System of Systems Architecture Modeling and Mission Reliability Analysis Based on DoDAF and Petri Net

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SUMMARY & CONCLUSIONS

SUMMARY: System of Systems (SoS) is widely studied as a class of Cyber-Physical Systems. The traditional method of systems engineering has limitations in analyzing SoS characteristics, including interaction, high dimensionality, emergent behavior, evolutionary development, etc. Therefore, mission reliability analysis of SoS is increasingly important.

In this study, we used DoDAF 2.0 (the DoD Architecture Framework) and Petri net to analyze mission reliability of the formation collaborative defense SoS (FCD-SoS). Firstly, according to the FCD-SoS mission process, we established an overall view and also a high-level operational concept view. Then, we achieved physical architecture and organization relationship model of FCD-SoS; and used a multi-view modeling method to describe evolution of critical elements through the top-down decomposition process of SoS. Finally, we established a hierarchical generalized Petri net (HGPN) by transforming the multi-view model, and got its mission reliability analysis by using Monte-Carlo simulation.

CONCLUSIONS: In this paper, we studied the FCD-SoS and proposed a hierarchical decomposition model based on critical elements. Then, according to the DoDAF view products and architecture hierarchy decomposition model, a HGPN model is applied to describe typical mission process and scenarios. Finally, we used the Monte-Carlo simulation method to solve the numerical problem. The mission reliability of FCD-SoS is achieved under a typical combat mission profile.

1 INTRODUCTION

In recent years, with the development of complex large systems, many new complex "giant" systems have emerged as System of systems (SoS) [1]. SoS is a concept proposed to solve complex system combination issues: a larger system combined by independent functional systems for implementing specific functions [2]. Traditional system engineering ideas and methods are effective in dealing with the complexity of a single system, but its effectiveness in dealing with SoS problems is limited, and then researches on system engineering came into being. Compared to conventional complex systems[3], SoS has many distinguish features, such as, operational and managerial independence of elements, evolutionary development, emergent behavior, geographical distribution of elements, interdisciplinary study, heterogeneity of systems, etc. In this paper, the SoS is defined as: a collection of various systems for executing a mission. SoSs meet requirements of each mission functionally, operate independently, dispersed in geography, and exchange information between each internal system. In addition, the entire SoS adapts and evolves alone with mission progresses continuously.

Since, the definition, architecture design, modelling, ‘ilities assessment and optimization of SoS have been extensively studied[4][5], we mainly considered the SoS architecture modelling and mission reliability analysis in this paper.

The DoDAF 2.0 [6] is an architecture framework which provides various views for multiple stakeholders. It can completely and unambiguously describe the SoS architecture. Griendling and Mavris [7] reviewed a paper related to create executable architecture by using DoDAF. The architecture modeling methods mainly include Markov Chains, Petri Nets, System Dynamics models and Mathematical graghs. They also summarized the mapping between SoS architecture modeling, simulation and DODAF product models. Griendling et al. [8] studied the architecture representation and modeling process by using DoD products. AbuSharekh et al. [9] developed the synthesis of executable model from DoDAF, which considered the temporal and queuing issues. Piaszczyk [10] presented a Model based systems engineering method that focuses the system engineering process on SoS modeling. Mordecai et al. [11] depicted a conceptual modeling framework for model-based interoperability engineering for SoS, which integrates multilayered interoperability specification, modeling, architecting, design, and testing.

Petri Net is a common implementation of discrete event simulation[12]. It mainly contains four elements: Place, token, transition and arc. Place represents a mission procedure or state; tokens move between places according to the transition rules. Marsan et al. [13] presented a generalized stochastic Petri nets (GSPN) which were applied to evaluate the performance of multiprocessor systems. Feng et al. [14] developed the

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Generalized Stochastic Petri Net which describes the procedure of getting a time window.

The creation of SoS is derived from the target mission. In engineering domain, researchers evaluated the SoS via reliability, safety, robustness and resilience [5], [15]–[17], etc. Ayyubc [18] presented a SoS resilience metric which consider the failure profile, recovery and various times.

As a typical SoS, which turned the single platform with mission self-view mode into the formation collaborative defense, the FCD-SoS is used for architecture modeling and mission reliability analysis in this paper. In addition, it enhanced air defense and anti-missile capability of the formation overall. Firstly, the FCD-SoS architecture is analyzed to study the element-level coordination of the formation-to-air operations. Then, DoDAF is used to view product and describe its architecture and mission scenarios. According to characteristics of the SoS, a hierarchical decomposition model of the architecture based on key elements is presented. Secondly, according to the DoDAF view products and architecture hierarchy decomposition model, a hierarchical generalized Petri net (HGPN) model is applied to describe typical scenarios, and a HGPN-based collaborative combat mission process model is established. Finally, according to the mission process, establishing a mission reliability model for a typical combat mission profile; and the Monte-Carlo simulation method is applied to solve its numerical problem.

2 SOS ARCHITECTURE HIERARCHICAL MODELING

2.1 SoS composition

In the FCD-SoS each formation needs to perform a set of missions or sub-missions (target or sub-target) to achieve the overall mission. In order to achieve target missions, it is necessary to solve problems of mission assignment, conflict handling, and formation mission capability, and so on. At the same time, coordination and cooperation between formation component systems also should be considered as an important aspect, including: 1) component system resource sharing issues from both time and space coordination aspects. Time coordination mainly relies on synchronizing the relative instructions and operations of each component system to analyze resource reuse problems. Spatial coordination mainly analyzes the space sharing between systems, which needs to avoid dynamic and static obstacles while avoiding collisions to ensure safe operation; 2) information fusion issues. Data interaction between components systems could enhanced through enhanced data link. However, due to the resource limitations of the component system and its limited information sharing capabilities, it is necessary to analyze the real-time problem of information interaction between component systems and the problem of information sharing capacity. Formation collaborative air defense operations are joint collaborative actions that have common interests or benefits. Coordination and cooperation between heterogeneous systems requires integration of sensing, control, reconnaissance and planning in a suitable architecture decision-making framework.

According to mission characteristics of FCD, a network-centered collaborative SoS is formed through "resource sharing and information fusion" to identify the network-centric mission system elements. Building an All Viewpoint for FCD-SoS based on DoDAF 2.0, the physical architecture and organizational relationships of the system are decomposed, and a critical elements-based architecture decomposition process model is established.

2.2 Hierarchical (module) partitioning and functional analysis

The division and decomposition of the architecture level plays an important role in SoS researches. The division of the hierarchy is also the embodiment of the SoS characteristics, such as emergent and evolutionary. Different hierarchical decomposition methods have different emphasis on SoS researches, and different levels also reflect different SoS attributes and characteristics [19]. The division of SoS's level is also beneficial to study and analysis, and the influence of different levels of characteristics or attributes on the attributes of the whole system is obtained. According to characteristics of different systems, and resource sharing and information fusion characteristics between key subsystems or modules in the system, this paper proposed a critical elements-based SoS hierarchy decomposition method.

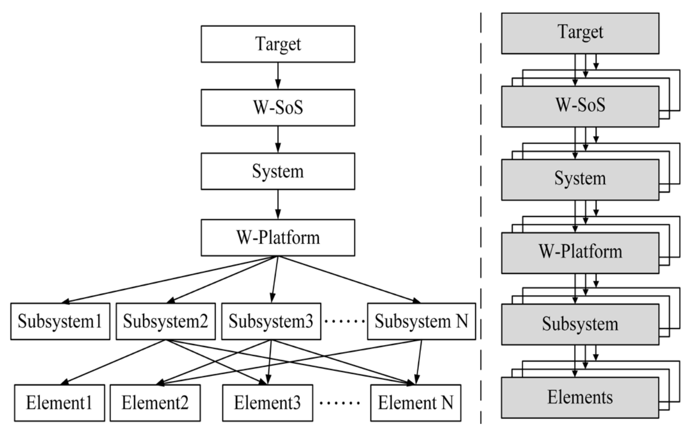

Fig. 1. Critical elements-based architecture hierarchy decomposition

The ultimate goal of FCD-SoS and anti-missile combat SoS is to improve the effectiveness of air defense operations (which may include reliability, safety, performance, flexibility, cost, etc.). In order to achieve target-level missions, the FCD-SoS should have three main functions, including detection pre-warning, communication and anti-missile operations. In addition, in order to realize these three functions, the FCD-SoS is divided into three main systems: reconnaissance system, communication support system and platform combat system.

The FCD-SoS consists of the following:

1) Destroyers, which have command and subsystems, weapon subsystems, communication subsystems and early warning detection subsystems;
2) Frigates, which have the same system function as the destroyers, command and control subsystems, weapon subsystems, communication subsystems and early warning

detection subsystems (radars);

3) Early warning airplanes, which have early warning detection subsystems, communication subsystems and command and control subsystems;

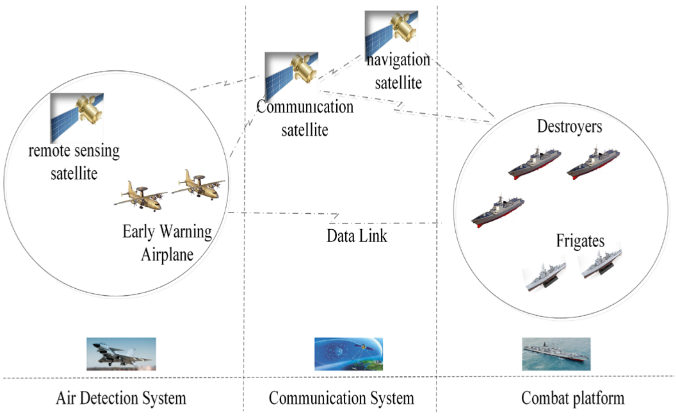

Fig. 2. SoS operational concept diagram (AV-1)

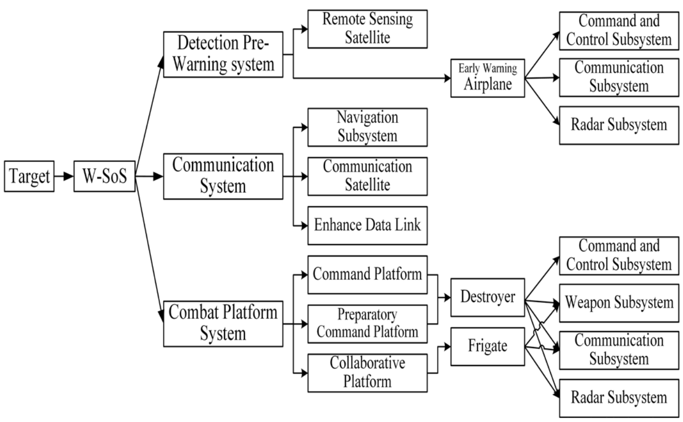

Fig. 3. Architecture hierarchy decomposition of FCD-SoS

The destroyer and the early warning airplane are collectively referred to as a platform. The platform consists of key operational equipment and systems, including radar (early warning detection subsystem), command and control subsystem (the platform's command and decision center, referred as the command and control subsystem), the weapon subsystem and communication subsystems. Only one platform's command and control subsystems is the main command and control subsystem, and the others are sub command and control subsystem. When the main command and control subsystem fails, one of the sub command and control subsystems on other platforms can replace all functions of the original main subsystem.

The enhanced data link, which consists of communication assurance system and communication subsystems of various platforms, including communication satellites and navigation systems, is used to achieve communication between platforms and information fusion.

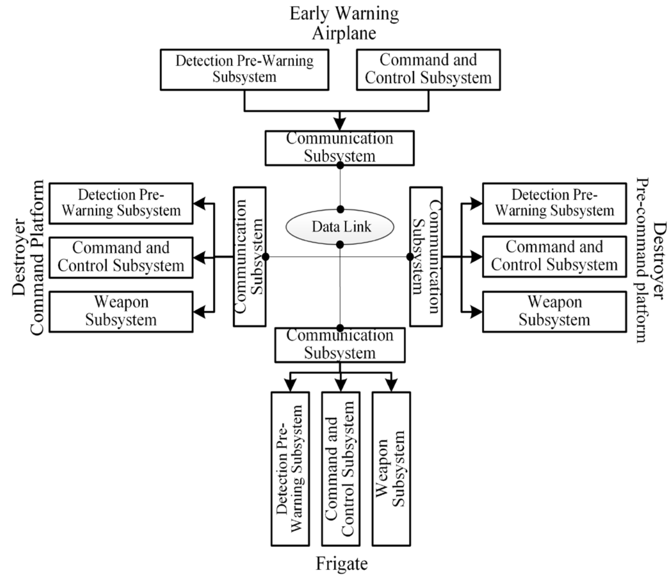

Fig. 4. System network-centric diagram

3 MISSION PROCESS ANALYSIS AND MODELING

3.1 Mission process analysis

The combat mission of FCD-SoS has multi-level and multi-stage characteristics. Each individual combat mission requires different levels of equipment to ensure their mission completion. The entire collaborative combat mission can also be divided into several different mission phases. Therefore, by considering these two characteristics, the mission model can be modeled by using the extensible Petri net. Operational activity sequence diagram (OV-6c) is illustrated in Fig. 5, operational event tracking description, and operational mission lines that make up the system nodes.

3.2 Mission process modeling

The multi-view products of DODAF are used to analyze the combat mission process, and the combat mission process model is established by the mission-oriented process method and hierarchical generalized Petri nets (HGPN).

First, the mission process is decomposed by modeling a multi-level Petri net for mission-oriented processes. The combat mission is broken down into three main phases: the discovery threat, the fire attack and the damage assessment mission phase. Place represents a mission flow or operational state. An extensible transition represents a phase in which a mission is executed or a sub-mission process, and a transition represents the execution of the mission. Therefore, a HGPN-based FCD mission process model is established as shown in the Fig. 6.

The first level is the overall extensible mission. After starting the mission, the Token in the first layer enters the second layer S_2, indicating that the enemy is found, and S_0 and S_2 represent the same state. Then enter the third layer, when Token enters S_6, enters the investigation mission stage, both S_8 and S_9 have Token, activate the transition t_4 so that Token enters S_{10}, indicating that the investigation mission is completed and the identification friend or foe (IFF) mission is completed. The result is fed back to S_3 in the second layer to continue the subsequent missions. S_4 and S_{11} also indicate the same state, indicating that the combat command is issued and enters the strike mission phase. Token enters S_{13} to indicate that the fire strike is completed. At this time, the result is fed back to the upper layer, and then the combat damage assessment is performed.

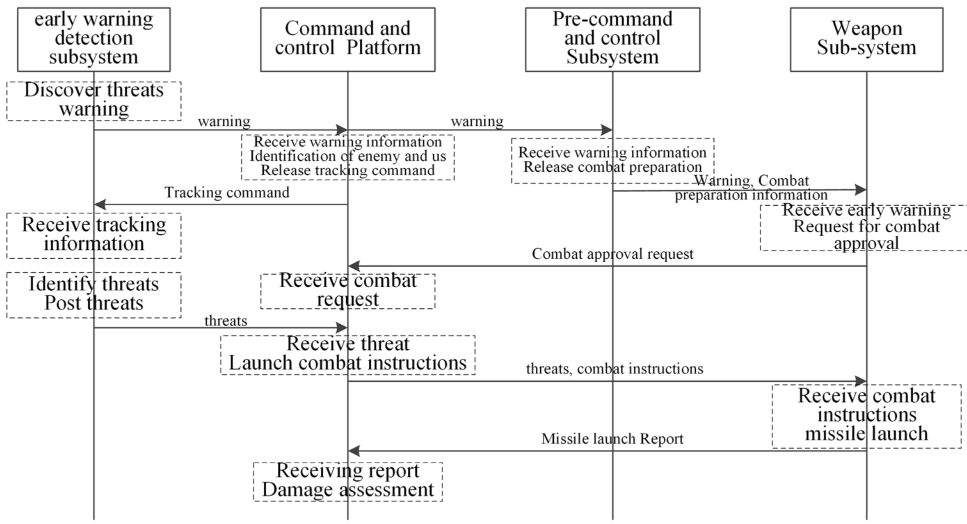

Fig. 5. Operational activity sequence diagram (OV-6c)

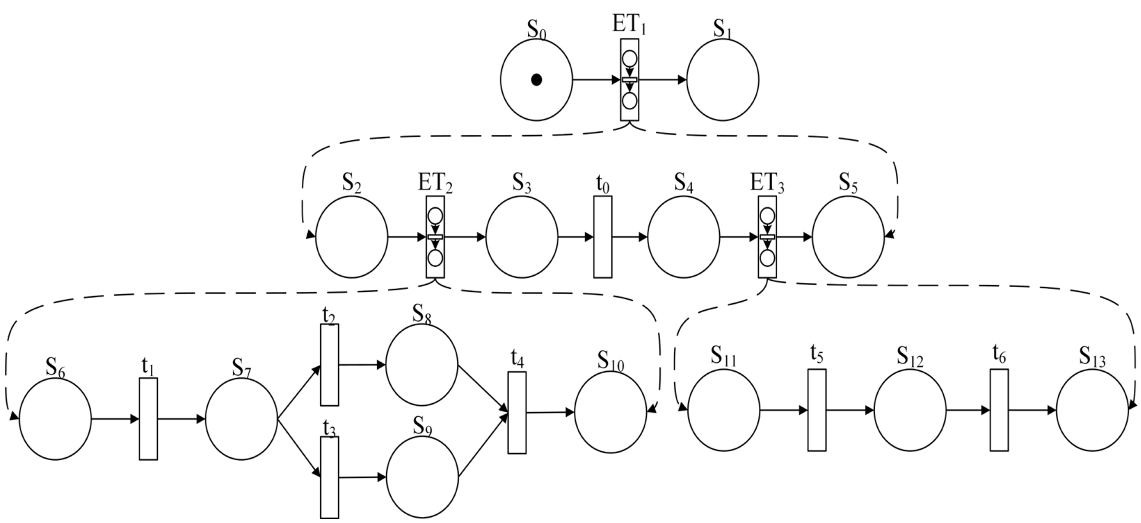

Fig. 6. HGPN-based collaborative combat mission process model

4 MISSION RELIABILITY ANALYSIS

The FCD-SoS described in the paper is used for mission reliability analysis. According to the specific operational scenarios, mission completion probability of different combat phases is analyzed. Then, according to the Petri net model, the Monte-Carlo method is used to analyze the mission reliability of the combat mission process, and then the mission reliability of the whole system in the anti-missile combat could obtain.

According to Section 3, we can get mission process model of SoS, and the mission reliability of its anti-missile operations is divided into three stages: IFF, fire attack and damage assessment. The calculation method of mission reliability is established according to the HGPN model. Probability of identification of the enemy includes two parts: probability of threat discovery ($r_1 = 0.9962$) and probability of IFF ($r_2 = 0.9250$). Fire strike MR mainly includes pre-war equipment support MR r_3, Accuracy rate of operational instruction r_4 and weapon strike success probability r_5. Assume that FCD-SoS only hits one target at a time.

After discovering the enemy's situation, carry out a fire attack, damage assessment after fire strike. If the strike fails, the firepower will be fired again, and multiple firepower strikes can be carried out during the effective strike time to conduct the damage assessment. According to the above analysis, the mission reliability of combat is shown as follow:

$$R_m = r_1 r_2 [1 - (1 - r_3 r_4 r_5)^n] \quad (1)$$

n is the strike number in the effective strike period.

Table 1 The implication of place and transition in HGPN

S_0	Mission begins
S_1	Mission executed successfully
S_2	Found the threats
S_3	Threat confirmation, issue warning
S_4	Issues combat instructions
S_5	Combat damage assessment completed
S_6	Detection systems find threats and issues warning
S_7	Command platform receives warning
S_8	Command platform issues the tracking command and the combat preparation mission.
S_9	Receive tracking information, identify threats, post threats
S_{10}	IFF, Receive threats, combat preparation
S_{11}	Threats confirmation, release of combat commands
S_{12}	Receive combat instructions, missile launch
S_{13}	Fire strike completed and sent a report
ET_1	Generalized transition, the entire collaborative combat mission time
ET_2	Detection and confirm threat time
ET_3	The time spent on the entire combat strike
t_0	Receive confirmation threats
t_1	The time from the issuance of warning information to the control subsystems received the information
t_2	The time taken by the control subsystems send tracking information to the detection system
t_3	The time taken by control subsystems issue pre-war information to combat system
t_4	Control subsystems receives information time
t_5	The time taken control platform to issue combat commands to the combat command
t_6	The time it takes for the combat command to be issued to complete the combat strike

Taking the reliability of pre-war equipment support MR r_3 as an example, the MR of sub-missions is analyzed. Pre-war equipment support mainly includes target situational awareness, missile locking, missile loading, and missile launch. The basic operational support missions must be completed within the prescribed time limit, and the operational guarantee success rate is r_3. The time distribution of the equipment support operation mission and its completion time limits are shown in the Table 2. The Monte-Carlo sampling method is used to simulate the pre-war equipment support mission reliability r_3. The simulation process is shown in the Fig. 7.

Number of simulations $n_s=1000$, Pre-war equipment support *MR*: r_3=0.9653, average pre-war equipment support time $t_{pes} = 7.462\text{s}$.

Similarly, we can also achieve r_4=0.95, $r_5 = 0.91$. And the fire strike $R_{Mfs} = r_3 r_4 r_5 = 0.8345$.

Then, the total mission time is:

$$ET_1 = t_0 + ET_2 + ET_3 = t_0 + t_1 + \cdots t_5 + n * t_6 \quad (2)$$

and $ET_3 = t_5 + n * t_6$. So the number of strikes is

$$n = \frac{ET_1 - t_0 - ET_2 - t_5}{t_6} \quad (3)$$

Given $ET_1 = 91.20s$. $t_0 = 2.82s$, $ET_2 = 20.50s$, $t_5 = 0.3\text{s}$, $t_6 = 22.1\text{s}$, it follows that $n \approx 3$.

Given $r_1 = 0.9962$, $r_2 = 0.9250$, the mission reliability of the cooperative combat mission follows that:

$$\begin{aligned} R_m &= r_1 r_2[1-(1-r_3 r_4 r_5)^n] \\ &= 0.9962 * 0.9250[1-(1-0.8345)^3] \\ &= 0.9173 \end{aligned}$$

Table 2 The pre-war equipment support mission process and parameters

pre-war equipment support	Distribution Type	Parameter	Time Up-limit(s)
Target Situational Awareness	Index Distribution	0.2	2
Missile Lock	Normal Distribution	2.5, 1	5
Missile Loading	Lognormal Distribution	1.2, 0.2	5
Missile launch	Evenly Distributed	0,0.2	0.2

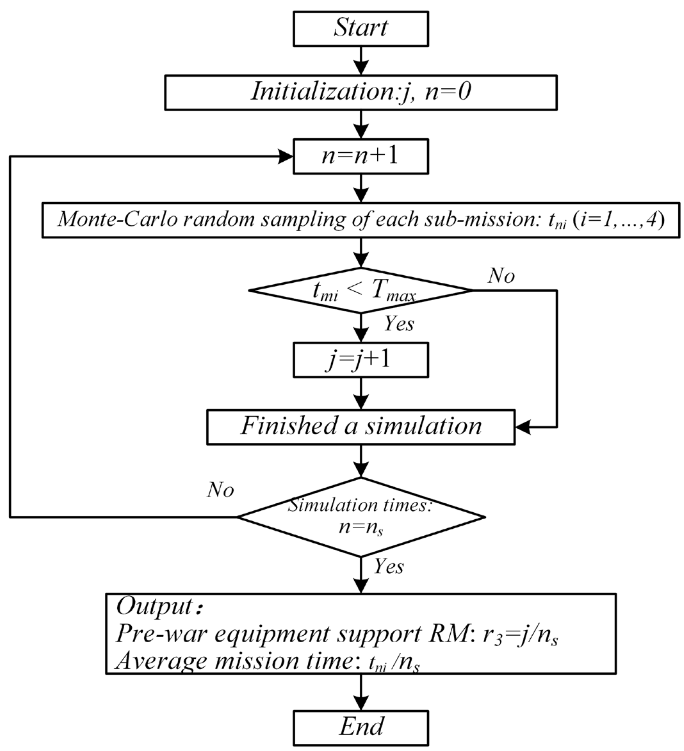

Fig. 7. The Monte-Carlo simulation process of Pre-war equipment support mission reliability

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