A Baseline Assessment Method of UAV Swarm Resilience Based on Complex Networks

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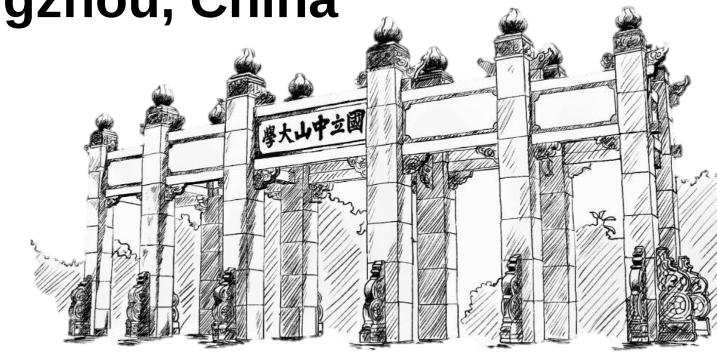

CONTENTS

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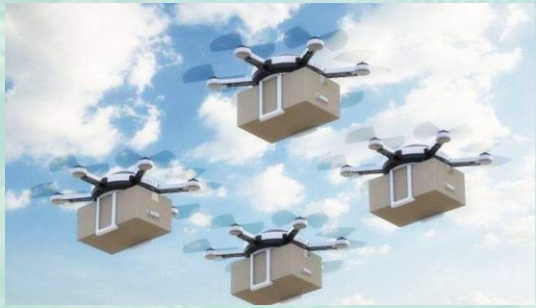
I. Introduction

Unmanned aerial vehicles (UAVs) have the characteristics of low maintenance costs and high maneuverability, which has been widely used as an efficient tool to perform the implementation of repetitive and dangerous missions.

- Express
- Irrigation
- Photography
- …

UAV swarm, a group of numerous UAVs, is more suitable for performing military operations than UAVs and is one of the most influential research areas now.

- Swarm show
- Reconnaissance
- …



Express

Swarm show

Reconnaissance

I. Introduction

The performance evaluation is an essential part whose goal is to understand the status of UAV swarm in time, strengthen the weak links, and improve the ability to resist risks and keep running. The methods includes:

- robustness assessment
- reliability assessment
- resilience assessment
- …

The resilience assessment of UAV swarm not only considers the anti-destroy capability, but also considers the recovery and reconstruction capability. In this way, we should take more attention on the analysis of the recovery ability of UAV swarm.

I. Introduction

To the best of our knowledges, existing researches on resilience assessment of UAV swarm have some limitations, that is mainly due to the unreasonable setting of assessment standards.

- ◆ When UAV swarm performs a mission, as long as the network performance during the life cycle is sufficient to meet the mission conditions, it can be considered that UAV swarm has the resilience required to complete the mission.

Therefore, a baseline assessment method of UAV swarm resilience based on complex networks is proposed in this paper. This method has two advantages.

- ◆ One is that it characterizes the functional expression of UAV swarm resilience assessment baseline.
- ◆ The other is the introduction of the λ variable, which expands the range of baseline selection and provides free thinking space for the actual implementation of military missions.

II. Preliminaries

In this paper, UAV swarm is represented by a topological network structure. The nodes in the network represent UAVs and the edges represent the information exchange between UAVs, as shown in Figure 1.

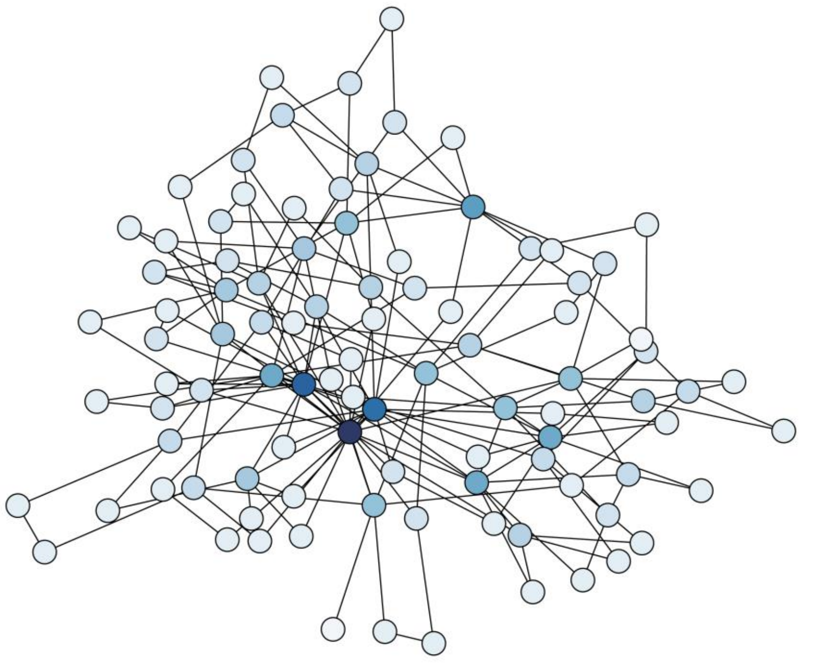


Fig. 1: Schematic diagram of the network topology of UAVs swarm

Suppose there are N_t nodes in the network at time t. Then the total number of information received by all nodes in the network at time t can be used to characterize the performance of the entire network, as[1]

$$y(t) = \sum_{i=1}^{N_t} \sum_{j=1}^{R_i(t)} \Delta^{d_j^i} \quad (1)$$

i, j : nodes,
N_t : the number of nodes in the network at time t,
R_i (t) : the number of information received for node i at time t,
Δ : the time-sensitive factor, $\Delta \in (0; 1]$,
d^i_j: the length of the shortest path obtained for the j_{th} message received by node i.

[1] G. H. Bai, Y. J. Li, Y. N. Fang, Y. A. Zhang, and J. Y. Tao, “Network approach for resilience evaluation of a UAV swarm by considering communication limits,” Reliability Engineering and System Safety, vol. 193, 2020.

III. Baseline assessment method

According to (1), a baseline assessment method of UAV swarm resilience based on complex networks is proposed, as shown in (2).

$$\overline{y(t)} = \sum_{i=1}^{N_t} \sum_{j=1}^{F_i(t)} \Delta^{(1-\lambda)d^i_{jshorest} + \lambda d^i_{jlongest}} \quad \textbf{(2)}$$

Remark 1: When $\lambda = 0$,

$$\overline{y(t)} = \sum_{i=1}^{N_t} \sum_{j=1}^{F_i(t)} \Delta^{(1-\lambda)d^i_{jshorest}}$$

Remark 2: When $\lambda = 1$,

$$\overline{y(t)} = \sum_{i=1}^{N_t} \sum_{j=1}^{F_i(t)} \Delta^{\lambda d^i_{jlongest}}$$

i, j **:** nodes;
N_t : the number of nodes in the network at time *t*,
$F_i(t)$: the minimum number of information received for node *i* at time *t* ,
Δ : the time-sensitive factor, $\Delta \in (0, 1]$,
$d^i_{jshorest}$: the length of the shortest path obtained for the j_{th} message received by node *i*,
$d^i_{jlongest}$: the length of the longest path obtained for the j_{th} message received by node *i*,
λ : the path adjustment factor, $\lambda \in [0, 1]$.

III. Baseline assessment method

According to (2), the value of $F_i(t)$ can be further given, as shown in (3).

$$F_i(t) = \sum_{j=1}^{R_i(t)} (1-\eta)^{d^i_{jlongest}} \cdot \mu_t \cdot N_t \qquad (3)$$

i, j **:** nodes;
R_i (t) **:** the number of information received for node *i* at time *t* ,
η: the information loss rate,
$d^i_{jlongest}$: the length of the longest path obtained for the j_{th} message received by node *i*,
$\mu_t \cdot N_t$: denotes the number of information generated at time *t*

IV. Simulation

Using the simulation scenario of [1] to generate a topological network with an initial scale of N=50, as shown in Figure 2.

When the critical nodes in the network are directionally removed, the network structure is shown in Figure 3.

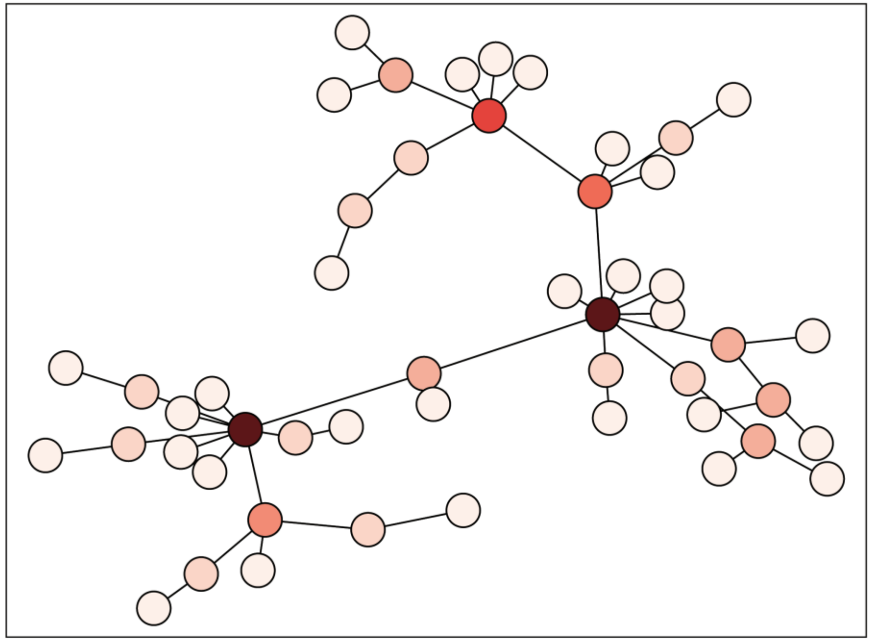


Fig. 2: Initial UAVs swarm network structure diagram

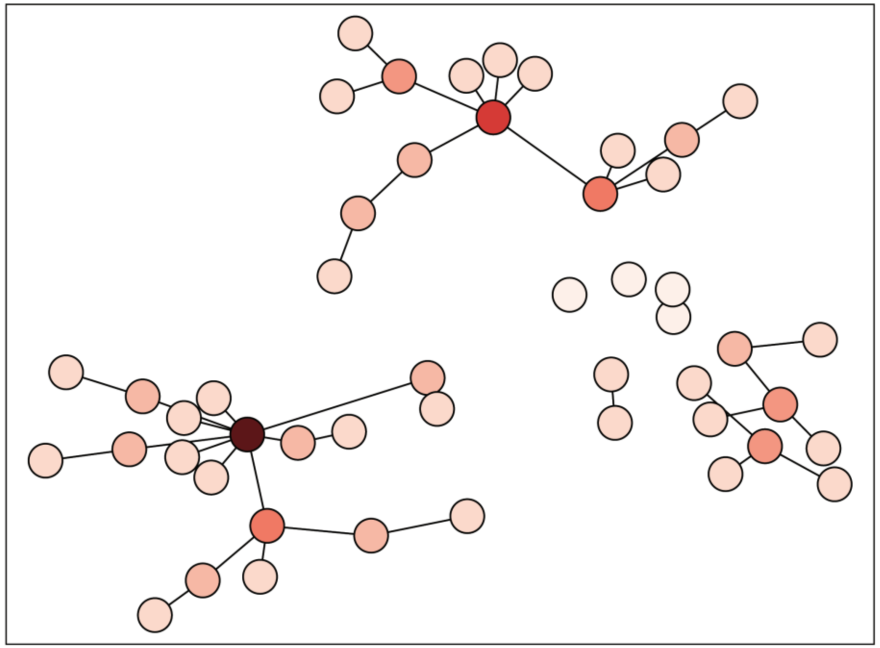


Fig. 3: Node attack network structure diagram

IV. Simulation

At this time, the recovery process is considered in two cases.

CASE 1: The first recovery state is to connect the communication link between critical nodes, so that information is directly transmitted from one critical node to another critical node, as shown in Figure 4.

Simulating the performance baseline value according to (2) and (3), where $\lambda = 1$, $\eta = 0.015$, $\Delta = 0.9$. The relationship between the performance line and the performance baseline can be clearly seen, as shown in Figure 5.

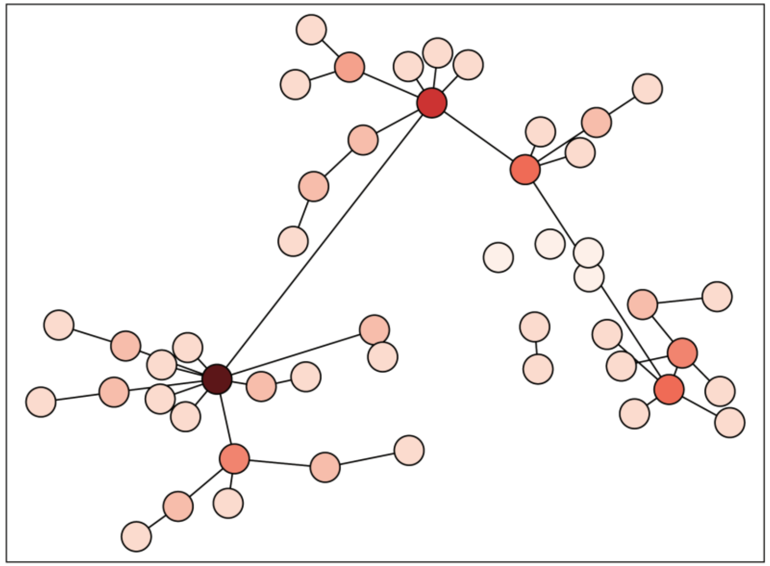


Fig. 4: Critical node restoration network structure diagram

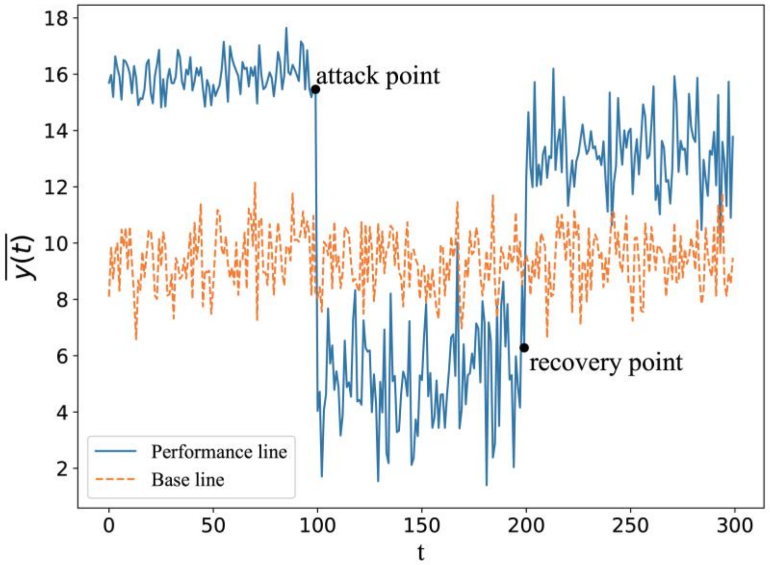


Fig. 5: Performance value and baseline comparison graph

IV. Simulation

CASE 2: **The second recovery state is to connect the communication link between non-critical nodes, The restoration effect is much worse than the connect the communication links between critical nodes, as shown in Figure 6.**

The relationship between the performance line and the performance baseline can be clearly seen, as shown in Figure 7 .

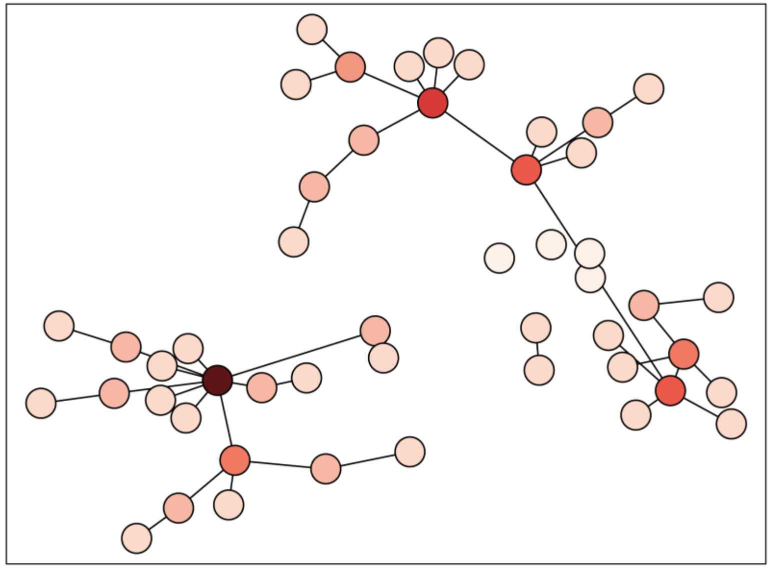


Fig. 6: Non-critical node restoration network structure diagram

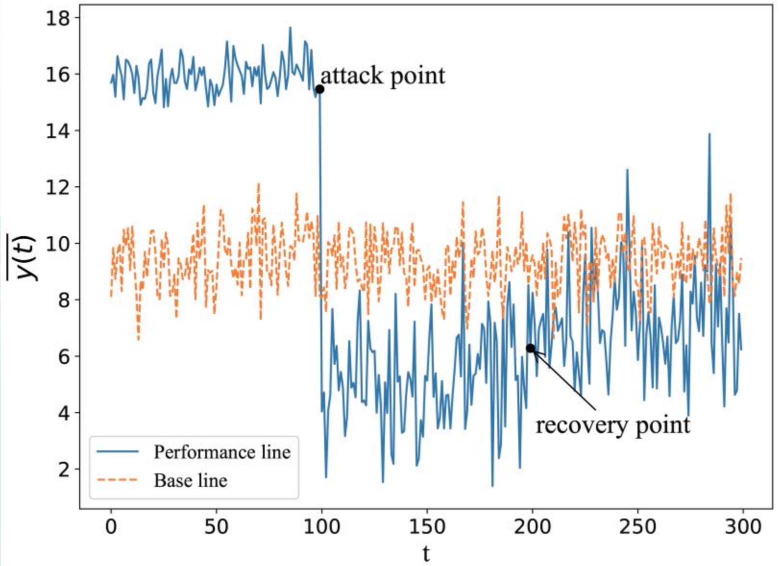


Fig. 7: Performance value and baseline comparison graph

IV. Simulation

Carried out 10 times of simulated disruption recovery process, applied resilience measurement model of Tran[2], and obtained the network resilience value and the network resilience baseline.

It can be clearly seen from Figure 8 that the baseline value of mission requirements is around 0.3, and the network resilience that can meet mission requirement during the 10 times of simulated disruption-recovery process accounts for a relatively large proportion.

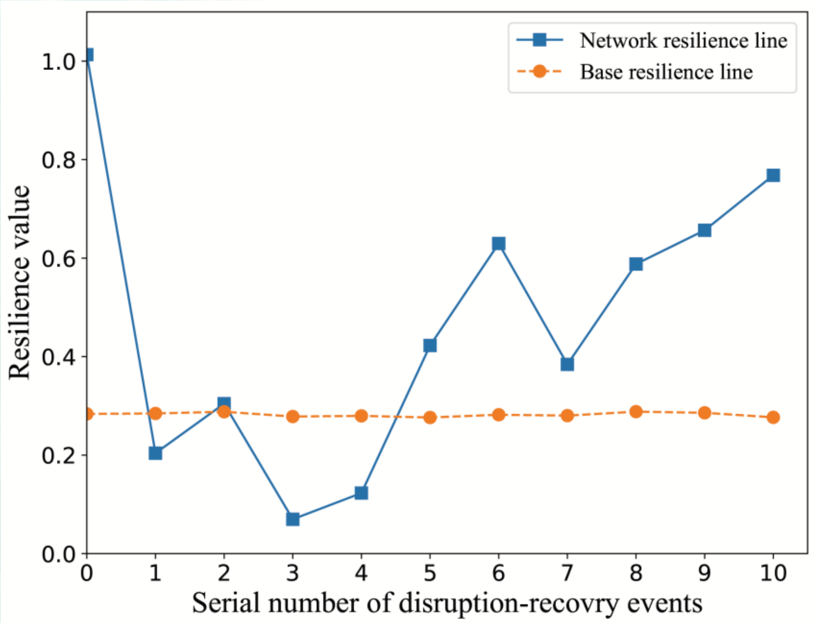


Fig. 8: Network value and baseline comparison graph

[2] H. T. Tran, J. C. Domercant, and D. N. Mavris, "A network-based cost comparison of resilient and robust system-of-systems," *Procedia Comput Sciences*, vol. 95, pp. 126–133, 2016.

V. Conclusion

As a new performance assessment index, the resilience assessment of UAV swarm has received increasing attention in recent years. Summarized as fellows:

- ◆ **a baseline assessment method of UAV swarm resilience based on complex networks has been proposed, and its effectiveness and feasibility have been verified by simulation.**
- ◆ **the proposal of the baseline leaves a large degree of space for UAV swarm to complete the task, relaxing the original harsh evaluation conditions.**
- ◆ **when UAV swarm is performing the mission process, as long as its performance reaches the baseline standard.**
- ◆ **in future research, we will focus on the impact of different recovery technologies on the resilience of UAV swarm.**

Thank you!

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