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Mission reliability modeling and evaluation for reconfigurable unmanned weapon system-of-systems based on effective operation loop

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Abstract: The concept of unmanned weapon system-of-systems (UWSoS) involves a collection of various unmanned systems to achieve or accomplish a specific goal or mission. The mission reliability of UWSoS is represented by its ability to finish a required mission above the baselines of a given mission. However, issues with heterogeneity, cooperation between systems, and the emergence of UWSoS cannot be effectively solved by traditional system reliability methods. This study proposes an effective operation-loop-based mission reliability evaluation method for UWSoS by analyzing dynamic reconfiguration. First, we present a new connotation of an effective operation loop by considering the allocation of operational entities and physical resource constraints. Then, we propose an effective operation-loop-based mission reliability model for a heterogeneous UWSoS according to the mission baseline. Moreover, a mission reliability evaluation algorithm is proposed under random external shocks and topology reconfiguration, revealing the evolution law of the effective operation loop and mission reliability. Finally, a typical 60-unmanned-aerial-vehicle-swarm is taken as an example to demonstrate the proposed models and methods. The mission reliability is achieved by considering external shocks, which can serve as a reference for evaluating and improving the effectiveness of UWSoS.

Keywords: mission reliability, unmanned weapon, system-of-systems, dynamic reconfiguration, effective operation loop.

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1. Introduction

An unmanned weapon system of systems (UWSoS) refers to a mix of heterogeneous, independently operated systems that interact with each other to achieve a common goal and mission through unmanned system cooperation. Examples of such a system can be found in DARPA’s OFFensive Swarm-Enabled Tactics (OFFSET) , low-cost unmanned aerial vehicles (UAV) swarming technology (LOCUST), the US Air Force’s Skyborg, and system-of-systems (SoS) integration technology and experimentation programs [1,2]. However, due to the areas in which this technology is applied, UWSoS often operates in hazardous, contaminated, and open environments, which inevitably results in external shocks. The mission reliability of UWSoS is defined as the ability of unmanned systems to complete their required mission in line with a specified mission profile. Mission reliability is an essential basis for the improvement and maintenance of unmanned systems’ combat effectiveness [3]. This reliability not only directly affects UWSoS’s combat mode, combat scale, and continuous combat capability, but also impacts improvements to its operational effectiveness as well as its cost throughout an entire life cycle [4–6].

The unmanned systems in an UWSoS carry a wide range of payloads that perform different roles and functions [7]. The high number of interconnected systems in UWSoS forms a series of synergistic kill chains and OODA (Observation, Orientation, Decision, Action) loops [8–10]. UWSoS’s complexity and interference uncertainty increase dramatically, resulting in preventive and protective strategies that are not all-inclusive. Scholars in previous studies have analyzed the combat capability and anti-damage capability of the UWSoS’s combat network from the perspective of network connectivity and operation-loop. However, the anti-destructive ability of the combat network cannot reflect the mission of the UWSoS in terms of actual combat process reliability.

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Mission reliability has been a constant subject of extensive research over the past decades in the fields of manufacturing systems [11], power systems [12], and the military [13,14]. Andrews et al. [15] proposed a fast mission reliability prediction method for phased-mission UAVs. Chen et al. [11] proposed a definition for the mission reliability of multi-state manufacturing systems and developed a mission reliability evaluation method. Yang et al. [16] developed a mission reliability-driven maintenance approach for multi-state manufacturing systems based on the quality stochastic flow network (SFN). Cheng et al. [17] studied an efficient approach for conducting reliability assessments for multi-state phased mission systems with common bus performance sharing by combining a modified Markov model and belief universal generating function. He et al. [18] put forward a mission reliability evaluation for fuzzy multi-state manufacturing systems based on an extended SFN, which comprehensively analyzed task execution, machine degradation, and quality state. Liang et al. [19] offered three reliability indexes: standard entropy of rank distribution, all-terminal reliability, and standard natural connectivity for a multi-autonomous underwater vehicle by assessing topological structure and underwater acoustic communication. Huang et al. [20] established an SoS mission reliability model based on the Markov chain by considering the relationship between SoS capabilities and mission reliability. Remenyte-Prescott et al. [21] analyzed phased mission reliability in real-time for autonomous vehicles using the binary decision diagram (BDD) and available diagnostics data.

However, these traditional methods of mission reliability analysis face critical challenges. Because the causes of external shocks that occur in UWSoS operations are becoming increasingly unpredictable and inevitable [22], it is difficult to evaluate mission reliability in the face of various external shocks. Therefore, the emphasis of research in recent years has shifted from traditional methods such as BDD or Markov to OODA and operation loops that are based on complex networks [20,23]. OODA and operation loops provide a novel perspective for UWSoS operations by considering external shocks such as trojan horses, electromagnetic strikes, and firepower attacks. Li et al. [24] established a temporal-combat-network-based and capability-oriented equipment contribution analysis method by taking advantage of OODA and the operation loop concept. By integrating a layered reference architecture and kill chain, Hahn et al. [25] presented a security analysis framework for cyber-physical systems, which can be used to analyze threats and physical impacts. Singh et al. [26] built a cyber kill chain-based hybrid intrusion detection system framework for the smart grid by integrating a network-based, model-based, and machine learning-based intrusion detection system. Li et al. [23] analyzed a structural robustness measure for the combat network of WSoS based on the operation loop, which can provide valuable insights for designing a more resilient WSoS. Jia et al. [27] explored a quantitative capability evaluation model for a search and rescue SoS that is based on a weighted super network. Bei et al. [28] established a failure analysis framework for an unmanned autonomous swarm, which includes swarm model development, a failure model, resilience evaluation, and a mechanism of cascading failure and self-repair. Liu et al. [29] proposed a complex-networks-based reliability assessment method for swarm systems by considering different malicious attack strategies. Li et al. [30] explored the functional robustness problem for a heterogeneous WSoS with different types of functional entities and information flows by taking advantage of OODA and operation loops, which can provide valuable insights for operational guidance. Sun et al. [8] established a multi-swarm-based cooperative reconfiguration model for resilient UWSoS; they selected the number of operation loops as a performance indicator. Li et al. [31] proposed a link-prediction-based heterogeneous combat networks operational capability disintegration for solving the WSoS's combat capability decomposition issue.

However, there appears to be a lack in research covering the reliability assessment of WSoS for operational missions. Many studies have solved the reliability or robustness analysis of WSoS and have proposed some evaluation indexes, such as maximum connectivity, global efficiency, betweenness, UWSoS scale [32,33], which pose a challenge for achieving the mission baseline. The mission baseline of operation loops is more accessible than other indexes for UWSoS mission reliability evaluation. However, most operation-loop-based system reliability or robustness studies are based on the number of operation loops yet ignore the constraints on the number of resources affecting the influence entities in most cases.

In light of these issues, traditional mission reliability methods cannot effectively deal with the mission reliability assessment of unmanned information system-based UWSoS for operational missions. Thus, this paper proposes a mission reliability evaluation method for UWSoS based on an effective operation loop by investigating dynamic reconfiguration. The main contributions of this study are as follows:

(i) A new definition of the UWSoS's effective operation loop is proposed on the basis of SoS engineering by considering the operational entities allocation and physical resource constraints;

(ii) An effective operation-loop-based UWSoS mission reliability model is proposed with regard to the mission baseline;

(iii) A mission reliability evaluation algorithm which fully considers random external shocks and dynamic reconfiguration is proposed.

The remainder of this paper is organized as follows. Section 2 introduces an effective operation loop network model. Section 3 describes the effective operation-loop-based mission reliability model. The mission reliability evaluation algorithm for reconfigurable UWSoS is proposed in Section 4. An illustrative case study is provided in Section 5 to verify the proposed model. Finally, some concluding remarks are discussed in Section 6.

2. Effective operation network model

In relation to the actual operational process, this section considers the heterogeneity of nodes and edges in the UWSoS operational network and proposes heterogeneous operational networks and the effective operation loop model for UWSoS by examining the allocation of operational entities and physical resource constraints.

2.1 Heterogeneity operational network

Given the heterogeneity of the UWSoS operational network, the UWSoS operational network is defined as a heterogeneous network $\boldsymbol{G}=(\boldsymbol{V},\boldsymbol{E})$, where $\boldsymbol{V}$ represents the set of nodes and $\boldsymbol{E}$ represents the set of edges between nodes.

The UWSoS is a combination of unmanned weapon systems with various capabilities, such as intelligence, command, control, and firing capacity. According to Cares' information-age combat model (IACM) [9] and Tan's operation loop [34], the unmanned weapon systems of UWSoS are divided into four categories.

(i) Sensor (S): Unmanned system used to collect information on enemy targets and battlefields, with the main functions of target reconnaissance, intelligence acquisition, and battlefield surveillance.

(ii) Decider (D): Unmanned system with functions of information processing and analysis, decision support, and control influencer system.

(iii) Influencer (I): Unmanned system featuring precision strike, fire damage, and electronic jamming for the purpose of sniping and destroying targets.

(iv) Target (T): Targets in operational missions, including all enemy equipment on the battlefield.

The network mode is the path in the heterogeneous network $\boldsymbol{G}=(\boldsymbol{V},\boldsymbol{E})$. According to the functions of systems and the actual meaning of edges between different systems, the details of the existing network modes in UWSoS are listed in Table 1.

Table 1 Network modes in the UWSoS operational network

Network mode	Implication
$T_i \to S_i$	How sensor equipment detects enemy targets and obtains intelligence information
$S_i \to S_i$	How one piece of sensor equipment exchanges intelligence information with another
$S_i \to D_i$	How sensor equipment uploads the detected intelligence information to the decider equipment
$D_i \to D_i$	How one piece of decider equipment exchanges intelligence information with another
$D_i \to S_i$	How the decider equipment transmits orders to the sensor equipment
$D_i \to I_i$	How the decider equipment transmits orders to the influencer equipment
$I_i \to T_i$	How influencer equipment attacks or harasses target equipment

The nodes in the UWSoS operational network are

$$\begin{cases} \boldsymbol{V}=\{\boldsymbol{S},\boldsymbol{D},\boldsymbol{IT}\} \\ \boldsymbol{S}=\{S_1,S_2,\cdots,S_{n_S}\} \\ \boldsymbol{D}=\{D_1,D_2,\cdots,D_{n_D}\} \\ \boldsymbol{I}=\{I_1,I_2,\cdots,I_{n_I}\} \\ \boldsymbol{T}=\{T_1,T_2,\cdots,T_{n_T}\} \end{cases} \tag{1}$$

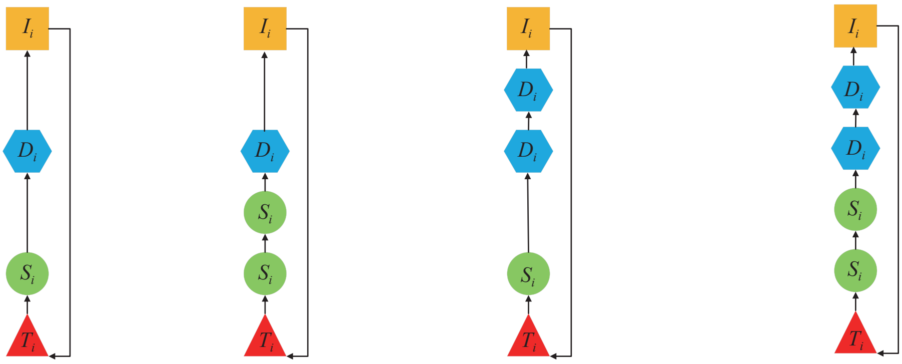
where n_S, n_D, n_I and n_T are the number of four types of nodes.The edges in the UWSoS operational network are

$$\begin{gathered} \boldsymbol{E}=\{\boldsymbol{e}_{TS},\boldsymbol{e}_{SS},\boldsymbol{e}_{SD},\boldsymbol{e}_{DD},\boldsymbol{e}_{DS},\boldsymbol{e}_{DI},\boldsymbol{e}_{IT}\}, \\ \boldsymbol{e}_{TS}=\{[T_i \to S_i]\}, \\ \boldsymbol{e}_{SS}=\{[S_i \to S_i]\}, \\ \boldsymbol{e}_{SD}=\{[S_i \to D_i]\}, \\ \boldsymbol{e}_{DD}=\{[D_i \to D_i]\}, \\ \boldsymbol{e}_{DS}=\{[D_i \to S_i]\}, \\ \boldsymbol{e}_{DI}=\{[D_i \to I_i]\}, \\ \boldsymbol{e}_{IT}=\{[I_i \to T_i]\}. \end{gathered} \tag{2}$$

2.2 Effective operation loop model

The operation loop refers to a mission closed-loop mode. Each of its link elements is based on a pre-set structure. Therefore, these elements are interdependent, and operate in sequence to produce a linear killing effect on a specific target.

In the UWSoS operational network, the operation loop refers to the closed loop against the target composed of some specific nodes and edges, denoted as $T_i \to S_i \to \cdots \to D_i \to I_i \to T_i$. $S_i \to \cdots \to D_i$ in the operation loop that represents the transmission and processing relationship of the detected information in the unmanned system network. The meaning of the resulting operation loop differs, according to the transmission and processing of the reconnaissance information by different systems and the actual connection relationship between the systems. Fig. 1. shows the different operation loops and their implications.



(a) Typical operation loop: $T_i \to S_i \to D_i \to I_i \to T_i$

(b) Operation loop with information sharing: $T_i \to S_i \to S_i \to D_i \to I_i \to T_i$

(c) Operation loop with collaborative decision-making: $T_i \to S_i \to D_i \to D_i \to I_i \to T_i$

(d) Operation loop with information sharing and collaborative decision-making: $T_i \to S_i \to S_i \to D_i \to D_i \to I_i \to T_i$

Fig. 1 Different types of operation loops

The greater the number of operation loops that are against a target, the more the number of ways to attack this target. This also increases the ability of the entire UWSoS to maintain its original operation function. In other words, the number of operation loops represents the redundancy of operation. The greater the number of operation loops results in higher redundancy, the less the system is likely to be affected. Therefore, the number of operation loops in the UWSoS operational network can reflect its combat capability to a certain extent, especially its anti-destruction performance.

However, the mission reliability of the unmanned systems focuses on the ability to finish their required mission above given mission baselines under a specified mission profile, which means the degree of mission completion in the actual operational process.

The mission reliability of UWSoS focuses on whether the unmanned systems complete their required mission, and more specifically, whether each target is successfully destroyed, jammed or cleared during actual operational process, and the ratio of destroying targets to the total. Therefore, the UWSoS operation mission baseline M_S is defined as follows: under the established operation mission planning scheme, the mission is deemed successful when the ratio of destroying targets is greater than or equal to M_S through coordinated detection, command and strike.

According to the heterogeneous network theory, the definition of an effective operation loop in UWSoS operational network is given as follows: for the specific target T_i, if the number of operation loops against this target reaches the set threshold $\mathcal{T}$, it is considered that an effective operation loop is formed for this target.

Considering the allocation of operational entities in the actual operational process, it is necessary to allocate missions between the influencer and the targets [35]. The characteristic function of the node T_i in the target system is defined as follows:

$$\chi_i = \begin{cases} 1, & T_i \text{ has an edge with nodes in } I \\ 0, & T_i \text{ has no edge with nodes in } I \end{cases}. \tag{3}$$

According to mission allocation, $\sum_{i=1}^{|T|} \chi_i$ takes the maximum value, where $|T|$ is the number of nodes in the target system T.

Considering the physical resource constraint in the actual operational process, the influencer node I_i cannot be reused, each node I_i can only connect to one target node T_i at the most. However, each influencer node I_i can connect with multiple decider nodes D_i. The number of edges between system M and N in the network can bedescribed by $\boldsymbol{e}_{MN}$, and the connection situation about influencer node I_i can be expressed as follows:

$$\begin{cases} \left\|\boldsymbol{e}_{I_iT}\right\| = 1,\ i = 1,2,\cdots,|I| \\ \left\|\boldsymbol{e}_{DI_i}\right\| = 1,2,\cdots,|D|,\ i = 1,2,\cdots,|I| \end{cases} \tag{4}$$

where $|I|$ is the number of nodes in the influencer system I, and $|D|$ is the number of nodes in the decider system D.

3. Effective operation-loop-based mission reliability model

Traditional methods for assessing mission reliability cannot effectively deal with the mission reliability assessment of unmanned information system-based UWSoS for operational missions. This section puts forward an effective-operation loop-based mission reliability model for heterogeneity UWSoS under random external shocks and dynamic reconfiguration processes.

3.1 Dynamic reconfiguration process

In the actual operational process of the UWSoS operational network, some equipment will fail due to external shocks. Each disrupted equipment of the UWSoS is subjected to complete disruption. Simultaneously, the edges connected to the disrupted equipment become disconnected. At this time, the corresponding operation loop in the operational network will be affected. Therefore, the operational performance of the operational network can be improved through dynamic reconfiguration.

With regard to the mission reliability analysis of the UWSoS operational network, this paper examines its dynamic reconfiguration process. The specific strategy of dynamic reconfiguration involves the following process: when a node in a system fails due to external shocks, find the non-failed nodes in the same system and randomly select a non-failed node to replace the function of the failed node. Finally, reconnect the edge which originally connected the failed node to the non-failed node.

Fig. 2 shows the dynamic reconfiguration process of the operational network of 10 nodes. The non-failed node S_2 in the same system replaces the failed node S_1.

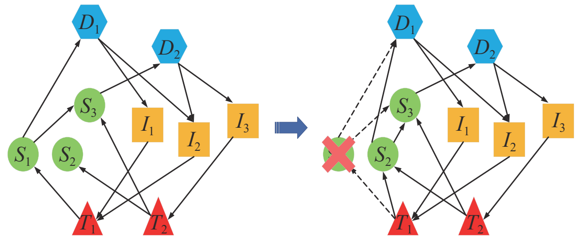


Fig. 2 Dynamic reconfiguration process

3.2 Mission reliability model based on effective operation loop

When the scale of UWSoS is large, it is difficult to calculate the number of operation loops. According to the characteristics of matrix calculation, the transition matrix $\boldsymbol{A}_{\mathrm{PQ}}$ and the arrival matrix $\boldsymbol{A}_{\mathrm{PP}}$ are defined as follows.

Transition matrix: $\boldsymbol{A}_{\mathrm{PQ}}$ is the transition matrix between node type P and node type Q about network mode $P \to Q$. If there is an edge between node $i \in P$ and node $j \in Q$, then the element $a_{ij} = 1$, else $a_{ij} = 0$.

Arrival matrix: $\boldsymbol{A}_{\mathrm{PJ}}$ and $\boldsymbol{A}_{\mathrm{JK}}$ are called adjacent transition matrices. The arrival node type of A_{PJ} is the same as the starting node type of $\boldsymbol{A}_{\mathrm{JK}}$. Through the transition between adjacent transition matrices, $\boldsymbol{A}_{\mathrm{PP}} = \boldsymbol{A}_{\mathrm{PJ}} \cdot \boldsymbol{A}_{\mathrm{JK}} \cdots \boldsymbol{A}_{\mathrm{MP}}$ can be obtained, where $\boldsymbol{A}_{\mathrm{PP}}$ is called the arrival matrix of node type P.

The number of operation loops can be calculated according to the transition matrix and the arrival matrix. Taking the typical operation loop $T \to S \to D \to I \to T$ as an example, the arrival matrix $\boldsymbol{A}_{\mathrm{TSDIT}}$ of the target system T under the operation loop TSDIT can be obtained as

$$\boldsymbol{A}_{\mathrm{TSDIT}} = \boldsymbol{A}_{\mathrm{TS}} \cdot \boldsymbol{A}_{\mathrm{SD}} \cdot \boldsymbol{A}_{\mathrm{DI}} \cdot \boldsymbol{A}_{\mathrm{IT}}. \tag{5}$$

Then, the number of operation loops of this type can be obtained as

$$N_{\mathrm{TSDIT}} = \sum_{i=1}^{|T|} A_{\mathrm{TSDIT}}(i,i) \tag{6}$$

where $|T|$ refers to the number of nodes in the target system T. Further, the number of operation loops against the specific target node T_i can be obtained as

$$N_i = \sum A_{\mathrm{TS\cdots DIT}}(i,i). \tag{7}$$

The summation is for different types of operation loops.

$$E_i = \begin{cases} 1,\ N_i \geqslant \mathcal{T} \\ 0,\ N_i < \mathcal{T} \end{cases} \tag{8}$$

Traversing all target nodes in the target system, the number of effective operation loops in the UWSoS operational network can be obtained as

$$N_{\mathrm{EOL}}=\sum_{i=1}^{|T|}E_i \tag{9}$$

where $|T|$ refers to the number of nodes in the target system T.

It should be noted that in the UWSoS operational network, once the effective operation loop for the specific target node T_i is formed, this target can be considered as having been successfully destroyed, interfered or cleared in the actual operational process. The maximum number of effective operation loops is the number of nodes in the target system T. Further, if $N_{\mathrm{EOL}}|T|\geqslant M_S$, the ratio of destroying enemy targets satisfies the mission baseline, and the mission is deemed to be a success.

The mission reliability of UWSoS is the ability to finish their required missions above given mission baselines. If UWSoS performs N simulations under the specified mission profile, and the mission baseline is reached N_s times, the mission reliability of UWSoS can be obtained as

$$R=N_s/N. \tag{10}$$

There are several assumptions for the proposed model, which are stated as follows:

(i) The connection probability between the influencer node I_i and the target node T_i is the success rate of the influencer I_i hitting the target T_i.

(ii) The disturbance situation is mainly assumed to be enemy attacks and external shocks. The sensor node S_i, the decider nodes D_i and the influencer node I_i randomly fail based on exponential distribution, the target node T_i does not fail.

(iii) Sampling nodes based on the Monte Carlo method to determine failed nodes.

(iv) Each disrupted node of the UWSoS operational network is subjected to complete disruption, simultaneously, the edges connected to the disrupted node are disconnected.

(v) Each disrupted node of the UWSoS operational network can be replaced by the same type of existing node.

4. Mission reliability evaluation algorithm

According to the effective operation-loop-based mission reliability model for the heterogenous UWSoS described above, this paper proposes a UWSoS mission reliability evaluation algorithm based on an effective operation loop, under random external shocks, and topology reconfiguration. The algorithm includes the following steps:

Step 1 Initialize the model. According to the connection probabilities $P_{\mathrm{SS}},P_{\mathrm{SD}},P_{\mathrm{DI}},P_{\mathrm{IT}},P_{\mathrm{TS}}$ among the nodes in the UWSoS operational network, construct the initialized UWSoS operational network $\boldsymbol{G}=(\boldsymbol{V},\boldsymbol{E})$.

Step 2 Input the number of simulations N, the simulation duration T, the mission baseline M_s, the initial simulation times $n=1$, and the initial simulation time $t=1$.

Step 3 Start the nth simulation.

Step 3.1 Node failure process.

Step 3.1.1 Input the failure rate λ_S of the nodes in the sensor system, the failure rate λ_D of the nodes in the decider system, and the failure rate λ_I of the nodes in the influencer system.

Step 3.1.2 According to the failure rate input in Step 3.1.1, sample to determine the failure situation of nodes at the current simulation time.

Step 3.1.3 According to the result of Step 3.1.2, remove the failed node and its connected edges.

Step 3.2 Dynamic reconfiguration process.

Step 3.3 Node repair process.

Step 3.3.1 Input the repair rate μ_S of the nodes in the sensor system, the repair rate μ_D of the nodes in the decider system, and the repair rate μ_I of the nodes in the influencer system.

Step 3.3.2 According to the repair rate input in Step 3.3.1, sample to determine the repair situation of the failed nodes at the current simulation time.

Step 3.3.3 According to the result of Step 3.3.2, restore the repaired nodes and their connected edges.

Step 3.4 Calculate the number of operation loops and effective operation loops, and record the current data.

Step 3.5 Determine the current simulation time t.

If the current simulation time t does not reach the simulation duration T, $t=t+1$, return to Step 3.1.

If the current simulation time t reaches the simulation duration T, proceed to Step 4.

Step 4 Determine whether the mission baseline M_s is reached, and record the number of successfully operated missions N_s.

Step 5 Determine the current number of simulations n.

If the current number of simulations n does not reach the number of simulations N, $n=n+1$, return to Step 3.

If the current number of simulations n reaches the number of simulations N, proceed to Step 6.

Step 6 Record the relevant simulation results, and calculate the UWSoS mission reliability according to the simulation results.

The algorithm flowchart is given in Fig. 3.

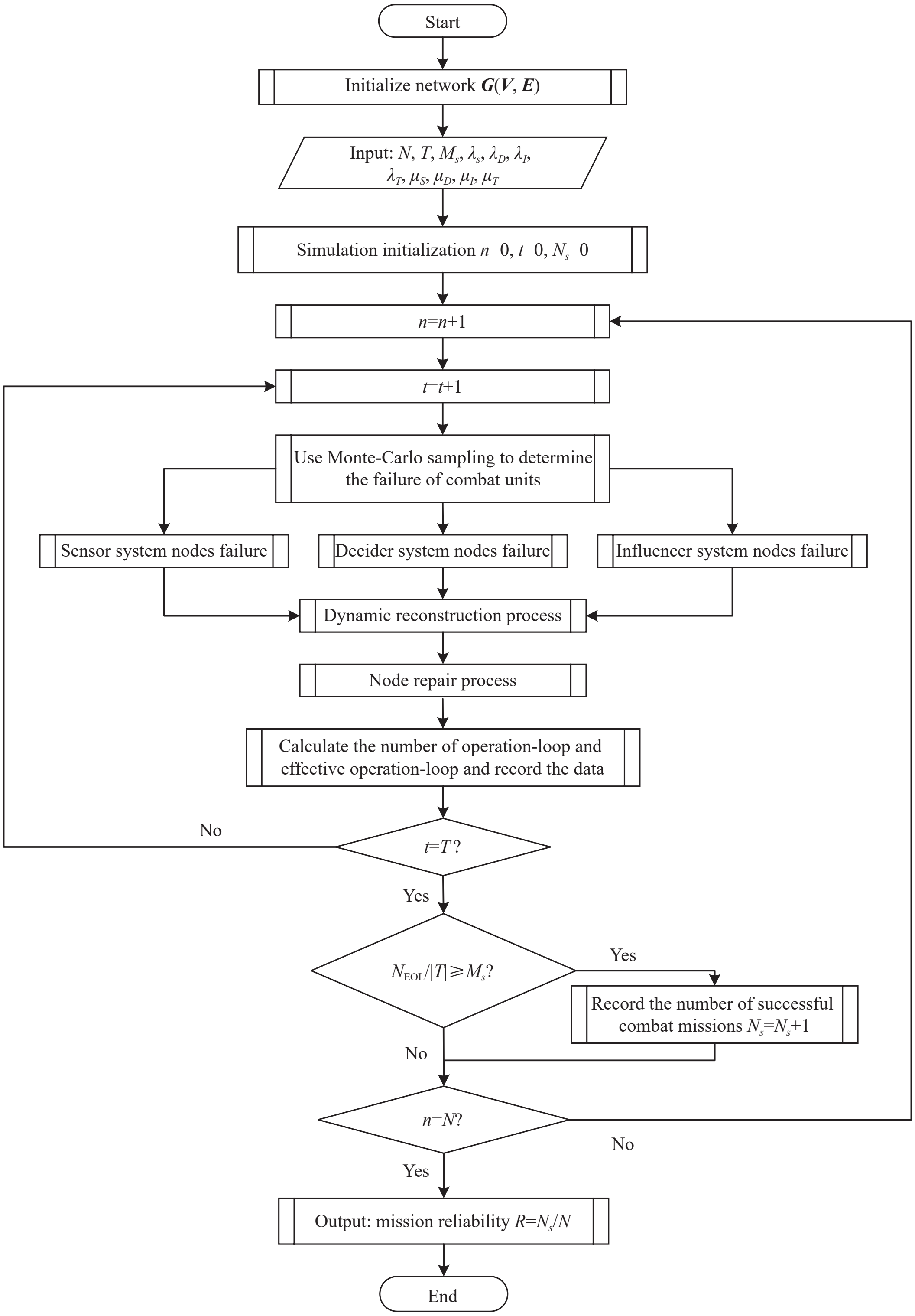


Fig. 3 Heterogeneous UWSoS mission reliability simulation algorithm

5. Case study and results analysis

In order to verify the effectiveness of the evaluation algorithm proposed in this paper, a typical 60-unmanned-aerial-vehicle-swarm is taken as an example to analyze its operational mission reliability in the actual operational process. Among them, the number of sensor node n_S is 20. The number of decider node n_D is 5, the number of influencer nodes n_I is 25 and the number of target nodes n_T is 10. The settings of other simulation parameters are listed in Table 2.

Table 2 Parameters of UMSoS evaluation algorithm

Parameter	Value	Parameter	Value
N	1 000	T	100
M_s	0.6	P_{SS}	0.6
P_{SD}	0.8	P_{DI}	0.9
P_{IT}	0.7	P_{TS}	0.7
λ_S	0.000 5	μ_S	0.002
λ_D	0.000 25	μ_D	0.007
λ_I	0.000 3	μ_I	0.002 5

The number of effective operation loops under external shock and dynamic reconfiguration is obtained by calculating the number of operation loops in the UWSoS operational network. The result is shown in Fig. 4.

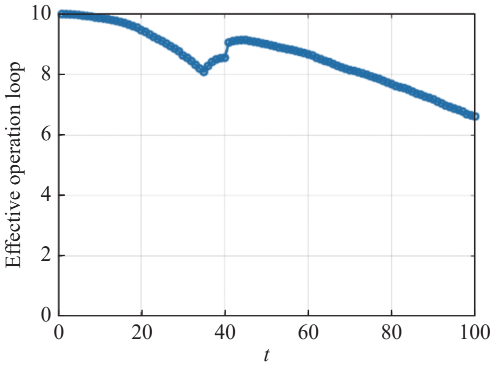


Fig. 4 Number of effective operation loops under external shock and dynamic reconfiguration

The variation of the mission reliability with time is obtained by calculating the mission reliability of UWSoS as shown in Fig. 5.

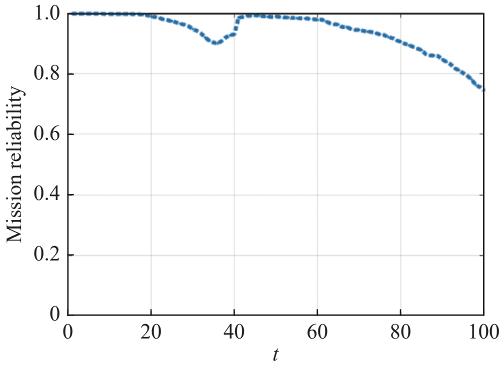


Fig. 5 Mission reliability of UWSoS under the mission baseline

As shown in Fig. 4 and Fig. 5, the number of effective operation loops and mission reliability of UWSoS have roughly the same trend with time under random external shocks and topology reconfiguration in the actual operational process with consideration to the operational entities allocation and physical resource constraint. At the initial stage, both types of data performed relatively stable due to dynamic reconfiguration, as the number of failed nodes increases, both show a downward trend. Subsequently, the rate of data degradation decelerates and shows a slight recovery due to node repair. The number of final effective operation loops on average in 1 000 simulations EKL is 6.609. At the same time, the success rate of UWSoS combat missions can be monitored and evaluated according to the trend of mission reliability with time, and the final mission reliability R is 0.746.

Under the established operation mission planning scheme, the mission is deemed successful when the ratio of destroying targets is greater than or equal to mission baseline M_s. In the case of a combat environment and combat strategy, the higher the mission baseline M_s, the lower the success rate of completing the mission, and the lower the mission reliability R. The simulation results of the UWSoS mission reliability with different mission baselines are shown in Fig. 6. The trend of mission reliability over time is essentially the same across different mission baselines, and the value of mission reliability R is negatively correlated with the mission baseline M_s.

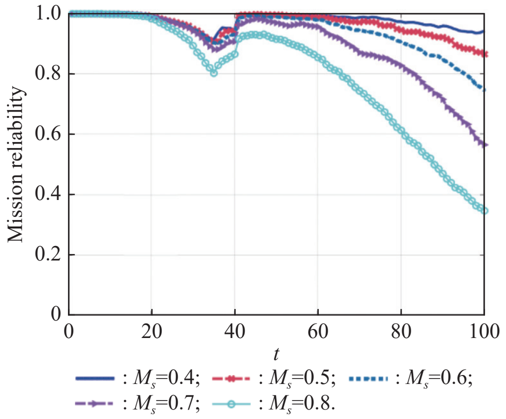


Fig. 6 Mission reliability under different mission baselines

6. Conclusions

Traditional mission reliability methods cannot effectively deal with the UWSoS mission reliability assessment for operational missions. In this paper, a new definition of an effective operation loop is proposed by considering the allocation of operational entities and constraints of physical resource. In addition, an effective-operation-loop-based mission reliability model is proposed for heterogeneous UWSoS under random external shocks and dynamic reconfiguration.

Based on the proposed model, this paper investigates a mission reliability evaluation algorithm. A typical 60-unmanned-aerial-vehicle-swarm is taken as an example to demonstrate the proposed model and algorithm. As can be seen from the simulation results, the number of effective operation loops and mission reliability of UWSoS has essentially the same trend with time. The success rate of UWSoS combat missions can be monitored and evaluated according to mission reliability. The effectiveness of the mission reliability evaluation algorithm in this paper is illustrated through extensive experiments, which could provide valuable insights for operational guidance and decision support for the design of UWSoS.

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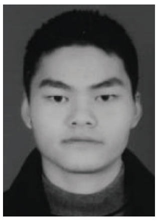

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