expected to be

\[
TWC(t) = \left( \frac{C_p + C_{dp}}{T} \right) R(t) + \left( \frac{C_f + C_{df}}{T} \right) F(t)
\]

It can be seen from the calculation formula of \( TWC \) that the equivalent maintenance cost brought by earlier maintenance is relatively large. It is consistent with the actual maintenance situation of the drone swarm; in addition, the formula does not involve accidental failure and self-degradation failure. The difference can be applied to the maintenance cost calculation in both cases.

In Section 2.2, we propose considering the different failure modes of a single drone. The above life prediction and cost calculation methods of a single aircraft are also applied to different structural ways of a single plane. The three nodes of communication, structure, and mission are used for node life prediction and cost calculation. Calculated to get the prevention-based node maintenance time and maintenance cost.

3.3. Maintenance Grouping Strategy and Cost

From Section 3.2, it can be seen that any node failure in a drone system requires drone maintenance. Single-machine maintenance will inevitably lead to increased maintenance costs, downtime, and reduced reliability at the swarm system level. Rest for maintenance results in extremely high maintenance costs and low mission reliability for the swarm.

We propose a swarm maintenance method based on mission completion time. The swarm system decomposes the total mission into sub-missions for different drone groups.
through mission allocation because of the characteristics of the completion time interval between sub-missions and little influence on mutual system reliability. It is assumed that there is a maintenance opportunity after each submission is completed, and the maintenance time is determined by the mission time. The maintenance opportunity divides the mission time of the entire swarm into multiple time intervals $t_1, t_2, \ldots, t_n$. According to the comparison between the preventive maintenance time $T$ of the stand-alone node in Section 3.2 and the corresponding time $t$ of the maintenance opportunity (that is, the completion time of the submission), select the drone near the maintenance time to enter the maintenance state at the corresponding maintenance time $t$, as shown in Figure 5. Unit 1 chooses to be repaired at the time $t_3$. Unit 2 and unit 3 can choose to be repaired at the time $t_1$. And unit 4 and unit 5 can choose to be repaired at the time $t_2$.

![Figure 5. Maintenance grouping strategy.](image)

At this time, according to Formula (8), the total cost of the equivalent maintenance of the actual single machine is

$$TWC_i(t_j) = \left( C_p + C_{dp} \right) R(t_j) + \left( C_f + C_{df} \right) F(t_j)$$

The total maintenance cost of all single-node nodes is accumulated to obtain the total system maintenance cost $TWC$ under this grouping strategy.

$$TWC = \sum_{j=1}^{n} \sum_{i=1}^{N} TWC_i(t_j)$$

where $N$ represents the total number of nodes and $n$ represents the total number of maintenance opportunities.

The cost calculation function includes maintenance cost and downtime cost. The cost function is related to the grouping strategy selection, the maintenance opportunity, and the actual maintenance time of a single machine. In terms of maintenance strategy selection, each node can choose to maintain in advance or lag. At this time, different combinations form a variety of maintenance strategies.

### 3.4. Mission Reliability Evaluation

For different maintenance grouping situations, it is necessary to perform swarm mission reliability evaluation on all maintenance opportunities under the grouping strategy in the entire mission cycle. For example, for the maintenance grouping situation shown in Figure 5, at maintenance time $t_1$, remove maintenance nodes 2 and 3, and evaluate the mission reliability $R_{11}$ of the remaining nodes to form a swarm network, remove maintenance
nodes 4 and 5 at maintenance time \( t_2 \), and evaluate the remaining nodes. The mission reliability \( R_{12} \) of the swarm network is formed, and so on, to obtain the swarm mission reliability \( R_{11}, R_{12}, \ldots, R_{1n} \) under all maintenance opportunities under the first group of maintenance strategies.

Among them, the swarm mission reliability \( R_{11}, R_{12}, \ldots, R_{1n} \) under all maintenance opportunities may exist if the swarm mission reliability is lower than the mission completion threshold at a particular maintenance time due to the centralized maintenance of multiple nodes. To be eliminated, the \( n \) groups of data for grouping decisions without abnormal data can be weighted and averaged, respectively, according to the weight value of maintenance opportunities, and the final swarm mission reliability \( R_i \) of this group strategy can be obtained:

\[
R_i = w_1 R_{i1} + w_2 R_{i2} + \cdots + w_n R_{in} \tag{11}
\]

Among them, \( w_i \) is the weight value of swarm robustness under the maintenance opportunity \( i \), \( w_1 + w_2 + \cdots + w_n = 1 \).

The swarm mission reliability index under each grouping strategy is obtained and combined with the total maintenance cost obtained according to the cost function under each maintenance plan in Section 3.3. It provides an index basis for the subsequent comprehensive optimization index and grouping decision.

### 3.5. Optimize Grouping Decision

In this method, the swarm maintenance grouping decision is a multi-objective optimization problem that finally considers the total maintenance cost and the reliability of the swarm mission. For the optimization problem of the two objectives of this method, we use the linear weighting method to solve the problem and propose the final optimization index \( V_i \), which can be expressed as:

\[
V_i = w_1 \phi(O_{1i}) + w_2 \phi(O_{2i}) + \cdots + w_n \phi(O_{ni}) \tag{12}
\]

Among them, \( w_i \) is the weight value of the optimization target, \( w_1 + \cdots + w_n = 1 \).

\( \phi(O_{1i}) - \phi(O_{ni}) \) represents the parameter value of each optimization objective. There are only two parameter values in this method, but the value ranges of different optimization objectives are different, such as the mission reliability index \( R \in [0, 1] \), but the total cost \( TWC \in (0, \infty) \). Therefore, it is necessary to normalize the optimization target parameter values.

\[
O_{ni} = \frac{\theta_{ni}}{\max(\theta_{n1}, \theta_{n2}, \ldots, \theta_{nk})} = \frac{\theta_{ni}}{\theta^*} \tag{13}
\]

Among them, \( \theta_{ni} \) is the parameter value of the policy \( i \) of the \( n \) optimization objective:

\[
V_i = w_1 \phi\left(\frac{\theta_{1i}}{\theta^*}\right) + w_2 \phi\left(\frac{\theta_{2i}}{\theta^*}\right) + \cdots + w_n \phi\left(\frac{\theta_{ni}}{\theta^*}\right) \tag{14}
\]

In the normalization process of the above indicators, we default that the larger the optimization target value, the better. For example, the closer the mission reliability index is to 1, the better. However, not all indicators obey this assumption, such as the total cost \( TWC \) in this method. Therefore, we add the \( \phi \) function, which is defined as follows:

\[
\phi(O_{ni}) = \begin{cases} 
\frac{\theta_{ni}}{\max(\theta_{n1}, \theta_{n2}, \ldots, \theta_{nk})}, & \text{if } \theta_{ni} > \theta^* \\
\frac{\theta_{ni}}{\min(\theta_{n1}, \theta_{n2}, \ldots, \theta_{nk})}, & \text{if } \theta_{ni} < \theta^*
\end{cases} \tag{15}
\]

Based on the above analysis, we establish the comprehensive optimization index of system mission reliability index and total maintenance cost as:
\[ V_i = w_1 R_i - w_2 \phi \left( \frac{TWC_i}{TWC^*} \right) \]  

where \( w_1 \) and \( w_2 \) are the index weights of system mission reliability and total maintenance cost respectively and \( w_1 + w_2 = 1 \). When \( w_1 > w_2 \), the system mission reliability index is the dominant factor in the final decision. When \( w_1 < w_2 \), the total maintenance cost is the dominant factor in the final decision. When \( w_1 = w_2 \), the two have equal status.

4. Simulation Analysis

To verify the effectiveness of this method applied to drone swarm maintenance, taking a typical case as an example, the total maintenance cost and swarm system reliability under the timely maintenance strategy is compared with the total cost and system reliability under the application of this method.

Assuming that multiple drone swarm with heterogeneous drones perform the overall mission, the assumed sub-mission completion times are 500 min, 650 min, 800 min, and 950 min, respectively. Taking a swarm composed of 10 drones as an example, the establishment of the swarm model structure and communication link situation of the swarm model are shown in Figure 6, and each drone reliability parameters are estimated based on experience shown in Table 1.

![Figure 6. Method to verify the 10-node swarm model.](image)

| Nodes | Life Distribution Model | Reliability Function | Cost ($) |
|-------|-------------------------|----------------------|----------|
| A, B, C, D | Index distribution | \( R(t) = e^{-\left(\frac{t^{750\times10^{-6}}}{900}\right)} \) | 2840 150 26 150 |
| E, F | normal distribution | \( R(t) = P\left(z > \frac{t-800}{200}\right) \) | 1200 150 3670 150 |
| I, H | Weibull distribution | \( R(t) = e^{-\left(\frac{t}{2840}\right)^{2.5}} \) | 960 150 7630 150 |
| J, G | Inverse Gaussian distribution | \( \mu = 900, \lambda = 8 \times 10^5 \) | 1984 150 18 150 |

The established drone node is the minor node of the system and does not continue to divide the three-layer network. In addition, the life distribution of the node is given randomly, covering different empirical distribution functions as much as possible to verify the universality of the method.
4.1. Maintenance Time and Grouping Strategy

The reliability function under the empirical distribution of each node is given in the Table 1. Under the condition that a large number of nodes obey the same distribution, the maintenance time based on prevention can be generated by a random method. According to the empirical data, we use its reliability for a single node to decrease. The preventive maintenance time of the node is calibrated at the corresponding time of 0.6, and the preventative maintenance time under the four life distributions is 611 min, 748 min, 559 min, and 936 min, respectively. Considering that each drone unit does not start the mission in the best state, there is an actual maintenance time ahead of schedule. Due to the possibility of theoretical maintenance time, the exact maintenance time of a single machine earlier than the academic maintenance time is randomly generated, as shown in Table 2.

Table 2. Maintenance time of nodes based on prevention.

| Nodes | A   | B   | C   | D   | E   | F   | G   | H   | I   | J   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Actual maintenance time (min) | 584 | 603 | 536 | 555 | 689 | 720 | 930 | 496 | 523 | 871 |

Each maintenance opportunity is allocated according to the completion time of the submissions, and the following maintenance grouping scheme will be obtained when considering the maintenance in advance.

For each grouping strategy in the Table 3, the cost function can obtain the total maintenance cost under the maintenance strategy. The complex network method is used to evaluate the mission reliability of the swarm and adjust the maintenance plan.

Table 3. Swarm maintenance group.

| Maintenance Plan | 500 min | 650 min | 800 min | 950 min |
|------------------|---------|---------|---------|---------|
| ①                | I, H, C | A, B, D | E, F    | J, G    |
| ②                | I, H, D, C | B, A, E | F, J    | G       |
| ③                | I, H, D | A, B, C | E, F    | J, G    |

4.2. Mission Reliability and Cost of a Swarm System

As shown in Section 2.4, the mission reliability assessment of a complex network system requires establishing a complex network model. For the model structure in Figure 6, the established complex network model is shown in Figure 7.

Figure 7. Complex network model.

Based on the complex network evaluation method, the corresponding nodes are removed from the swarm network under the related maintenance opportunity, and the
reliability changes of the system missions are evaluated. As shown in the Figure 7, since the initial swarm network is not fully connected, the initial network mission of the evaluation is not 1, it is normalized. The mission reliability index values and total maintenance cost results under each maintenance strategy are obtained as shown in the Table 4, and the comparison of each maintenance scheme pair over time is shown in Figure 8.

Table 4. Mission reliability and total maintenance cost under each maintenance strategy.

| Maintenance Strategy | Mission Reliability | Total Maintenance Cost ($) |
|----------------------|---------------------|---------------------------|
|                      | 500 min | 650 min | 800 min | 950 min |                      |
| ①                    | 0.803   | 0.735   | 0.892   | 0.933   | 23,620               |
| ②                    | 0.718   | 0.779   | 0.917   | 0.970   | 22,343               |
| ③                    | 0.819   | 0.714   | 0.906   | 0.937   | 22,864               |

(a) Mission reliability varies with task time

(b) Cost varies with task time

Figure 8. Graph of the change of indicators over time under different maintenance strategies for 10 nodes: (a) describes the change of mission reliability with mission time; (b) describes the change of the total cost of swarm maintenance with mission time.

4.3. Comparison Summary

In the following, for the maintenance scenario considering timely maintenance, the swarm model in Figure 6 is used to analyze the cost and system mission reliability. Under the condition that convenient maintenance is considered, every drone needs to be shut down immediately for maintenance at the expected maintenance time. Under the condition of viewing the downtime cost, the complex network model is used to remove the nodes corresponding to the four-time points, and the number of nodes with different numbers of nodes is obtained. Figures 9–11 compares the system mission reliability changes and the total maintenance cost with the results of group maintenance.
In the following, for the maintenance scenario consider drones in the whole mission cycle of the swarm that need to be maintained.

**4.3. Comparison Summary**

The time and space complexity of this method is calculated as follows:

Based on the above conclusions, the group maintenance method considering mission control, but has no obvious ad-

**Figure 9.** Comparison of timely maintenance and group maintenance strategies under 10 nodes: (a) describes the change of system mission reliability with mission time; (b) describes the change of total maintenance cost with mission time.

**Figure 10.** Comparison of timely maintenance and group maintenance strategies under 50 nodes: (a) describes the change of system mission reliability with mission time; (b) describes the change of total maintenance cost with mission time.

**Figure 11.** Comparison of timely maintenance and group maintenance strategies under 100 nodes: (a) describes the change of system mission reliability with mission time; (b) describes the change of total maintenance cost with mission time.
According to the comparison of the system mission reliability index and maintenance cost under the timely maintenance strategy and the group maintenance strategy, the following conclusions can be drawn:

(1) In terms of system reliability: (a) As the scale of the swarm increases, the impact of node maintenance brought by timely maintenance strategy and group maintenance strategy on the reliability of swarm missions will gradually decrease. This is because there are many nodes, and the maintenance and removal of nodes have relatively little impact on the reliability of the remaining swarm missions; (b) The average mission reliability under the timely maintenance strategy is generally higher than that under any group maintenance. Because timely maintenance only repairs one node at a time, it has less impact on the reliability of the remaining swarm missions; (c) The reliability of system missions fluctuates under the timely maintenance strategy. Because the system is forced to be repaired during non-mission completion time and many repair opportunities, the system mission reliability fluctuates wildly. Still, the system mission reliability fluctuation will weaken with the expansion of the swarm scale.

(2) In terms of maintenance costs: (a) Considering the cost of downtime, the maintenance cost of timely maintenance is far greater than the maintenance cost of group maintenance under any strategy. The cost has a specific impact, that is, the cost of maintenance in advance is reduced, whereas the cost of maintenance increases; (b) As the scale of the swarm continues to expand, the cost of timely maintenance is higher than the cost of any grouped maintenance. The scale has grown exponentially.

Based on the above conclusions, the group maintenance method considering mission reliability has great advantages in maintenance cost control, but has no obvious advantages in mission reliability. When considering the method selection in specific scenarios, the timely maintenance strategy should be applied in scenarios with high requirements for cluster task reliability, and the group maintenance method considering mission reliability should be applied in scenarios with high requirements for maintenance cost.

In addition, under the group maintenance strategy, different group strategies can be selected to meet the different requirements for maintenance cost and system mission reliability during mission execution.

The time and space complexity of this method is calculated as follows: Assuming that there are n drones in the whole mission cycle of the swarm that need to be maintained. Then the nodes of the swarm need to be removed in sequence for a single calculation of the robustness parameter under a limited number of maintenance opportunities, and the time complexity is $O(n) \times O(n)$, so the total time complexity of the algorithm is $O(1)$. The process needs to establish a one-dimensional data space, and the space complexity is $O(n)$.

5. Case Study

This section will take a widely used drone swarm performing a long-endurance tour mission as an analysis case and formulate an optimal group maintenance strategy to maximize the mission reliability of the swarm system.

In this case, the drone swarm adopts the control structure of the distributed pilot method (wolves). The swarm system is divided into five sub-mission swarm, each with 20 single drones (including one central drone with communication relay and distributed decision center functions and 19 mission execution drones), totaling 100. According to the theory of each multi-layer complex network. There are a total of 300 unit nodes. The distributed link relationship of the communication network between every single node is shown in Figure 12.
Among them, one communication relay drone in each group of drones establishes a communication link connection with all drones in the sub-swarm. The drones in the group establish connections randomly, and five communication relay drones are used in pairs. Establish connections to each other to form the network topology of the entire swarm.

The three-layer complex network model established according to the drone node connection diagram is shown in Figure 13.

This drone swarm performs three missions in its life cycle, with three mission profiles. The missions will be performed in a particular order. The sequence is shown in Figure 14, and missions 1, mission 2, and mission 3 are executed each cycle. Among them, the single execution time of mission 1 is 60 min, the single execution time of mission 2 is 120 min, and the single execution time of mission 3 is 180 min. The number of working cycles is 10, so the working time limit is 3600 min, and the maintenance opportunities of the drone swarm system are 60 min, 180 min, 360 min, …, 3600 min, a total of 30 maintenance nodes.

![Figure 12. Distributed connection diagram between individual nodes.](image1)

![Figure 13. Three-layer complex network model.](image2)

![Figure 14. Mission profile sequence.](image3)
According to empirical data and observation data, it is assumed that the structural layer nodes, communication layer nodes, and mission layer nodes of the drone swarm obey exponential distribution, Weibull distribution, and inverse Gaussian distribution, respectively. Figure 15 shows the single-node prevention-based maintenance time distribution map generated by random distribution.

![Node failure time distribution](image)

**Figure 15.** The distribution of maintenance time based on prevention for a single node.

According to the prevention-based maintenance node distribution and maintenance node time of each node, multiple groups of maintenance grouping decisions can be obtained. Taking a group decision as an example, the number of drones for maintenance under each maintenance opportunity is shown in Figure 16.

![Node distribution under maintenance opportunity](image)

**Figure 16.** Distribution of maintenance nodes corresponding to maintenance opportunities.

In each maintenance opportunity, the maintenance node is regarded as the node removed. Under the nodes with different maintenance times, the mission reliability value of the swarm system with the maintenance node removed is considered. The mission reliability change diagram of the swarm system under the total mission time is obtained, as shown in Figure 17.
Aiming at the problem that the traditional unit maintenance method cannot meet the mission reliability requirements of the drone swarm system, a mission-oriented system maintenance grouping method is proposed in this paper.

According to the mission reliability evaluation results, the maintenance plan at 1800 min and 2880 min after the mission start leads to a sudden drop in the reliability of the swarm system.

Given this problem, the diversity of group maintenance schemes is used to repair some nodes in advance or lag in forming an optimized maintenance scheme and evaluate the reliability of system missions, as shown in Figure 18.

Optimizing the maintenance plan has a significant positive impact on the reliability of the drone swarm system. The maintenance plan can be further optimized for different drone mission requirements, reflecting the critical advantages of swarm group maintenance. Combined with the maintenance cost of the drone swarm, the optimal solution can be formulated and applied to the actual swarm maintenance research.

6. Conclusions

Aiming at the problem that the traditional unit maintenance method cannot meet the maintenance requirements of the complex swarm system, a mission-oriented system maintenance grouping method is proposed in this paper. Based on many maintenance groups proposed based on the failure model of drone functional nodes, complex network modeling and evaluation methods are used as tools. According to the topology information of the swarm network, the maintenance effects of the drone are spread to the mission capability changes of the swarm system network. The cost and swarm system mission reliability is the final objective function, and the grouping strategy is optimized.
The method validation and case analysis results show that the complex network method can effectively evaluate system-level reliability, solve the trade-off between cost and system reliability, and ensure the drone swarm system maintenance during mission execution. Swarm missions can be carried out effectively when the node part of the drone maintenance is in progress. Compared with the traditional maintenance method, the maintenance method can significantly save maintenance costs and reduce the number of downtimes while ensuring that the reliability of system missions is less fluctuated. It has the advantage of reducing maintenance costs. The cost increases exponentially. The method is more effective in larger and more complex swarm scenarios.

There are still many challenges to be solved in the future for the research and improvement of this method. For example, when setting the accidental failure model, the mission’s real-time mission environment and accidental conditions can be considered, the failure model information can be updated in real time, and the strategy can be adjusted.

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