A Method of Communication Constellation Resilience Evaluation

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Abstract. The resilience of the communication constellation is an important measure of the communication mission assurance capability of the communication constellation. In order to effectively measure the strength and weakness of the communication constellation, the research on the elastic evaluation method of communication constellation is carried out. First, according to the definition of the space system elasticity of the US Air Force Space Command, the definition of the communication constellation elasticity is given. Subsequently, the covering ability and reconstruction energy index are proposed as the objective function of the restored constellation performance recovery, and the damaged constellation performance recovery model based on NSGA-II algorithm is constructed. Finally, a resilience evaluation method for communication constellation with a single communication constellation as the evaluation target is established, and the simulation calculation is carried out by taking the MUOS constellation as an example. It is concluded that the constellation is poor in terms of robustness, and because of the lack of satellite performance, the task guarantee capability is limited.

1. Definition of communication constellation resilience

Resilience, originated from the Latin resiliere, that is, "rebound or recoil." In a broad sense, Resilience refers to a property of the object itself. It is a property that can restore its original state after a destructive event occurs. Resilience is widely used in many disciplines and fields such as physics, sociology, ecology, and internet. [1]

In recent years, with the advent of “resilience engineering” in the field of engineering systems, the United States has proposed to strengthen the resilience of critical infrastructure. The resilience of the space system is thus proposed and regarded as an important reference standard for future space capacity building. [2]

The resilience of the space system given by the Air Force Space Command (AFSPC) is defined as: " Resiliency is the ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary actions. "[3-4]

According to AFSPC’s research and analysis on the resilience of space system, this paper proposes the definition of the resilience of communication constellation:

Resiliency of communication constellation is the ability of a system architecture to continue providing required communication capabilities in the face of system failures, environmental challenges, or adversary actions.
Unlike the resilience of space system proposed by the AFSPC, the resilience of the communication constellation is considered to be the internal property of the constellation itself and does not involve external effects. Therefore, the spatial support actions outside the constellation (such as reissuing satellites and mobilizing other constellation satellites) improve the performance of the communication constellation through external actions. It does not belong to the behavior of the constellation to improve the constellation performance, and does not belong to the category of communication constellation resilience.

2. Research on resilience recovery method of damaged communication constellation

The fast recovery capability of a compromised communication constellation refers to the ability to recover partially compromised communication performance through short-term adjustments. It can reduce the impact of adverse events on communication mission assurance, and it is an important part of communication mission assurance. It is also a key link to evaluate the resilience capabilities of communication constellations.

When multiple satellites fail, the methods for quickly recovering the damaged constellation include rapid response satellites, near space vehicles, and damaged constellation reconstruction. However, the rapid response satellite needs to have backup satellites and can only supplement the low-orbit constellation. The near space vehicles can only meet the service needs of a specific area. Moreover, both fast-sounding satellites and adjacent-space vehicles recover damaged communication capability through external support. But the purpose of this paper is to evaluate the resilience of the communication constellation itself, and its recovery is reflected in the ability to restore the damaged communication function only through the internal adjustment of the communication constellation. Therefore, the damaged constellation reconstruction is not only the main way to quickly recover the communication capability of the damaged communication constellation, but also an important means to ensure the elastic capability of the communication constellation.

2.1. Reconstruction indicators

(1) Covering ability

Coverage is a measure of the extent to which a system can support a communication transmission when a user makes a request. To simplify the indicator model, the inter-satellite link problem is ignored. That is to say, when the satellite can cover the area, it can provide communication services for the area without considering whether the communication link can be established.

The location of the satellite determines the range of services it can provide. Due to mission needs, national interests, etc., users must have different levels of communication needs for different regions of the world. Based on this consideration, regional coverage based on communication requirements is proposed. The world is divided into 60 grid areas. Because the high latitudes in the map have a certain deformation, the area grid size has some differences at different latitudes. According to the degree of demand for communication satellites in the region, communication needs are divided into three levels: necessary, urgent need and general need.

Taking the United States as an example, the distribution and coverage of a total of 29 satellites in the DSCSIII, Milstar, MUOS, SDSIII, SDSIV, UFO, WGS series, etc., which were launched after 2000, are shown in figure 1[5]. Based on this, the communication demand distribution map is drawn. As shown in figure 2, necessary is red, urgent need is yellow, and general need is colorless.
The calculation formula for coverage is:

\[ C = \sum_{i=1}^{\lambda} \lambda_i c_i / \sum_{i=1}^{\lambda} \lambda_i \]  

(1)

Where \( \lambda_i \) is the communication requirement of the i region (\( \lambda = 1, 5, 10 \)), and \( c_i \) is the average coverage of the communication constellation for the i region in one regression period.

2) Reconstruction energy

Reconstructing energy is an indicator of the energy consumption required to measure a constellation reconstruction scheme. Since most of the communication satellites are located in the GEO orbit, the launch is difficult and costly. Every energy is invaluable without considering the on-orbit energy filling. At the same time, the residual energy of the satellite determines the remaining life of the satellite to a certain extent. Therefore, the energy consumption should be minimized when performing reconstruction optimization.

The total energy consumed for reconstruction refers to the sum of the energy required to participate in the orbital maneuver of all reconstructed satellites, which is represented here by the total speed increment \( \Delta V_{all} \).

\[ \Delta V_{all} = \sum_{i=1}^{n} \Delta V_i \alpha_i \]  

(2)

Where \( n \) is the number of satellites required to reconstruct the constellation, \( \Delta V_i \) is the total speed increment required for the reconstruction of the i-th satellite, and \( \alpha_i \) is the energy weighting factor determined from the remaining energy of the i-th satellite. The more residual energy of the satellite, the smaller the factor. The less energy available, the larger the factor. In this way, the possibility of orbital maneuvering of a satellite with relatively few remaining energy is reduced, so that the life of the reconstructed communication constellation is longer. A detailed comparison table is shown in table 1 below:

| Residual energy ratio | Energy weighting factor |
|-----------------------|-------------------------|
| 80~100                | 1                       |
| 60~80                 | 2                       |
| 40~60                 | 3                       |
| 20~40                 | 4                       |
| 0~20                  | 5                       |

2.2. Damaged constellation reconstruction method based on NSGA-II

Due to the small number of communication satellites in the medium and high orbits, the configuration of the communication constellation is relatively simple. When a satellite failure event occurs, the orbital maneuver is mainly based on the mission requirements and the experience of the expert. The
reconstruction scheme can achieve the mission requirement, but it is not necessarily optimal. With the rise of multi-objective optimization algorithms in recent years, the method of modeling and analysis through simulation software has gradually become the main way to solve multi-objective optimization problems [6-9].

Debu et al. proposed the NSGA-II algorithm in 2000. Most of the NSGA algorithm's flaws have been improved, making it one of the most widely used multi-objective optimization algorithms. The NSGA-II algorithm is simple and efficient, including initialization, hybridization, and mutation. Combined with the actual requirements of on-orbit reconstruction of the damaged communication constellation, the main flow of the algorithm is shown in table 2.

| Table 2. Damaged communication constellation reconstruction method calculation process |
|---------------------------------|--------------------------------------------------|
| **Step** | **Process** |
| **Input:** | **Initialization parameters:** population number N; evolution algebra M; hybrid probability Cr; mutation probability α. Set the objective function $\min F$; communication demand distribution; communication constellation current state; constraints and so on. |
| **Step1:** | **Generate initial population:** $g=1$ $P_{g} = \left( X_{1,g}, X_{2,g}, \ldots, X_{N,g} \right)$ |
| | **Evaluation of the initial population:** $F \left( P_{g} \right) = \left[ F \left( X_{1,g} \right), F \left( X_{2,g} \right), \ldots, F \left( X_{N,g} \right) \right]$ |
| **Step2:** | **Hybridization:** for $t = 1: \left( N \times Cr \right)$ $X_{c} = \left[ C_{1} C_{2} \right] \begin{bmatrix} X_{i} \\ X_{j} \end{bmatrix}$ $P_{c} \left( t \right) = X_{c}$ |
| | **End for** |
| **Step3:** | **Mutation:** for $k = 1: \left( N \times \alpha \right)$ $X_{m} = X_{\text{new}}$ $P_{m} \left( k \right) = X_{m}$ |
| | **End for** |
| **Step4:** | **Select:** $P = \begin{bmatrix} P_{g} & P_{c} & P_{m} \end{bmatrix}$ Sorting population P based on Pareto's dominant idea, retaining the first N: $P_{s} = \text{sort}(P)$ $P_{g} = P_{s} \left( 1: N \right)$ |
| **Step5:** | **Evolution:** if $g \leq M$ $g = g+1$, And return Step2 |
| **Output:** | Deriving the Pareto optimal solution set and determining the optimal reconstruction scheme according to the constraints |
3. Analysis of communication constellation resilience

3.1. Communication constellation resilience assessment method

Resiliency of the communication constellation is the ability of the communication constellation architecture to continue providing required communication for mission success in the face of system failures, environmental challenges, or adversary actions. When the communication constellation encounters an adverse event, if the degree of functional degradation of the communication constellation is lower, the performance recovery is better, the recovery time is shorter, and the recovery cost is smaller, the resilience of the constellation is better.

Refer to MITRE's assessment method for the resiliency of the space system, the process of constellation performance in the event of an adverse event is defined as a function that varies over time \([10-11]\). And the constellation resilience is embodied as the residual communication capability under complex events where multiple satellites are at risk of failure. When a multi-satellite failure event occurs, the adverse event is divided into several sub-level scenarios according to the number and location of the possible failed satellites, and the subsequent performance changes of the sub-level scenario are analyzed and calculated to obtain performance over time in the scenario. The probability of occurrence of the sub-level scene is the \(Y\)-axis, and the performance of the time and communication constellation is changed to the \(X\) and \(Z\) axes. Construct a three-dimensional matrix of coverage loss, and the remaining volume of the matrix is a measure of the communication constellation resilience. A schematic diagram of the three-dimensional matrix is shown in figure 3.

![Three-dimensional matrix of communication constellation resilience evaluation](image)

\(3.2.\) Simulation case

(1) Parameter setting
Referring to the current US MUOS military communications constellation construction plan, the simulation scenario is set to five communication satellites. According to the launch time of the satellites in the constellation and the planned service time, the remaining fuel level of the satellite can be roughly estimated, and the energy weighting factor can be determined. The specific parameters are shown in Table 3.

| Satellite number | Track semi-major axis (km) | Sub-satellite longitude (°) | Energy weighting factor |
|------------------|---------------------------|-----------------------------|------------------------|
| 1                | 42166.3                   | -176.96                     | 3                      |
| 2                | 42166.3                   | -100.1                      | 2                      |
| 3                | 42166.3                   | -15.48                      | 2                      |
| 4                | 42166.3                   | 74.8                        | 1                      |
| 5                | 42166.3                   | -104.13                     | 1                      |

The multiple coverage of the complete constellation is shown in Figure 4:

At this time, the global coverage rate based on communication requirements is 99.73%, which ensures that all key areas are covered. It can be seen from the multiple coverage maps that the important areas can basically guarantee double coverage, and the surrounding areas of the United States can guarantee triple coverage, which provides a good guarantee for completing communication tasks.

**Constellation performance:**
The main communication performance of the MUOS constellation is shown in Table 4.

| Indicator                          | Safety protection | Coverage | Information transmission | Business | Communication |
|------------------------------------|-------------------|----------|--------------------------|----------|---------------|
| Capability                         | 0.8816            | 0.9973   | 1                        | 0.9162   | 0.8055        |

**Mission requirements:**
- The communication constellation needs to ensure that the global coverage based on communication needs reaches more than 99%.
- The performance recovery of the damaged constellation is no more than 3 days.

**Scene settings:**
- Due to the high orbital position of the GEO satellite, the factors and possibilities for satellite failure are relatively small. Therefore, the evaluation scenario is set to have three satellites with a risk of failure.
- The start time of the failure event is 0.5 days after the start of the scene.
- After the constellation performance is restored, it must be debugged for 0.5 days to ensure the normal operation of the satellites in the constellation. When all the sub-scene debugging ends, the event is terminated.
(2) Failure event analysis and functional degradation

Considering various satellite protection methods, it is considered that there are three satellites with risk of failure, and the probability of failure of each satellite is 70%. At this time, the probability of failure of all three satellites is 34.3%, the probability of failure of only two satellites is 44.1%, the probability of failure of only one satellite is 18.9%, and the probability of no satellite failure is 2.7%.

(3) Performance recovery analysis

When the satellites 1, 3, and 4 fail, the constellation coverage is shown in figure 5. It can be seen that there is a large area without satellite coverage at this time, and the global coverage of the constellation based on communication needs is only 50.93%. At this time, it is necessary to adopt constellation orbit reconstruction to restore the global coverage of the communication constellation.

Figure 5. Multiple coverage when satellites 1, 3 and 4 fail

Objective function:

\[ \min F = (C, \Delta V_{all}) \]  \hspace{1cm} (4)

- Global coverage based on communication needs;
- Reconstruct the total energy consumed.

The optimization results are shown in figure 6.

Figure 6. Pareto frontier with \( C \) and \( \Delta V_{all} \) as the objective function

As can be seen from the frontier of Pareto, satellite reconstruction cannot meet the mission requirements. To provide communication capabilities for tasks as much as possible, the solution that rebuilds to achieve greater coverage is used as the final refactoring scheme. Considering the cost-effective factor, the scheme of (0.1015, 0.3878) coordinate points is selected as the reconstruction scheme. The total energy consumption required for the reconstruction is 0.3878km/s, and the global
coverage based on communication requirements after reconstruction is 89.85%. The global coverage is shown in figure 7.

![Figure 7. Reconstructed communication constellation global coverage](image)

In the same way, the performance recovery process of other scenes can be obtained.

(4) Building a capacity loss matrix

The three-dimensional matrix takes the time, scene occurrence probability, and constellation performance as the X, Y, and Z axes. The specific parameters are shown in table 5 and table 6.

| Time(day) | Scene 1 | Scene 2 | Scene 3 | Scene 4 |
|-----------|---------|---------|---------|---------|
| 0.5       | 2.8762  | 0.4114  | 0.4114  | 0.4114  |
| 0.1052    |         |         |         |         |
| 0.0071    |         |         |         |         |
| 0.5       |         |         |         |         |

| Probability |
|-------------|
| Scene 1     | 0.343     |
| Scene 2     | 0.441     |
| Scene 3     | 0.189     |
| Scene 4     | 0.027     |

The three-dimensional evaluation matrix of the communication constellation resilience can be obtained as shown in figure 8.

![Figure 8. MUOS constellation three-dimensional evaluation matrix](image)
At this time, the resilience characteristics of the communication constellation are as shown in table 7 below:

| Indicator | Avoidance | Robustness | Recovery | Resilience |
|-----------|-----------|------------|----------|------------|
| Performance | 0.027     | 0.6901     | 0.9347   | 0.6133     |

As can be seen from the table 7, due to the relatively small number of satellites, the MUOS communication constellation is inferior in terms of robustness. And because the task satisfaction of the complete communication constellation is only 0.8055, the resilience of the constellation in the face of adverse events is not very satisfactory.

4. Conclusions
For the single communication constellation, according to the definition and understanding of the space system resilience of the US Air Force Space Command, the definition of the communication constellation elasticity is proposed to provide an evaluation method for the communication constellation mission guarantee capability. The in-orbit reconstruction model of the damaged constellation based on NSGA-II algorithm is constructed and used as the main way of fast recovery performance after constellation damage, which is the main component of the constellation resilience recovery capability. The communication constellation resilience evaluation method is proposed, and the remaining communication capability in the process of encountering adverse events in the communication constellation is taken as a measure of resilience. Taking the MUOS constellation as an example, the simulation calculation is carried out, and its resilience ability is only 0.6133. The mission guarantee capability under adverse conditions needs to be strengthened. In addition, the evaluation of the performance of the communication constellation is relatively simple, and a more detailed study can be conducted in subsequent studies.

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