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A GSPN-based Dynamic Reliability Modeling Method for UAV Data Link System

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The reliability of data link system of unmanned aerial vehicle (UAV, or unmanned system) is the key to determine the success of unmanned system mission execution, and is also a difficult point of reliability modeling and analysis of unmanned system. Aiming at the characteristics of multi-service integration, complex structure and dynamic reconfiguration of UAV data link system, this paper proposes a method to build a dynamic reliability simulation model of data link service based on generalized stochastic Petri net (GSPN). By analyzing the characteristics of the UAV data link system, this method uses the resources, places, transitions and other elements in the GSPN model to describe various resources, states, behaviors and collaborative relationships in the data link system, and uses specific random variables to represent the component states and their durations to simulate the dynamic operation process of the data link system. Three typical services modes of UAV data link system as uplink remote control, downlink telemetry and downlink mission load transmission are modeled and simulated by using the Pipe software tool, which could accurately describe the synchronization, concurrency, distribution, conflict, resource sharing or competition, and reliability of the data link with dynamic reconfiguration behavior under the multi-service background could be evaluated. Finally, this paper proves that the GSPN based method could obtain reliable reliability evaluation results for the data link through a case analysis.

Keywords: reliability modeling，data link system，UAV， dynamic performance, Petri net, service reliability.

1. Introduction

With the application and popularization of unmanned aerial vehicles (unmanned systems) in more and more scenarios, the role of data link system is increasingly prominent and critical. As the information "adhesive" of unmanned system, data link system enables all unmanned platforms to realize data exchange, interconnection and sharing. Therefore, the reliability of unmanned aerial vehicle data link has received more and more attention. For example, Geng proposed a UAV data link reliability simulation analysis method based on mission profile by focusing on the impact of the complex electromagnetic environment on the data link system. Li applied advanced wireless digital communication technology and error correction coding technology to focus on the design method of aviation data link system with good performance and high reliability. Liu proposed the method of establishing IMA platform reliability model by using AADL language, and the "availability" index was calculated for multi-task in the data link. Traditional system reliability modeling methods such as reliability Block Diagram and Fault Tree Analysis (FTA), are static methods, which are difficult to describe the time sequence, dependency, environmental and human factors. Markov model can solve the problem of dynamic time series, but the number of Markov states will expand rapidly with the increase of system complexity, which greatly increases the difficulty of model establishment and solution. Therefore, traditional system reliability methods can not describe data link's dynamic behaviours such as dynamic reconfiguration, service integration, resource competition for reliability assessment.

This paper proposed a GSPN-based service reliability modeling and analysis method for UAV data link. The system reliability model could describe the service realization and link connectivity process of the data link, as well as the complex characteristics of strong coupling and nonlinearity under the characteristics of multi-source heterogeneous attributes.

2 Features and Service Modes of UAV Data Link System

2.1 Features of UAV Data Link

UAV data link system is generally composed of UAV terminals, ground station terminals, and a large-scale network system composed of many network information infrastructures and strategic infrastructures, which are designed to support military and civilian tasks within a certain space range, as shown in Figure 1. They can not only realize data information exchange between airborne, land-based and ship-based tactical data systems, but also form point-to-point and point-to-multipoint data link. The data link enable the computer system of the mission platform to form a tactical data transmission, exchange and information processing network, which can provide relevant data and complete battlefield situation information for the commander and mission executor at the same time.

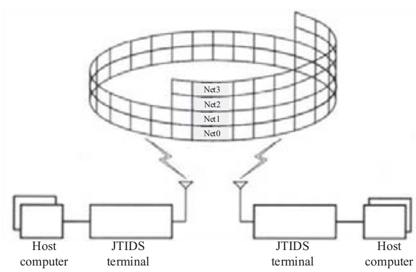

Figure 1 Composition of data link system

Due to the complexity and dynamic features of the data link system itself, the service modes running on the data link system usually have strong coupling features. Typical features of the data link system as follows:

- Complexity

The data link system is distributed on multiple devices, which determines the complexity of system architecture. Multi-service process has a great impact on the reliability of the system. Because of the links, equipment and other resources involved in different services are crossed, the faults generated in the implementation process will directly affect the reliability of other services. At the same time, in the context of multi-services, there will also be problems such as node performance degradation caused by mixed traffic and resource deadlock caused by resource sharing.

- Dynamic

The data link system faces various threats in its environment, such as physical attack, all kinds of electromagnetic interference, the harsh battlefield environment, these threats may reduce the service life and increase the possibility of damage. In addition, the high-speed of aircraft leads to the constant change of node location, and the need of mission or the change of flight situation lead to the communication network joining or exiting some nodes at uncertain time, which will cause the change of network topology. Therefore, the data link network system is highly dynamic.

- Coupling

A typical UAV data link is divided into three categories: the first one is to issue orders, so it is necessary to ensure the accuracy and reliability of the data; The second type is mainly to meet the requirements of data transmission in the battlefield, so it has high requirements for data transmission rate and bit error rate; The third one is mainly to meet the requirements of information transmission and sharing on the mission field. Therefore, when different types of data are transmitted upstream or downstream in the data link system, it also causes service coupling.

2.2 Typical Service Modes of UAV Data Link

Data link system has two typical service modes includes the uplink data link used to transmit the control command of the ground station to the UAV, the downlink data link used to receive the downlink data of the UAV. The amount of information transmitted by the downlink is large, and the information transmitted by the uplink requires higher reliability, and there is obvious asymmetry of the uplink and downlink. According to whether the distance between the UAV and the ground station is intervisibility, the UAV data link is mainly divided into LOS link and over-LOS link.

Table 1 Service task of the data link system

UAV data link service	line-of-sight link	over line-of-sight link
Uplink (remote control/flight control/optional control) data transmission service	C+UHF	Ku
Downlink telemetry data transmission service	C+UHF	Ku
Downlink mission load data transmission service	C	Ku

Through the above analysis of the functions and structural characteristics of the data links system of the UAV, it could be known that a good modeling method that can describe the synchronization, concurrency, conflict or competition of system resources is needed to carry out the reliability simulation analysis for the data link system.

3. GSPN-based Dynamic Behavior Modeling and Analysis of Data Link Reliability

3.1 Brief Introduction of GSPN Model

GSPN has outstanding dynamic modeling and analysis capabilities, can accurately define various event relationships in the data link. The concepts of tokens, places, and transitions can better describe the high coupling and dynamic behavior of the data link system. In the analysis of dynamic operation process of data link, it is often necessary to assign time attributes to transition points to describe the time required for the occurrence of events. In order to overcome the SPN requirement that the parameters obey exponential distribution and alleviate the problem of state explosion in complex system modeling, GSPN is proposed, which can be expressed in 7-tube model

GSPN=(P，T，F，K，W，M0，λ)。

Where

$N=(P,T,F)$ is a net model

$M:P\rightarrow Z$ (non negative integer level) is the representation function, M_0 is initial mark；

K,W,M are the capacity function, weight function and identifier of submodel *N*. M_0 is the initial mark of。

λ={λ_1， λ_2， …， λ_m} is the set of the average excitation rate of the transition, which represents the number of excitation times per unit time of the excitable transition. The reciprocal of the average excitation rate is the average delay of the transition. In reliability analysis, λ can be used to represent the distribution of component failure rate and maintenance rate.

If the transition $t\in T$ ， $\forall p\in{}^*t:M(p)\geq 1$ ， then the transition t is enabled，written as $M[t>$； if transition $t\in T$ could get the Subsequent mark M' after the enabled mark M, then $M[t>M'$。 For all $p\in P$， there is

$$M'(p)=\begin{cases} M(p)-W(p,t), p\in{}^*t-t^* & \text{(former not back)} \\ M(p)+W(p,t), p\in t^*-{}^*t & \text{(back not former)} \\ M(p)+W(t,p)-W(p,t), p\in{}^*t\cap t^* & \text{(fomer as well as back)} \\ M(p), p\in{}^*t\cup t^* & (t\ \text{extension}) \end{cases} \tag{1}$$

The transition conditions and occurrence rules can be explained as follows:

(1) A transition is enabled. At present, only if the number of tokens in each input repository of the transition is greater than or equal to the weight of the input arc, and the sum of the number of existing tokens in the output repository of the transition and the weight of the output arc is less than the capacity of the output repository; In short, it is "enough for the front and enough for the back";

(2) The necessary and sufficient condition for the change is that the change is effective;

(3) When a transition occurs, the number of tokens equal to the weight of the input arc is removed from the input repository of the transition, and the number of tokens equal to the weight of the output arc is generated in the output repository of the transition.

3.2 GSPN Simulation Modeling Principle of UAV Data Link

In this paper, the GSPN reliability simulation model is built by combining GSPN and Monte Carlo simulation, which is used for dynamic reliability evaluation of complex systems such as UAV data link. The simulation principle could be seen in Figure 2.

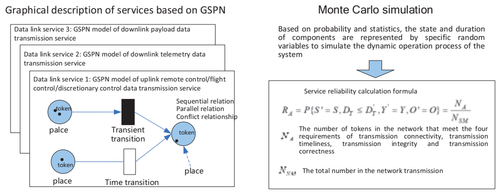

Figure 2 Analysis of simulation modeling principle based on GSPN

The GSPN network has excellent ability of graphical description. The place represents the local state of the system, and the transition represents the system action that changes the system state. The black dots distributed in some places are called the Token in the system, representing the type and quantity of system resources. According to the operation logic of the system, time transition and transient transition are used to connect these places representing the status of the equipment, and the dynamic operation process of the data chain business is expressed through the model languages of sequence relationship, parallel relationship and conflict relationship.

The transition of the marks state is essentially the change of the number of Tokens contained in the database before and after the transition. However, if there are too many nodes in the model, then the calculation is too large to solve. Monte Carlo simulation can express the component state and its duration through the setting of time transition random variables, and can simulate the dynamic operation process of all service modes. It is not sensitive to the dimension of the model and has no strict requirements for parameter distribution, which could offset for the shortcomings of SPN in model solving.

3.3 Reliability Modeling of UAV Data Link

The data link reliability simulation model could provide not only the analysis of the logic structure of service completion at the static level, but also the service behavior of the system's combined call process of resources during the "dynamic" level. After the system model of service function behavior is established, the dynamic process of system state transition can be analyzed.

(1) Graphical representation of service processes

Uplink telecommand and downlink telemetry services can work simultaneously with C link, UHF link and satellite communication link within the range of sight distance. The downlink mission load data transmission service can work at the same time with the C link and the satellite communication link within the sight range. Any control position and flight control position can be used as backup for each other, and can be described by "parallel relationship".

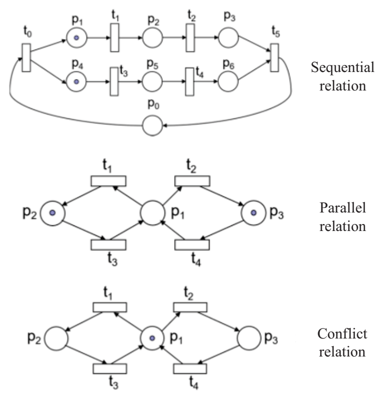

Figure 3 Description of three relationships between t_1 and t_2

There is only one backup computer. When more than one computer fails, it will compete for the backup computer, indicating that the change of the conflict relationship points to the main computer replaced by the backup computer, which can be described by conflict relationship. The optical transceiver can send data only after the switch successfully sends data, which can be described by sequence relationship.

(3) GSPN modeling of the service process

The place is used to represent the equipment or component status of the data link system, and the token represents the resources carried on the system. According to the operation logic of the system, these places are connected, and time transition and transient transition are used respectively. Time transition represents that when the transfer is triggered, it will delay for a certain time, such as the delay of signal processing or the duration of normal work, etc., and the transient transfer is the delay time of 0. Take the uplink remote control/flight control/arbitrary control data transmission service as an example to build the GSPN simulation model, as shown in the figure 4.

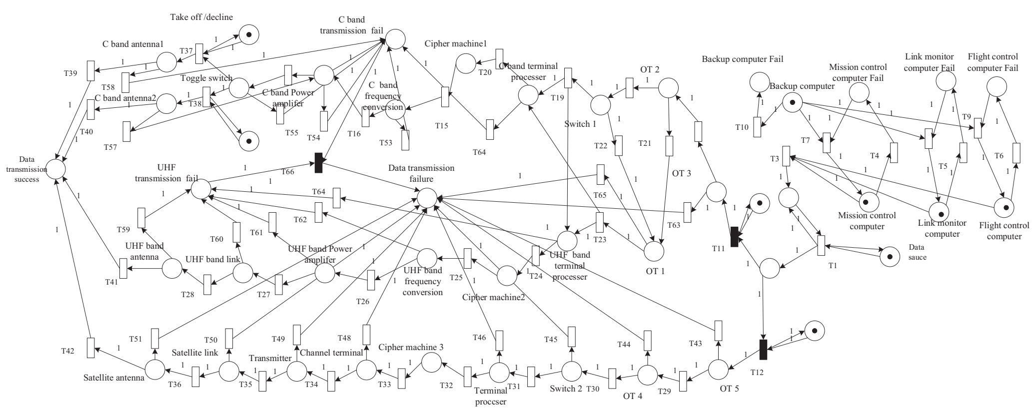

Figure 4 GSPN model of uplink (remote control/flight control/arbitrary control) data transmission service

3.4 Simulation Analysis Settings

After connecting the places with transfer, the weight is determined for the directed arc between connecting the place and transition according to the system characteristics. The weight represents the number of tokens consumed from the place above the arc, as *m*, after the transfer below the arc is enabled and fired, and the number of tokens transmitted from the transfer to the downstream place, as *n*, where *m* is not necessarily the same as *n*. Finally, confirm to add the correct number of tokens to the places.

For time transition, it is necessary to associate a delay that obeys a specific random distribution. Set the *rate* parameter in the transition to set the distribution function to which the transition occurs. Therefore, set the *rate* parameter value of the transition associated with equipment failure in the GSPN model of data link service as its corresponding failure rate, and set the number of Monte Carlo simulations for simulation analysis.

4 Case analysis

4.1 GSPN Simulation Model Construction

According to the above modeling method, Pipe2.5 (Platform Independent Petri Net Editor) software tool is used to formally model and describe the GSPN of a certain UAV data link system service reliability, correctly express the conflict, parallelism and other resource competition of signals, and set the *rate* parameter value of the transition associated with equipment failure as its corresponding failure rate. The simulation module is used to analyze the established type, Random Firing 20000 times (i.e. Monte Carlo simulation times), simulate the continuous data transmission process, and repeat for 5 times.

4.2 Results Analysis

According to the above settings, the average number of tokens and its 95% confidence interval of each place, and the simulation results are obtained as shown in Table 2. The service reliability are calculated as follows:

$$R_{\text{ULDT}} = \frac{1021.40593}{1021.40593 + 0.21689} = 0.99979$$

$$R_{\text{DLTDT}} = \frac{841.22749}{841.22749 + 0.34318} = 0.99959$$

$$R_{\text{DLMLDT}} = \frac{957.46763}{957.46763 + 0.75261} = 0.99921$$

Table 2 Simulation results of the data link system

Service	Token	Average number of tokens	Confidential interval of 0.95

Uplink data transmission	Data transmission succeeded	1021.4059	6.88951
	Data transmission failure	0.21689	0.63216
Downlink telemetry data transmission	Data transmission succeeded	841.22749	48.2656
	Data transmission failure	0.34318	0.75639
Downlink payload data transmission	Data transmission succeeded	957.46763	18.0979
	Data transmission failure	0.75261	1.17054

Taking the uplink data transmission service as an example, in the case of ignoring its dynamic reconfiguration behavior, it is simplified to a series-parallel system, and RBD is selected to verify the correctness of the GSPN simulation model. The data transmission path depends on whether the aircraft is in the range of LOS or beyond the range of LOS. Assuming that the aircraft is in two states with the same probability, the calculated reliability is 0.99856. On the basis of considering the dynamic reconfiguration behavior, the calculation result of GSPN simulation model is slightly higher than that of RBD, which conforms to the actual situation, indicating that the method is correct and reasonable for the reliability modeling and analysis of UAV data link service.

5 Conclusion

This paper proposes a GSPN-based reliability modeling and evaluation method for UAV data link system, which can accurately describe the reliability statues of the data link, which has good application valued in data link reliability assessment:

1) Considering the UAV data link provides the realization of different system functional requirements through the scheduling and combination of multi resources, so MTBF is no longer applicable for this process. This paper proposes to use service reliability to describe the reliability of the data link system;

2) The data link service behavior is constructed from the static and dynamic perspective by constructing the sequence relationship, parallel relationship and conflict relationship, which breaks through the traditional reliability modeling difficulty in describing the dynamic behavior relationships such as time sequence and competition;

3) With the help of simulation tools such as Pipe and based on the Monte Carlo simulation principle, the directional arc weight, time transition and simulation times are set application, which can alleviate the problems of state explosion and solution difficulty in the complex system modeling, and has good application value in real engineering.

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