Reliability Engineering and System Safety 215 (2021) 107879

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Mission reliability modeling of UAV swarm and its structure optimization based on importance measure

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ARTICLE INFO

Keywords:
Reliability
Structural optimization
UAV swarm
Importance measure

ABSTRACT

The mission reliability of an unmanned aerial vehicle (UAV) swarm is the capability of the swarm to complete its intended missions under specified operating conditions for a specified period of time. In order to achieve high mission reliability, the optimal structure of UAV swarm needs to be determined when some UAVs fail during the mission. In this paper, the mission reliability and structure optimization of UAV swarm are studied based on importance measure. Firstly, the mission reliability model of the UAV swarm based on polygonal linear consecutive-*k*-out-of-*n*: F systems is proposed. Secondly, based on the importance measures, the performance of the UAV swarm given different reliability of a UAV at different locations is analyzed. Thirdly, with the three indicators, namely conditional reliability, conditional failure rate, remaining useful life, the structure optimization of UAV swarm during the mission process is analyzed. Numerical examples of triangular and quadrilateral UAV swarms are given to demonstrate the proposed method. The proposed model and metric can be used to support mission planning and the design of a UAV swarm.

1. Introduction

1.1. Background

With the advent of intelligence era, there is an increasing interest in the use of unmanned aerial vehicles (UAVs) for both civil and military applications. Particularly in military applications, the missions suitable for UAVs are diverse, including reconnaissance, surveillance, communications relay, marine search and rescue, damage assessment and etc. As the battlefield becomes more complex, it is difficult for a single UAV to complete complex combat missions due to limited reconnaissance scope and/or damage ability. The number of UAVs required for completing the assigned mission has gradually developed from single UAV to multiple UAVs. Multiple UAVs can expand the mission capability of the single UAV and the overall combat effectiveness. In addition, the low cost of UAV provides a cost-effective strategy for air defense breakthrough, as the air defense missiles are far more expensive.

UAV swarm is a group of numerous UAVs perform tasks in a self-organized and self-adaptive manners, to achieve an overall mission objective. It is a system that achieves the overall task through real-time data sharing, dynamic networking and coordination among UAVs. Under the advantages of quantity and scale, they can combine different functional models according to the type of missions. Thus, the swarm has stronger survivability, scalability, and diversity.

Because the UAV swarm itself has a certain degree of redundancy, in the face of a complex and highly confrontational battlefield environment, the advantage of scale enhances the swarm with better survivability and can ensure the mission's success rate. Even if some UAVs fail or crash due to their own failures, external environment, enemy interference and other factors, the swarm system can still complete the task. The linear formation of UAV swarm is equivalent to a one-dimensional swarm that can be fitted to a consecutive- k -out-of- n: F system, while the rectangular formations of UAV swarm is equivalent to a two-dimensional swarm and can be fitted to a consecutive- (r, s)-out-of-(m, n): F system. If it is ensured that there is no consecutive k or (r, s) rectangular areas in the UAV swarm, the swarm will continue to complete the mission.

The mission reliability of the UAV swarm is the ability of the swarm complete the specified tasks in the specified task time and the specified task environment. The main difference between the mission reliability of

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https://doi.org/10.1016/j.ress.2021.107879
Received 13 June 2020; Received in revised form 29 April 2021; Accepted 10 June 2021
Available online 16 July 2021
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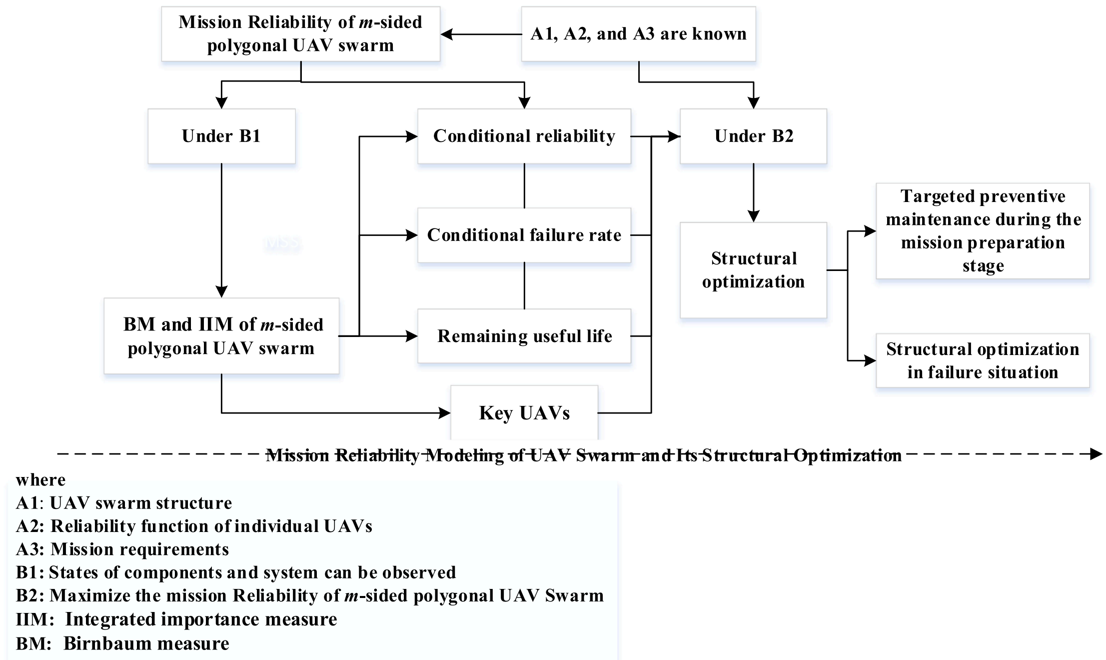

Fig. 1. Novelty and contribution in this paper.

UAV swarm and traditional system reliability is the transition from platform-centric reliability evaluation to task-centric reliability evaluation. Traditional system reliability is more inclined to analyze the influence of the reliability of the components on the system reliability. The topology of the system is often assumed to be fixed. However, the UAV swarm are required to perform various types of missions. The topology of the UAV swarm will change as the position of each individual UAV changes under different missions or mission phases.

In addition, when the components in the system fail due to external damage or degradation of self-performance, the traditional system reliability can only be improved through subsequent maintenance to restore the system from the failure state to the working state. However, UAV swarm is a group of numerous UAVs perform tasks in self-organized and self-adaptive manners. When some UAVs fail or crash due to their own failures, external environment and enemy interference, the UAV swarm can still restore its mission reliability to a certain level through dynamic adjustment and self-restructuring. Upon such reconfiguration of swarm topology, the swarm is able to continue its mission. Thus, it is necessary to extended the tradition system reliability to the mission reliability for UAV swarm.

With the increasing size of the UAV swarm, some recent works have studied the mission reliability of cooperative UAVs. Yang et al. [1] studied a balance between mission reliability and system survivability through a case study of UAVs performing grid inspection tasks. They designed the optimal mission abort policies based on the information of early-warning signals, which indicate the possible forthcoming fatal malfunction. Qiu et al. [2] further proposed degradation-based abort policy and duration-based abort policy. The mission success probability and system survivability under these two policies are evaluated and the optimal mission abort thresholds balancing the tradeoff between the mission success probability and system survivability are investigated. Ning et al. [3] proposed a two-layer mission planning model based on simulated annealing algorithm and tabu search algorithm. This method can greatly improve the survivability of UAVs while ensuring maximum mission reliability. Cao et al. [4] improved mission reliability by optimizing the UAVs reconnaissance path. However, there is a lack of research on how to self-adjust to improve mission reliability when the UAV swarm fails to perform tasks. Because the UAV is often required to carry out dangerous missions in hazardous circumstances, it is important to provide an accurate prediction on the mission reliability of the UAV swarm. Therefore, it is important to evaluate and predict the mission reliability of UAV swarms in a denied environment, which can be used for mission planning, decision making.

Regarding the reliability of the UAV swarm, Prescott et al. [5] first studied this problem and proposed a reliability analysis method using binary decision diagrams and phased-missions techniques. In order to response to changes of mission planning as quickly as possible, Andrews et al. [6] proposed two strategies to speed up the mission reliability prediction for UAV. Prescott et al. [7] considered the mission performed by several autonomous systems and proposed a method to predict the mission reliability by extending the binary decision diagrams techniques. For the reliability of UAV swarms, Guo and Elsayed [8] proposed the reliability modeling and estimation of the multi-level balanced UAV for the continuous system and performed a series of studies on fitting the UAV swarm to a consecutive- k -out-of- n: F/G system or a consecutive-(r, s)-out-of- (m, n): F/G system. Liu et al. [9] studied the effects of system reliability and mission uncertainty on patrol and target recognition missions on UAV performance. Given that UAV swarm is a type of reconfigurable system, Zhao et al. [10] proposed an integrated method to improve the reconfigurable system reliability cost-effectively, combining the advantages of the rearrangement method and replacement method.

The linear formation of the UAV swarm is equivalent to a one-dimensional swarm, which can be fitted as a consecutive- k -out-of- n: F system. For the consecutive- k -out-of- n: F system, Lin et al. [11] proposed a consecutive- k_r -out-of- n_r : F system model with shared nodes, and gave the reliability calculation formula. Zhu et al. [12] analyzed the importance of joint reliability of components related to Markov in multiple consecutive- k -out-of- n: F system. Zhao et al. [13] proposed a new more efficient method, which reduces the size of the state space by combining some states into one state. It is presented to reduce the computing time. For the exact reliability evaluation of k-out-of-n systems with identical components subject to phased-mission requirements and imperfect fault coverage, Xing et al. [14] proposed the method based on the total probability law, conditional probabilities, and an efficient recursive formula to compute the overall mission reliability

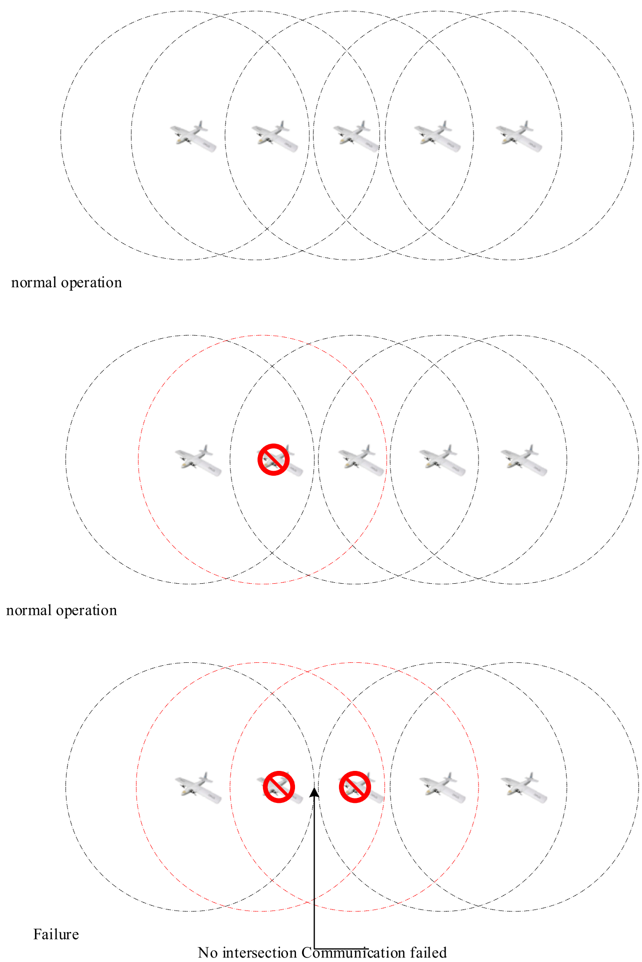

Fig. 2. Failure model for UAV swarm.

with the consideration of imperfect fault coverage. However, UAVs swarm can also perform tasks in two-dimensional forms such as triangles and quadrilaterals. Therefore, it is necessary to generalize the mission reliability model of current UAV swarm into polygonal formation.

For a system, the determination of key components plays a guiding role for system optimal design. Through the importance analysis, the key UAVs in the UAV swarm can be determined. Dui et al. [15] proposed an analysis of the importance of the optimal structure of consecutive- k -out-of- n: F system. Based on Birnbaum importance measure, Zuo et al. [16] proposed an evidential network model to assess system reliability with interval valued probabilistic common cause failures and epistemic uncertainty associated with components^{\prime} state probabilities. For network systems, the failure of key components can cause cascaded failure of the system [17-19]. Some research has been done on the fault detection and prognosis of UAV swarms [20-23]. For the remaining useful life prediction and prognosis of the UAV swarm, Nick et al. [24] discussed the remaining life prediction in six random flights starting from a fully charged battery. Several special indicators are used to evaluate the performance of the prognostic algorithm, and the relevant prognostic capabilities potential conclusion. For a redundant system such as a UAV swarm, it is necessary to control the cost. Zhu et al. [25] considered a tradeoff between cost and reliability in order to pursue the cost-effective optimal design. The relationships between the total cost and corresponding parameters are discussed thoroughly. For the evaluation the resilience of a UAV swarm, Bai et al. [26] proposed an improved UAV swarm model by incorporating the effect of limited communication range into the existing model. A UAV swarm mitigates the effects of possible threats and disruptions via self-adaptation.

1.2. Motivation

Given the existing literatures, it can be seen that the importance measures have not been studied and used for optimal allocation of UAV swarm. When some UAVs fail, the optimal structure of UAV swarm may be changed. It is important to identify the important UAVs in the swarm and determine the optimal structure of UAV swarm.

(1) The above-mentioned literature lacks the mission reliability models of UAV swarm with the specific formations.
(2) The above-mentioned literature lacks the determination of the key UAVs in the UAV swarm.
(3) They lack of guidance on the performance improvement for the UAV swarm. More importantly, they lack of guidance on how to optimize the structure if some UAVs fail during the mission.

In response to the above problems, this paper proposes corresponding solutions and Fig. 1 shows the novelty and contributions in this paper.

(1) The mission reliability model of the UAV swarm with polygonal formation is developed based on consecutive- k -out-of- n: F system. Based on the mission reliability model, the two importance measures, namely Birnbaum importance and integrated importance measure of the UAV swarm are given.
(2) We combine the two importance models to analyze the importance measure of UAVs in different locations in the UAV swarm and find the UAVs with higher importance measure in the swarm. Then the key UAVs and weak links of the UAV swarm are determined. On the other hand, combining mission reliability and importance measure, the remaining useful life of UAV swarm based on the mission reliability can be predicted.
(3) During the phase between two missions, limited resources are used to maintain key UAVs to maximize the overall reliability and average remaining life of the swarm. If there are some UAVs fail or damaged in the mission, the mutual change and repositioning among UAVs is implemented. This mechanism is to ensure that the UAVs in key positions are function properly, which maximize overall mission reliability and extend the average remaining life of the swarm.

1.3. Overview

The rest of the paper is organized as follows. Section 2 establishes the reliability model of the polygonal UAV swarm and two importance models of Birnbaum importance and integrated importance measure. Section 3 gives key indicators and structural optimization of UAV swarms. Section 4 uses numerical examples to verify the correctness and effectiveness of the proposed method. Section 5 summarizes the full text and subsequent prospects.

2. UAV swarm reliability modeling

In this section, we first give the mission reliability model of UAV swarm based on consecutive voting system with two dimensions. Then, two importance measures, namely Birnbaum importance and integrated importance measure, are introduced for UAV swarm.

2.1. UAV swarm reliability model

The focus of reliability on the UAV swarm has switched from the platform-centered reliability to mission-centered reliability. Thus, the reliability of the UAV swarm is indeed its mission reliability. Given the definition of UAV swarm, the mission reliability of a UAV swarm is the probability of the swarm to complete its intended missions under specified operating conditions for a specified period.

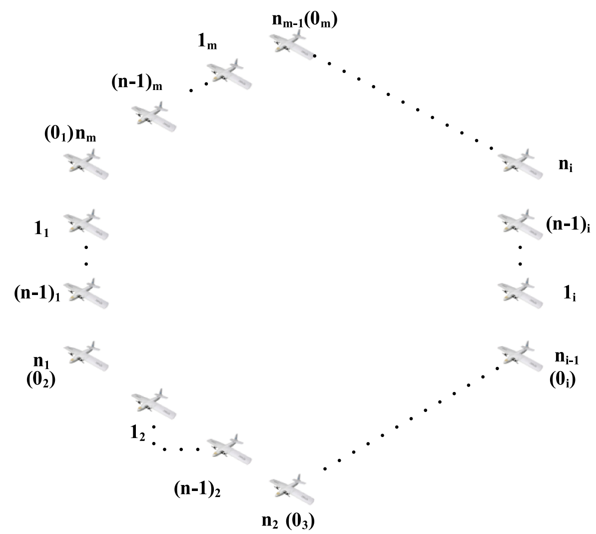

Fig. 3. m-sided UAV swarm.

UAV swarm consists of numerous UAVs carrying out missions in a self-organized and self-adaptive manners. In order to be self-organized, each UAV must be capable of communicating with each other. Currently, this is done through wireless network. Note that the effective range of wireless communication is limited. In order to improve the overall communication reliability, the UAVs often formed as a linear or circular spatial distributed system, in which each UAV can communicate the closest 1 or 2, or k UAVs.

As shown in Fig. 2, the UAV swarm contains n UAVs which are function properly at the beginning of the mission. In order to complete the mission, at most consecutive k-1 UAVs can be failed at the end of the mission. In order to be self-organized, each UAV must be capable of communicating with each other. In order to improve the overall communication reliability, the UAVs are formed as a linear or circular spatial distributed system, in which each UAV can communicate the closest k UAVs. It indicates the UAV can communicate with $k/2$ UAVs from one side and $k/2$ UAVs from another side. The meaning of the dashed circle is the communication range of the UAV. If the communication range shared by any two UAVs, that is, the dashed circles have the intersection, it is considered that the two UAVs can communicate normally without failure. Thus, the failed UAVs could not consecutively reach k UAVs. If k or more UAVs failed in succession, there will be a communication interruption leading to the failure of the UAV swarm. We further assume that the UAVs on the node position can communicate adjacent UAVs from each side. However, the UAVs on different sides cannot communicate with each other because of communication protocol issues. Another scenario that suits for this model is for UAV swarm to perform a light show. UAV swarms form various shapes through different polygon formations. In this scenario, in order to increase the mission reliability, the UAVs on each side is redundantly designed so that individual UAV failure of the UAV will not affect the overall effect of the show. However, if successive UAVs fail, the shape will not be visible, which will cause the mission to fail.

The linear formation of the UAV swarm is equivalent to a one-dimensional swarm. It can be fitted to a consecutive- k -out-of- n: F system. When m linear formations are combined, an m-sided polygonal UAV swarm can be formed. The linear UAV formation on the side has the same node UAV.

In recent years, Cui et al. [27] and Lin et al. [11] have used the finite Markov chain imbedding approach to obtain the reliability evaluation equation of a consecutive- k -out-of- n: F system. For the linear consecutive- k -out-of- n: F system, through the finite Markov chain embedding method a Markov chain $\{Y(t), t = 0, 1, 2...\}$ can be obtained with finite state space $S = \{0, 1, ..., k\}$.

$$S = \begin{cases} 0, \\ j(j = 1, 2, \dots k-1) \\ k \end{cases}$$

where 0 represents the component i is working, j represents component $(i-j+1), (i-j+2), ..., i$ is failed and k represents there is at least consecutive k failed components. Matrix Λ_i is the state transition probability matrix of component i, where p_i represents the probability that component i works normally.

$$\Lambda_i = \begin{bmatrix} p_i & 1-p_i & 0 & \cdots & 0 \\ p_i & 0 & 1-p_i & \ddots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_i & 0 & \cdots & 0 & 1-p_i \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}_{|k+1| \times |k+1|} , (i = 1, 2, ...n).$$

Then each component is embedded into the system one by one by the finite Markov chain embedding method. The reliability equation of the consecutive- k -out-of- n: F system is obtained:

$$R = \pi_0 \prod_{i=1}^{n} \Lambda_i U^T \tag{1}$$

$\pi_0 = (1, 0, ..., 0)_{1\times|k+1|}$ is the probability distribution of the initial state of the system. $\pi_1 = (0, 1, ..., 0)_{1\times|k+1|}$ and so on. The matrix $U = (1, 1, ..., 1, 0)_{1\times|k+1|}$ is to sum the probabilities of the system in working state.

As shown in Fig. 3, m linear formation UAV swarms are connected to form an m-side UAV swarm. The first UAV on each side is recorded as 0_r and is also the nth UAV on the previous side recorded as n_r. For the m-sided polygonal UAV swarm, the UAV n_r at the node position is the most critical, which affects the reliability of the rth and r + 1th UAV sequences, where when $r = m$, it affects mth and first UAV sequence. Regarding the reliability of the m-sided UAV swarm, it can be regarded as a system of m consecutive- k -out-of- n: F system. And the product of the reliability of these systems is the reliability of the polygon UAV swarm. Since node UAVs affect different sequences of UAV sequences, their reliability status as a shared node is extremely important. Aiming at the consecutive- k -out-of- n: F system of shared nodes, Lin et al. [11] gave the reliability calculation formula. Combined with m-sided UAV swarm, we can get:

I. When component n_{r-1} and component n_r are working normally

$$R_{A_r} = p_{n_r} \pi_0 \prod_{i=2_r}^{(n-1)_r} \Lambda_i U^T \tag{2}$$

%1 II. When component n_{r-1} fails and component n_r works normally

$$R_{B_r} = p_{n_r} \pi_1 \prod_{i=2_r}^{(n-1)_r} \Lambda_i U^T \tag{3}$$

%1 III. When component n_{r-1} works normally and component n_r fails

$$R_{C_r} = \begin{cases} \sum\limits_{l=n_r-k_r+1}^{(n-1)_r} \left[p_l \prod\limits_{j=l+1}^{n_r} (1-p_j) \pi_0 \prod\limits_{i=1_r}^{l-1} \Lambda_i U^T \right], k_r \le \dfrac{n_r}{2} \\ \sum\limits_{l=k_r+1}^{(n-1)_r} \left[p_l \prod\limits_{j=l+1}^{n_r} (1-p_j) \pi_0 \prod\limits_{i=1_r}^{l-1} \Lambda_i U^T \right] + \sum\limits_{l=n_r-k_r+1}^{k_r} \left[p_l \prod\limits_{j=l+1}^{n_r} (1-p_j) \right], k_r > \dfrac{n_r}{2} \end{cases} \tag{4}$$

%1 IV. When component n_{r-1} and component n_r fail

$$R_{D_r}=\begin{cases}\sum_{l=n_r-k_r+1}^{(n-1)_r}\left[p_l\prod_{j=l+1}^{n_r}(1-p_j)\pi_1\prod_{i=1_r}^{l-1}\Lambda_i U^T\right], k_r\le\frac{n_r}{2}\\ \sum_{l=k_r+1}^{(n-1)_r}\left[p_l\prod_{j=l+1}^{n_r}(1-p_j)\pi_1\prod_{i=1_r}^{l-1}\Lambda_i U^T\right]+\sum_{l=n_r-k_r+1}^{k_r}\left[p_l\prod_{j=l+1}^{n_r}(1-p_j)\right], k_r>\frac{n_r}{2}\end{cases} \tag{5}$$

When $m = 4$, for quadrilateral UAV swarm, the four-node UAVs are n_1, n_2, n_3, n_4. For the four-node UAVs, there are two states, normal operation, and failure. So, there are 16 situations. Such as:

a When n_1, n_2, n_3, n_4 are working normally, the reliability equation of quadrilateral UAV swarm is: $R = R_{A_1}R_{A_2}R_{A_3}R_{A_4}$.
b When n_1 and n_3 work normally, n_2 and n_4 fail, the reliability equation is: $R = R_{B_1}R_{C_2}R_{B_3}R_{C_4}$.
c When n_3 works normally, n_1,n_2 and n_4 fail, the reliability equation is: $R = R_{D_1}R_{D_2}R_{B_3}R_{C_4}$
d When n_2,n_3 and n_4 work normally, n_1 fails, the reliability equation is: $R = R_{C_1}R_{B_2}R_{A_3}R_{A_4}$

2.2. UAV swarm importance measure

For a consecutive- k -out-of- n: F system, Papastavridis [28] proposed the Birnbaum importance measure of component i at time t as:

$$\begin{aligned}I(BM)_i^t &= \frac{\partial R_{k/n}^t}{\partial p_i(t)} = R_{k/n}^t(X_i(t)=1) - R_{k/n}^t(X_i(t)=0)\\ &= \frac{R_{k/i-1}^t R'^{\,t}_{k/n-i} - R_{k/n}^t}{1-p_i(t)}\end{aligned} \tag{6}$$

where $R_{k/n}^t$ is the reliability of the consecutive- k -out-of- n: F system at time t. $R_{k/i-1}^t$ is the reliability of the consecutive- k -out-of- i-1: F system (composed of component $1, 2, ..., i-1$) at timet $R'^{\,t}_{k/n-i}$ is the reliability of the consecutive- k -out-of- n-i: F system (composed of components $n-i+1, n-i+2, ..., n-1, n$) at time t.

For component i, the reliability of the system is:

$$\begin{aligned}R = p_i(R(p_1,...,p_{i-1},1,p_{i+1},...,p_n) - R(p_1,...,p_{i-1},0,p_{i+1},...,p_n))\\ +R(p_1,...,p_{i-1},0,p_{i+1},...,p_n)\end{aligned} \tag{7}$$

And for the consecutive- k -out-of- n: F system:

$$R(p_1,...,p_{i-1},1,p_{i+1},...,p_n) = R(p_1,...,p_{i-1})R(p_{i+1},...,p_n) = R_{k/i-1}R'_{k/n-i} \tag{8}$$

According to the definition of Birnbaum importance of component i:

$$I(BM)_i = R(p_1,...,p_{i-1},1,p_{i+1},...,p_n) - R(p_1,...,p_{i-1},0,p_{i+1},...,p_n) \tag{9}$$

Combining the above Eqs (7) (8) (9), the Birnbaum importance equation of the component i at time t can be obtained.

Since 2012, Dui et al. [29-31] have proposed and expanded the integrated importance measure of component states, which evaluates how changes in component states affect system performance. For the consecutive- k -out-of- n: F system, the integrated importance measure of component i at time t is defined as:

$$I(IIM)_i^t = \Pr\{X_i(t)=1\}\cdot\lambda_i(t)\cdot I(BM)_i^t = p_i(t)\cdot\lambda_i(t)\cdot\frac{R_{k/i-1}^t R'^{\,t}_{k/n-i} - R_{k/n}^t}{1-p_i(t)} \tag{10}$$

For non-node UAVs, there is an importance measure for the UAV sequence, and the UAV sequence has an importance measure for the overall UAV swarm. So, the Birnbaum importance of the certain non-node positions UAV to the polygonal UAV swarm is:

$$I(BM)_{nn}^t = \frac{\partial R^t}{\partial p_i(t)} = \frac{\partial R^t}{\partial R^{rt}}\cdot\frac{\partial R^{rt}}{\partial p_i(t)} \tag{11}$$

where the R^{rt} is the reliability of the rth UAV sequence at the time t. Where $\frac{\partial R^t}{\partial R^{rt}} = \prod_{l=1\&l\neq r}^{m} R^{lt}$ is the reliability product of the UAV sequences different from sequence r, and $\frac{\partial R^{rt}}{\partial p_i(t)}$ is the Birnbaum importance of component i at time t in the consecutive- k -out-of- n: F system,

$$\frac{\partial R^{rt}}{\partial p_i(t)} = \frac{R_{k/i-1}^{rt} R'^{\,rt}_{k/n-i} - R_{k/n}^{rt}}{1-p_i(t)} \tag{12}$$

Combining Eq (11) and (12), the Birnbaum importance equation of a non-node UAV is:

$$I(BM)_{nn}^t = \prod_{l=1\&l\neq r}^{m} R^{lt}\cdot\frac{R_{k/i-1}^{rt} R'^{\,rt}_{k/n-i} - R_{k/n}^{rt}}{1-p_i(t)} \tag{13}$$

Combining Eq (10) and (13), the integrated importance measure equation of a non-node UAV is:

$$I(IIM)_{nn}^t = p_i(t)\cdot\lambda_i(t)\cdot\prod_{l=1\&l\neq r}^{m} R^{lt}\cdot\frac{R_{k/i-1}^{rt} R'^{\,rt}_{k/n-i} - R_{k/n}^{rt}}{1-p_i(t)} \tag{14}$$

There are two importance measures for the node UAV relative to the two UAV sequences. Therefore, the impact on the polygon UAV swarm will be reflected in the two UAV sequences. Combined with the non-node UAV importance equation, the Birnbaum importance of the node UAV to the polygonal UAV swarm is:

$$\begin{aligned}I(BM)_n^t &= \frac{\partial R^t}{\partial p_{0/n}(t)} = \frac{1}{2}\left(\frac{\partial R^t}{\partial p_n(t)} + \frac{\partial R^t}{\partial p_0(t)}\right)\\ &= \frac{1}{2}\left(\frac{\partial R^t}{\partial R^{rt}}\cdot\frac{\partial R^{rt}}{\partial p_n(t)} + \frac{\partial R^t}{\partial R^{(r+1)t}}\cdot\frac{\partial R^{(r+1)t}}{\partial p_0(t)}\right)\end{aligned} \tag{15}$$

where $p_{0/n}(t)$ stands for $p_0(t)$ or $p_n(t)$. The $p_0(t)$ represents the reliability of the first UAV in a UAV sequence. The $p_n(t)$ represents the reliability of the last UAV in a UAV sequence. Because of the node position, the UAV is the last UAV in the previous UAV sequence and the first UAV in the latter UAV sequence. It has same effects on the two UAV sequences, so the average value is used to calculate its importance measure to the entire UAV swarm.

Therefore, the Birnbaum importance equation of the node UAV is:

$$I(BM)_n^t = \frac{1}{2}\left(\prod_{l=1\&l\neq r}^{m} R^{lt}\cdot\frac{R_{k/n-1}^{rt} - R_{k/n}^{rt}}{1-p_n(t)} + \prod_{l=1\&l\neq r+1}^{m} R^{lt}\cdot\frac{R'^{\,(r+1)t}_{k/n-1} - R_{k/n}^{(r+1)t}}{1-p_0(t)}\right) \tag{16}$$

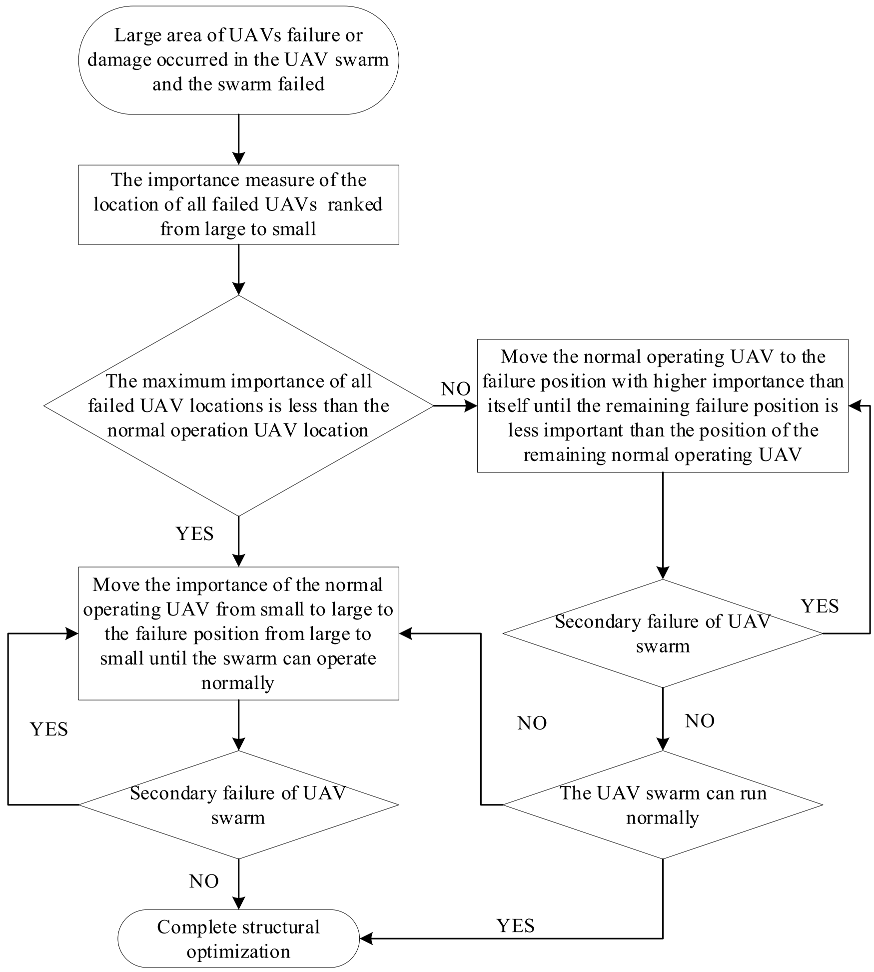

Fig. 4. Structural optimization flow chart.

the integrated importance measure equation of the node UAV is:

$$I(IIM)_n^t = \frac{1}{2}\left(p_n(t)\cdot\lambda_n(t)\cdot\prod_{l=1\&l\neq r}^{m} R^{lt}\cdot\frac{R_{k/n-1}^{rt}-R_{k/n}^{rt}}{1-p_n(t)}+p_1(t)\cdot\lambda_1(t)\cdot\prod_{l=1\&l\neq r+1}^{m} R^{lt}\cdot\frac{R'^{(r+1)t}_{k/n-1}-R_{k/n}^{(r+1)t}}{1-p_0(t)}\right) \tag{17}$$

3. Structure optimization of UAV swarm based on importance measures

According to the importance measure, the location of the key UAVs in the polygonal UAV swarm can be identified. The status monitoring of the UAVs can provide useful information on the current and future health status of the drones. This information is usually transmitted through some key performance indicators. These key indicators can help managers to optimize the structure of UAV swarms. The key indicators discussed in this section include conditional reliability, conditional failure rate and remaining useful life (RUL). These key indicators change with the operation of the drone and external influences. The RUL of the UAV swarm is the length of time until the mission reliability of the UAV swarm is reduced to the threshold value of the mission reliability of the next phase of the mission. The RUL of a single UAV in the UAV swarm has little effect on the mission reliability of the overall UAV swarm. However, the RUL of the UAV swarm has guiding suggestions on whether the UAV swarm can complete the mission. Since the tasks performed by UAV swarms are multi-stage tasks, after each stage of tasks is completed, the mission reliability of the next stage of the UAV swarm needs to be predicted, which is used for mission planning and decision support.

3.1. Conditional reliability

Conditional reliability is an indicator to measure system performance. It represents the probability that the system will continue to run to time t without the failure at time $t_p (t > t_p)$. Moghaddass and Zuo [32] gave the calculation details of the conditional reliability function. Combined with the importance analysis, the conditional reliability of the polygonal UAV swarm can be expressed as:

$$\begin{aligned} R\left(t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) &= \Pr\left(L > t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) \\ &= \frac{\Pr\left(L > t, I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)}{\Pr\left(L > t_p, I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)} \end{aligned} \tag{18}$$

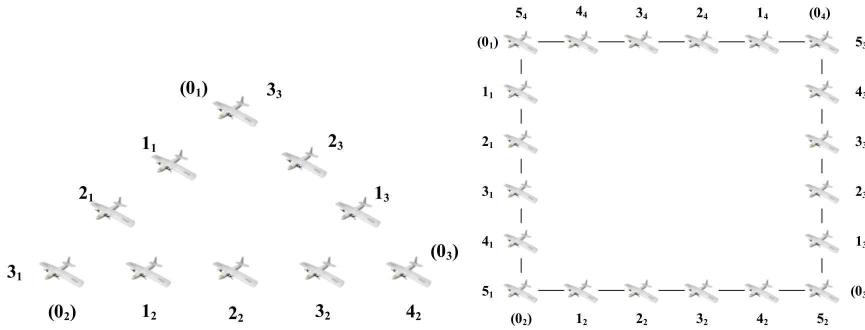

Fig. 5. Triangular and quadrilateral UAV swarms.

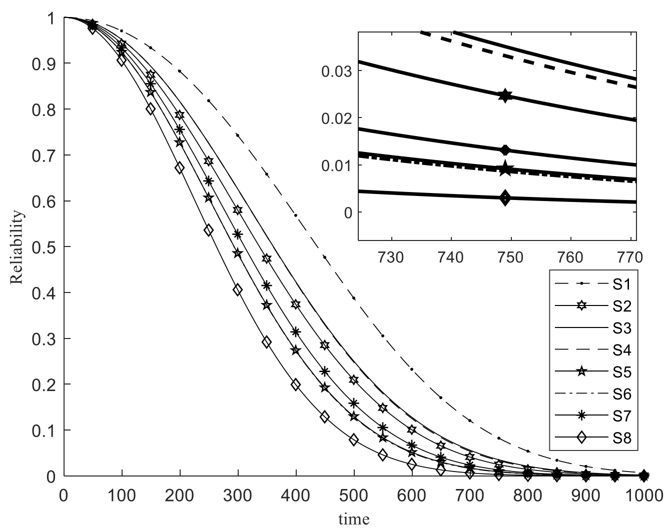

Fig. 6. System reliability of triangular UAV swarm under different node states.

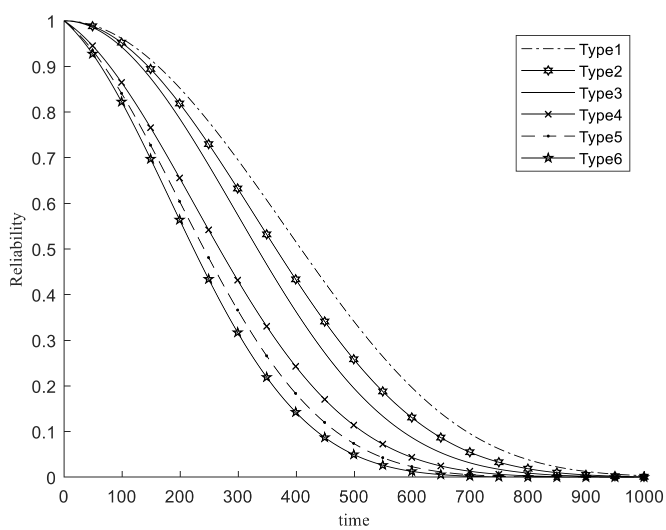

Fig. 7. System reliability of quadrilateral UAV swarm under different node states.

where L is the total life of the system. $I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}$ represents the importance measure of components at time t_p.

3.2. Conditional failure rate

Generally, the system runs normally until time t, and the probability of failure in the unit time after time t is called the failure rate of the system. When the system runs normally to the time t_p without failure, and the importance measure of each component at time t_p is obtained, the probability of failure per unit time after time $t (t > t_p)$ is called the system^{\prime}s conditional failure rate. The conditional failure rate of the polygonal UAV swarm can be defined as:

$$\begin{aligned}\lambda\left(t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) &= \lim_{\tau\to 0}\frac{\Pr\left(t < L < t+\tau|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)}{\Pr\left(L > t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)\tau} \\ &= \lim_{\tau\to 0}\frac{R\left(t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) - R\left(t+\tau|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right)}{\tau R\left(t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right)}\end{aligned} \tag{19}$$

3.3. Remaining useful life

The RUL is one of the important indicators in health monitoring, mainly for systems that will continue to degrade over time. Using the calculated 95% confidence interval of the average RUL as a prognostic indicator can provide a possible range of remaining service life under a certain degree of confidence. It shows a more practical remaining service life. As an important measure of RUL, it is defined as:

$$\begin{aligned}&\Pr\left(RUL < t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right) = \Pr\left(L - t_p < t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) \\ &= \Pr\left(L < t_p + t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right) = 1 - R\left(t_p + t|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)\end{aligned} \tag{20}$$

The average RUL can be calculated as:

$$\begin{aligned}&\overline{RUL}\left(t_p|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right) = E\left[\left(L - t_p\right)|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}, L > t_p\right] \\ &= \int_0^{\infty} R\left(t_p + \tau|I_1^{t_p}, I_2^{t_p}, \ldots, I_n^{t_p}\right)d\tau\end{aligned} \tag{21}$$

3.4. Structure optimization

Faced with a complex and highly confrontational battlefield environment, some UAVs will fail or be damaged due to their own failures, external interference, enemy damage, and other factors. The polygonal UAV swarm is composed of multiple consecutive- k -out-of- n: F system and has a certain degree of redundancy. However, if there is a large area of UAVs failure or damage, it will still directly lead to system reliability degradation or even failure.

The UAV swarm can use limited resources to perform preventive maintenance on the UAVs in a critical position in the swarm during the mission preparation stage. It can improve performance and maximize the reliability of the UAV swarm. In the task execution stage, if a large area of UAV swarm failure or damage occurs locally, there will be one or more edges that cannot meet the requirements of the consecutive- k -out-of- n: F system. Currently, it is necessary to move the UAVs that are still in normal operation under the premise of satisfying the normal operation of consecutive- k -out-of- n: F system. The UAVs that are still in normal operation should be moved to the position of the invalid UAVs according to a certain process. The process is shown in the Fig. 4.

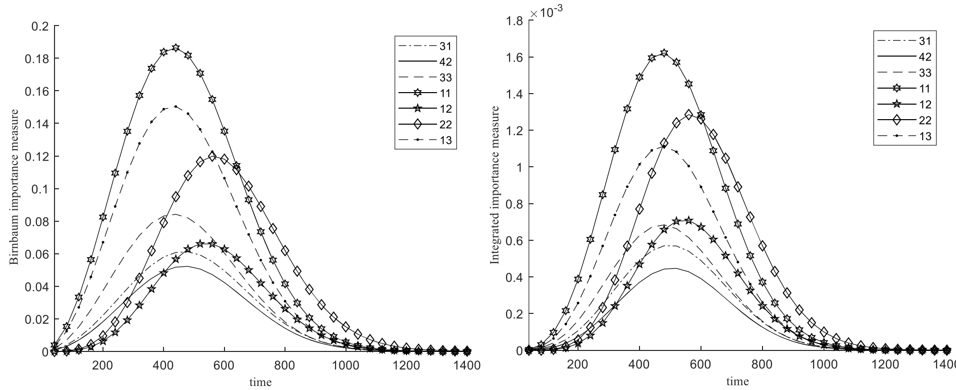

Fig. 8. Birnbaum importance and integrated importance measure of triangular UAV swarm.

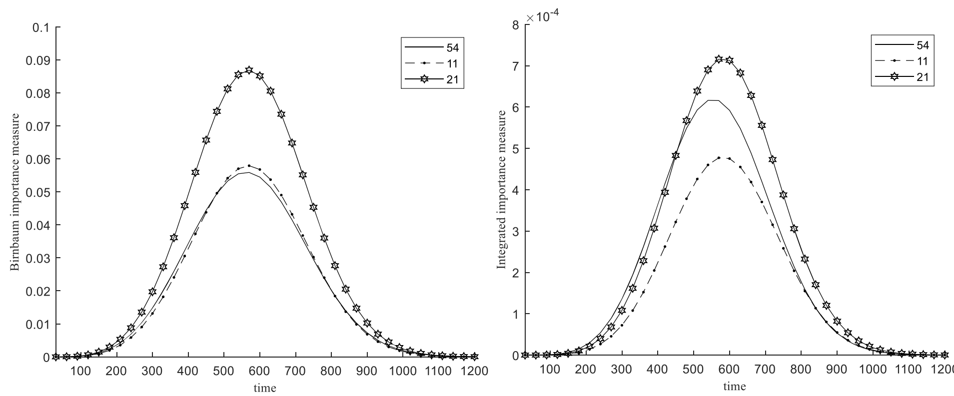

Fig. 9. Birnbaum importance and integrated importance measure of quadrilateral UAV swarm.

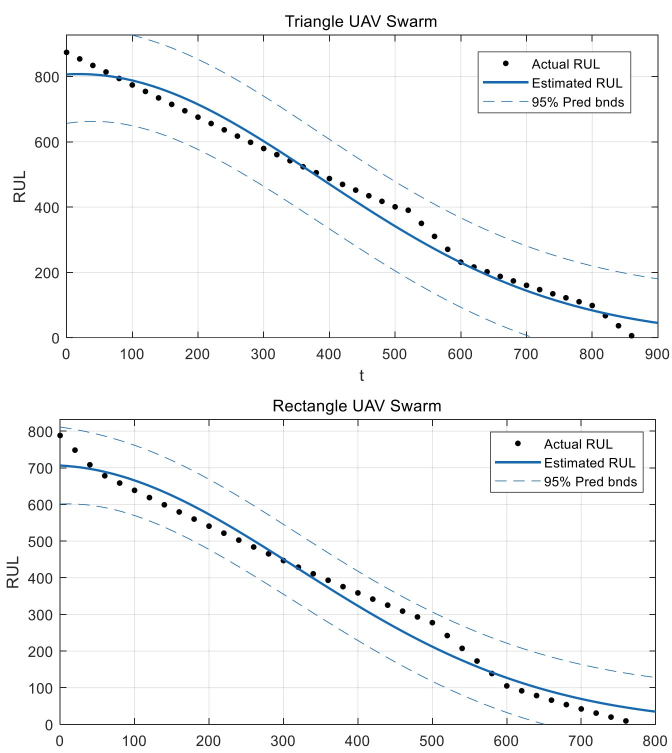

Fig. 10. RUL of triangular and quadrilateral UAV swarm.

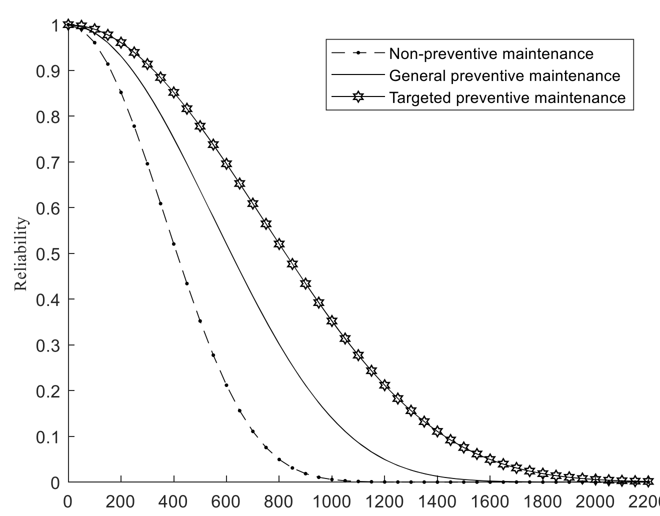

Fig. 11. Reliability changes of different preventive maintenance for polygonal UAV swarm.

Through Eqs (13) (14) (16) (17), the importance of each position in the UAV swarm is calculated for comparison, and the goal is to maximize the function (2) (3) (4) (5) value through structural optimization, which is

$$\max\left(\prod_{r=1}^{m} R_r\right) \tag{22}$$

$$s.t.\begin{cases} R_r \in \{R_{A_r}, R_{B_r}, R_{C_r}, R_{D_r}\} \\ \min\{R_r\} > \xi \end{cases}$$

where R_r is one of the four situations of $R_{A_r}, R_{B_r}, R_{C_r}, R_{D_r}$, and ξ is the reliability threshold of the mission. It is ensured that the reliability of the edge with the least reliability greater than the reliability threshold of the mission. After structural optimization, the reliability of any edge needs to meet the mission reliability threshold, otherwise the mission will fail.

4. Numerical examples

The UAV swarm we consider is a two-dimensional polygon UAV formation composed of multiple consecutive- k -out-of- n: F systems.

where η is the scale parameter and β is the shape parameter. We assume that all UAVs are the same types of UAV, in which their reliability follows the same lifetime distribution, which is Weibull distribution in this case. However, due to manufacturing issue, Ma et al. [34] discussed the mechanism of leading-edge manufacturing error on aerodynamic performance. Cui et al. [35] proposed it is necessary to consider the influence of manufacturing errors in numerical calculations. Therefore, different UAVs have slightly different distribution parameters because of manufacturing errors.

As shown in Fig. 5, the two linear consecutive- 2 -out-of- 4: F system UAV sequences and one linear consecutive- 3 -out-of- 5: F system UAV sequences consist the triangle UAV swarm. There are three shared nodes in the triangular UAV swarm $3_1, 4_2, 3_3$. The three shared nodes have two states: working and failed, so there will be 8 combined states:

$$S = \{(1,1,1),(1,1,0),(1,0,1),(0,1,1),(1,0,0),(0,1,0),(0,0,1),(0,0,0)\}$$

where 1 represents the normal operation of the node, and 0 represents the failure of the node. The swarm reliability function corresponding to the 8 combination states is:

$$S1 = R_{A_1|2/4}R_{A_2|3/5}R_{A_3|2/4}, S2 = R_{B_1|2/4}R_{A_2|3/5}R_{C_3|2/4}, S3 = R_{A_1|2/4}R_{C_2|3/5}R_{B_3|2/4}, S4 = R_{C_1|2/4}R_{B_2|3/5}R_{A_3|2/4}$$
$$S5 = R_{B_1|2/4}R_{C_2|3/5}R_{D_3|2/4}, S6 = R_{D_1|2/4}R_{B_2|3/5}R_{C_3|2/4}, S7 = R_{C_1|2/4}R_{D_2|3/5}R_{B_3|2/4}, S8 = R_{D_1|2/4}R_{D_2|3/5}R_{D_3|2/4}$$

Wang et al. [33] applied the UAV Weibull distributed UAV fading model for numerical simulation. Assuming the life of each UAV obeys the Weibull distribution, its cumulative failure function is:

$$F = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{23}$$

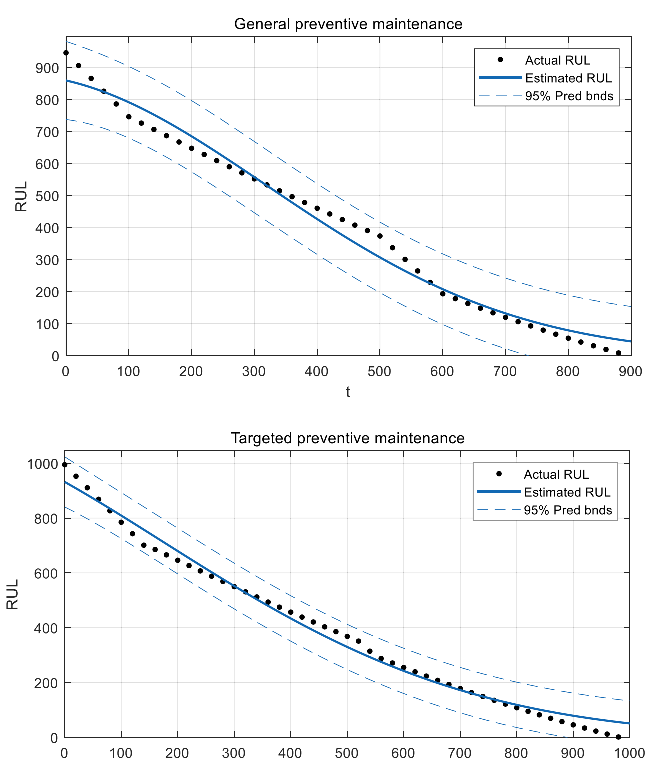

Fig. 12. Changes in RUL of quadrilateral UAV swarm with different preventive maintenance.

Like the triangular UAV swarm, the four linear consecutive- 3 -out-of- 6: F system UAV sequences consist the quadrilateral UAV swarm. There are four shared nodes in the quadrilateral UAV swarm $5_1, 5_2, 5_3, 5_4$. So there are 16 combined states for the quadrilateral UAV swarm. In general, the 16 states are divided into 6 types: 1) All four nodes are working normally 2) Only one node fails 3) Only 2 adjacent nodes fail 4) Only 2 non-adjacent nodes fail 5) Only 3 nodes fail 6) 4 nodes fail.

As shown in Fig. 6, when the nodes are in different states, the reliability of the triangular UAV swarm is different. When the nodes status is different, the system reliability will change from 1 to 0 in different downward trends. This phenomenon shows that the state of the node has a significant effect on the overall performance of the system. In general, the system reliability changes under different node states are:

$$R_{S1} > R_{S3} = R_{S4} > R_{S2} > R_{S6} = R_{S7} > R_{S5} > R_{S8}$$

Although there are obvious size differences, the system reliability can be divided into four levels under different node states. In the first level, all three nodes are running normally. The second level is that there is only one node failure. Because each UAV has differences in the manufacturing process and the environment when performing tasks, different UAVs have different attributes in their own data. Although S2, S3 and S4 are different, it is because different UAVs have different attributes, and the whole still belongs to the same level. Similarly, at the third level, there is only one node operating normally, and at the fourth level, all three nodes fail.

Like the triangular UAV swarm, when the nodes status is different, the system reliability will change from 1 to 0 in different downward trends. The relationship between different types of reliability is:

$$R_{T1} > R_{T2} > R_{T3} > R_{T4} > R_{T5} > R_{T6}$$

The rules it exhibits are like triangular UAV swarms. The more nodes that operate normally, the higher the system reliability.

After the reliability model of the polygon UAV swarm is determined, the importance model of the swarm can be calculated through the reliability model. Due to the high degree of symmetry in the location of the polygonal UAV swarm, only one of the UAVs in the symmetrical position

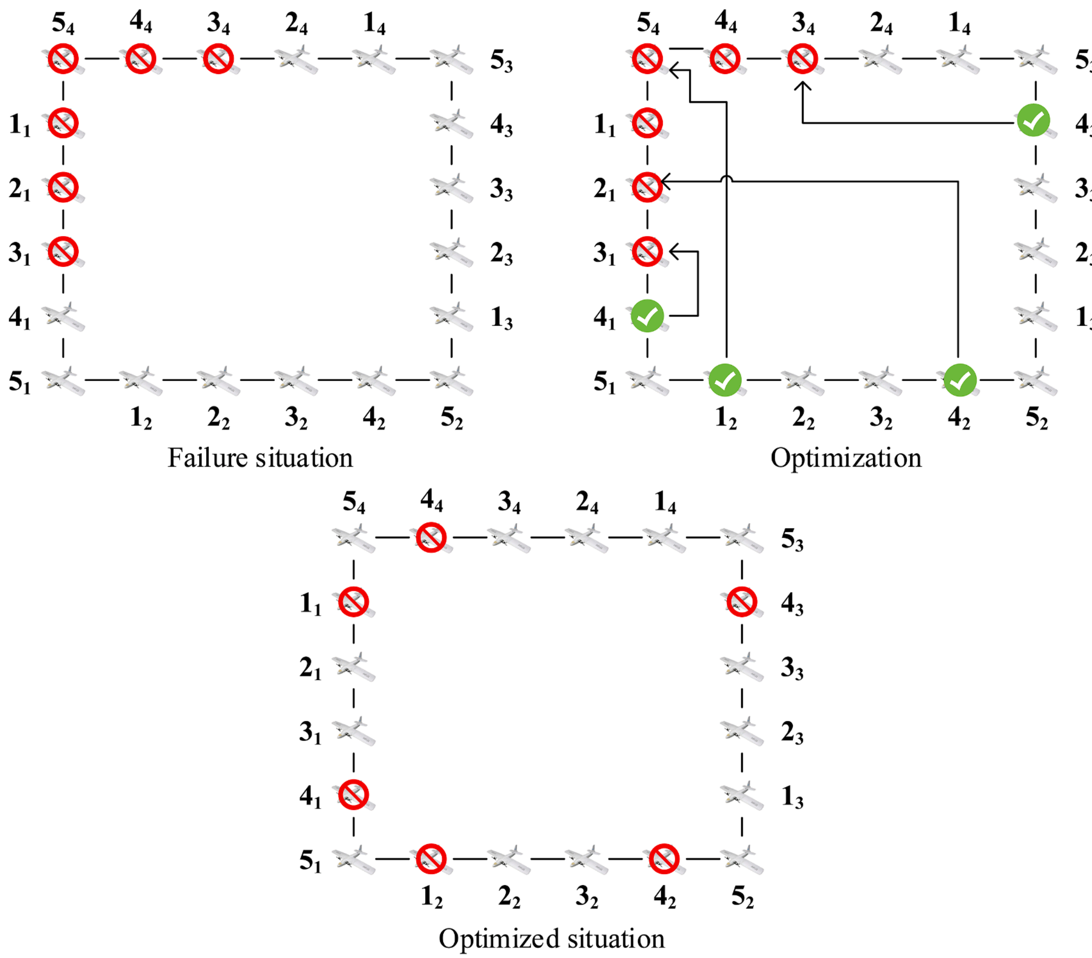

Fig. 13. Failure situation and optimization of quadrilateral UAV swarm.

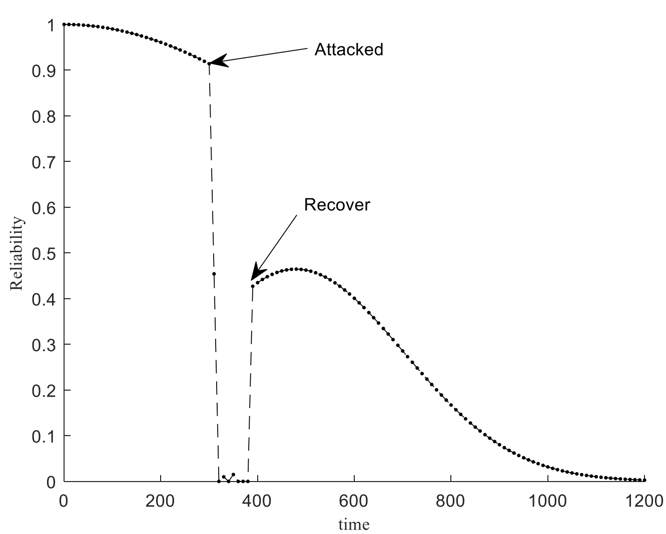

Fig. 14. Reliability changes before and after structural optimization when quadrilateral UAV swarm fails.

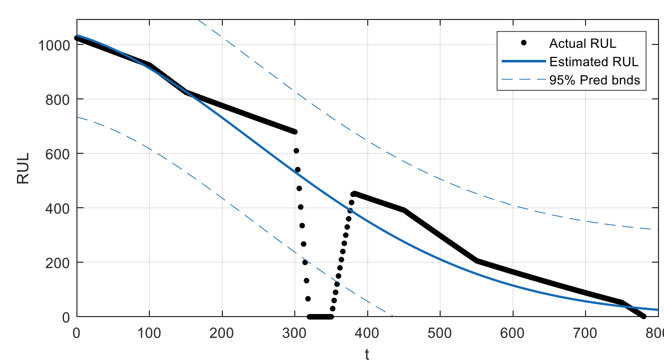

Fig. 15. RUL changes before and after structural optimization when quadrilateral UAV swarm fails.

is selected for importance analysis. Although there are differences in some attributes of different UAVs, it does not affect the overall situation.

It can be seen from Fig. 8 that the importance of the UAVs in different positions of the triangular UAV swarm is very staggered. The presence of UAVs in different positions at different time periods has the greatest impact on the overall performance of the swarm. Based on the analysis of the two importance levels, the importance of UAVs $3_1 4_2 3_3$ at the node position is significantly lower than that of most non-node positions. When the reliability of UAVs $1_1 1_3 2_2$ change, it has a greater impact on the performance of the swarm. These are key UAVs. Among them, the UAV 1_1 is the most important and when resources are limited, it should be given priority to preventive maintenance. When the UAV at this location fails, it should also be given priority to fill the UAV at this location. Due to the high symmetry of the quadrilateral UAV swarm, one node location 5_4 and two non-node location $1_1 2_1$ UAVs were selected for analysis. As shown in Fig. 9, the importance of the node position of the quadrilateral UAV swarm is different from that of the triangular UAV swarm, and it is not significantly lower than that of most non-node locations. Among them, the importance of UAV 2_1 is obviously higher than that of the other two positions, so UAV 2_1 and UAV $3_1 2_2 3_2 2_3 3_3 2_4 3_4$ in symmetrical positions are the key UAVs in the swarm.

For the polygonal UAV swarm, all its optimization is to improve its reliability and remaining service life in the mission phase. Through the analysis of its importance, the preventive optimization of the pre-task preparation stage and the structural optimization when performing the task are determined. The prognosis of the UAV swarm based on the importance and reliability is also used to make decision-making for the UAV swarm. It provides a reference and basis for optimizing the structure of the mission process and improving the success rate of the mission. We calculate the actual remaining useful life of the two formation UAV swarms according to formula (21). And then we obtain the fitted distribution curve by fitting the actual data points that is the estimated remaining useful life. As shown in Fig. 10, a prognostic analysis of the triangle and quadrangle UAV swarms results in the RUL of them and their 95% confidence interval. The two predicted RUL curves both underestimated the RUL of the swarm in the initial stage and overestimated the RUL of the swarm in the final stage, while it was gentler in the middle. There are some fluctuations in the actual RUL curve of both, but the fluctuations are mostly within the confidence interval. It can be drawn from the figure that the RUL curves of the two polygonal UAV swarms decline slowly over time, but in the later period the curve declines faster and the RUL is lower than expected.

Take the quadrilateral UAV swarm as an example, combining the importance analysis and prognosis analysis that have been completed to optimize the structure. In the mission preparation phase, preventive maintenance has a certain time limit and resource limitation. If there is no clear guidance, the swarm will usually perform general preventive maintenance, that is, all UAVs will be maintained. Limited maintenance resources and maintenance time will be allocated to all UAVs. But due to time and resource constraints it cannot be greatly improved. Through the importance analysis, the key UAV position of the quadrilateral UAV swarm is obtained. At this time, the limited time and resources can be used to repair UAVs$2_1 3_1 2_2 3_2 2_3 3_3 2_4 3_4$. UAVs with the highest important measure are promoted to maximize the UAV swarm performance under limited conditions. In the model, general preventive maintenance will improve the performance of all UAVs to a certain level, while targeted preventive maintenance will improve the performance of more important UAVs. The overall performance level improved by the two schemes is the same.

It can be seen in conjunction with Figs. 11 and 12 that targeted preventive maintenance improves reliability and RUL significantly. In terms of reliability, targeted preventive maintenance slows down the decline of swarm reliability more than general preventive maintenance, and improves the reliability of swarm at different time points. In terms of RUL, general preventive maintenance increased the RUL from less than 800 to nearly 900, while targeted preventive maintenance increased to nearly 1,000, and the swarm did not experience a rapid decline in the RUL curve at the end. Like the initial RUL prediction curve, the predicted RUL curve after preventive maintenance also underestimated the RUL of the swarm in the early stage. However, the fitting in the mid-term is perfect, and the fitting curve almost matches the actual data. And the actual curve is within the confidence interval. In general, preventive maintenance can improve the reliability and RUL of the swarm, but targeted prevention can be more effective and make full use of time and resources.

Still taking the polygonal UAV swarm as an example, during the execution of the mission, the UAVs will be invalid or damaged due to their own failure, external interference, enemy damage and other factors. Due to the linear consecutive- k -out-of- n: F system has certain fault tolerance, if there are only a few discrete UAVs failure or damage, the swarm can still run normally to complete the task. If there are local large-scale UAVs failure or damage, the swarm will fail, as shown in Fig. 13.

Polygonal UAV swarm have a large area of UAV failure or damage locally, which makes it impossible to meet the reliability requirements of linear consecutive- 3 -out-of- 6: F system and the swarm fails. Because it is impossible to carry out human maintenance during the task execution phase, if any self-adjusting actions cannot be taken, this task will fail. According to the structure optimization method of this paper combined with the theory of criticality and critical components, the remaining unreliable UAVs can be adjusted to the position of the failed UAV. So, the reliability of the entire swarm can be restored to the state of operable and executable tasks. As can be seen from the above, the highest importance in the rectangular UAV swarm is that the position of the key UAVs are $2_1 3_1 2_2 3_2 2_3 3_3 2_4 3_4$, followed by the UAVs at each node position, and the remaining UAVs have the lowest importance. On the premise that the structural adjustment of the UAV swarm will not cause the swarm to fail again, the swarm will carry out self-structural adjustment based on the principle of importance and proximity. The operating UAVs will move to the location of the failed UAVs. According to the structural optimization flow chart shown in Fig. 5, the UAV with the lowest importance and the closest distance to the failed UAV is selected for position supplement. The weight of the importance factor is much higher than the distance factor. Then we can get:

$$\begin{cases} UAV4_1 \rightarrow UAV3_1 \\ UAV1_2 \rightarrow UAV5_4 \\ UAV4_2 \rightarrow UAV2_1 \\ UAV4_3 \rightarrow UAV3_4 \end{cases}$$

After optimization, the UAV swarm will continue to perform tasks. The reliability change of the UAV swarm from failure to self-adjustment to complete system restart is shown in Fig. 14.

It can be seen from the figure that when the UAV swarm is attacked, the reliability drops rapidly to 0. After a short period of self-structure adjustment, the reliability of the swarm recovers but cannot be restored to the level before the attack. Then there is a short-term increase in reliability followed by a slow decline over time. As shown in Fig. 15, the same as the reliability curve, the actual RUL curve quickly drops to 0 after being attacked and then recovers, or even recovers above the predicted RUL curve, showing the effectiveness of structural optimization. Except for the short-term actual RUL curve after being attacked is not within the confidence interval, the rest are within the interval.

5. Conclusions

In this paper, the UAV swarm with polygon formation is modeled as a consecutive- k -out-of- n: F system. Based on the reliability equation of the multilateral consecutive- k -out-of- n: F system with shared nodes, the mission reliability model of the polygon UAV swarm is established. Then, the two importance models of Birnbaum importance and integrated importance measure are established based on the reliability model. These are used to calculate the UAV that has the greatest impact on the performance of the UAV swarm and is determined as the key UAVs. The RUL of the UAV swarm is the length of time until the mission reliability of the UAV swarm is reduced to the threshold value of the mission reliability for the next phase. By calculating the RUL of the UAV swarm, it can be observed whether the UAV swarm can complete the next phase of the mission. Combining the above-mentioned importance measure model and RUL model, we analyzed the self-structure adjustment method of the UAV swarm after some UAVs fail under attacks. Meanwhile, the reliability curve and the RUL curve before and after the failure can be obtained. Finally, a numerical example was analyzed to prove the effectiveness of the above methods.

Through these analysis, decision support and mission planning can be provided for the commander or administrator in operation. For future study, we plan to analyze the impact of changes in the reliability of individual UAVs or the maintenance models of the swarm on various parameters of the UAV swarm. Next, we plan to consider the changes in mission reliability when UAV sequences on different sides can communicate with each other. Then we plan to work on the reliability model and importance model of UAV swarms with other formations as well as swarm in three dimensions. On the other hand, we also plan to study the resilience and other special properties of UAV swarms.

Author statement

Hongyan Dui and Chi Zhang conceived and designed the methodology and model; Hongyan Dui and Guanghan Bai proposed the idea of this paper; Chi Zhang and Liwei Chen performed the experiments and analyzed the data. All authors have contributed to the editing and proofreading of this paper.

Declaration of Competing Interest

None.

Acknowledgements

The authors gratefully acknowledge the financial support for this research from the National Natural Science Foundation of China (72071182, U1904211), and the ministry of education's humanities and social sciences planning fund (No. 20YJA630012), Science and Technology Commission of the CMC (GrandZZKY-YX-10-03 and 2019-JCJQ-JJ-180), program for young backbone teachers in Universities of Henan Province, and program for Science & Technology Innovation Talents in Universities of Henan Province.

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