ISBN: 978-981-18-7950-0
2023 the 13th International Workshop on Computer Science and Engineering (WCSE 2023)
doi: 10.18178/wcse.2023.06.046

Reliability Analysis of Manual Complex Mission Systems based on Petri Nets

Jieyi Zhang [1, 2], Hongqi Yang [1, 2, +], Yujie Liu [1, 2], Qi Yang [1,2], Ning Hu [1, 2] and Guojian Nie [1, 2]

[1] China Electronic Product Reliability and Environmental Testing Research Institute, Guangzhou, China
[2] Key Laboratory of Industrial Equipment Quality Big Data, MIIT, Guangzhou, China

Abstract. Aiming at the problems of difficulty in reliability modelling and evaluation for manual complex mission systems, a Petri net based reliability analysis method for manual complex mission systems is proposed. Firstly, analyze the scene of the manual complex mission systems, and sort out the relevant elements of the mission; Secondly, the CPN model of manual complex mission operation process and GSPN model of manual complex mission equipment resources are constructed; Finally, the quantitative analysis of reliability of manual complex mission is carried out from three aspects: failure probability of operation steps, failure probability of operation response and failure probability of equipment resources. The analysis results show that the method has good engineering applicability, and provides a new idea for the simulation of the manual complex mission process.

Keywords: manual complex mission system, reliability analysis, Petri nets

1. Introduction

The manual rendezvous and docking system and other manual complex mission system are key systems for the crew to complete system docking and other missions in emergency situations. In order to meet different mission requirements, the structure and functions of equipment systems such as spacecraft are becoming increasingly complex, and the coupling effects of crew, equipment, and various complex operating environments are becoming increasingly evident. Therefore, how to conduct reliability modeling and simulation analysis for a human in loop complex mission system composed of crew, equipment, and complex usage environments has important research significance.

Markov method has certain advantages in solving state changes and computing of complex systems. Alam M and Al-Saggaf U M established a quantitative reliability model for multistage task systems using Markov processes, and solved the multistage task system by solving a series of single stage systems with appropriate initial conditions [1]. Yong O and Dugan J B used Markov chains to solve dynamic fault trees and evaluate the reliability of complex mission systems [2]. The Markov method is simple and feasible, and the probability of each Markov state transition can be indirectly obtained from the relationship between the failure probability and reliability of equipment components, making it more convenient for practical application. However, this method has the problem of state space explosion and is not suitable for analyzing and evaluating the mission success of complex systems. Petri nets can not only visually represent and analyze the impact of various resources on the process of complex tasks, but also provide the required quantitative analysis results for specific application scenarios. Chew et al. established a Petri net model for the reliability analysis of Phased-Mission Systems, and implemented a direct conversion from stage fault trees to Petri nets [3]. However, in current work, the impact of human factor related failures on mission system reliability is often ignored, and the relationship between human factor failures and equipment failures is not systematically treated, resulting in inaccurate reliability analysis results.

Aiming at the manual rendezvous and docking mission process, this paper building a coloured Petri net(CPN) model for the manual rendezvous and docking operation process and a generalized stochastic Petri nets(GSPN) model for the manual rendezvous and docking equipment resources, and conducting simulation

+ Corresponding author.
E-mail address: yhqceprei2021@163.com

analysis from three aspects: the failure probability of operation steps, the failure probability of operation response, and the failure probability of equipment resources, to obtain the quantitative evaluation results of the reliability of the manual rendezvous and docking task system.

2. Analysis of Manual Complex Mission Scene

2.1. Mission phases

The manual rendezvous and docking mission is a typical manual complex mission, which generally includes four phases[4]: before docking, remote docking operations, docking and holding, and final approach. In before docking phase, Astronauts observe and diagnose the current state, and connect the manual control line. In remote docking operation phase, astronauts observe the wide field of view image on the LCD screen, locate the docking target, manipulate the translation handle and posture handle based on the target image to gradually eliminate position and posture deviations, and establish an initial docking speed. In docking and holding phase, when the distance from the docking target is 30 meters, astronauts stop the operation, turn off the engine on the translation handle, maintain the current position and posture, observe the surrounding docking environment, switch to a narrow field of view, and prepare for the final docking. In final approach phase, astronauts observe the target image to eliminate positional and attitude deviations, establish the final approach speed, drive the spacecraft slowly towards the docking target, and stop the handle operation when the green light on the docking ring is on.

2.2. Mission resources

Manual rendezvous and docking mission resources[5] include measuring devices, display equipments, control equipments, execution equipments, and astronauts.The measurement devices are responsible for monitoring the attitude and relative distance of the docking object and target object. Astronauts use the display equipments to determine the docking status and perform operations. The control equipments convert astronaut operation instructions into corresponding control signals, and ultimately the execution equipments adjusts the attitude and speed of the docking object. The functional architecture relationship between these resources is shown in Fig. 1.

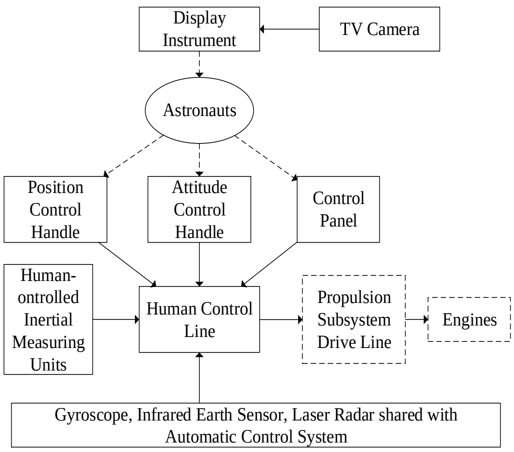

Fig. 1: The functional architecture relationship between manual rendezvous and docking mission resources

(1) Measuring devices

The measuring devices are the "eyes" of the entire manual rendezvous and docking system, providing important information input for subsequent display equipments work and astronaut operation judgment. The human controlled special measurement equipment includes human-controlled inertial measuring units and a TV camera; Some measuring components shared with automatic control systems include liquid floatation, infrared earth sensors, and laser radar. Gyro and infrared earth sensors are used for attitude determination, and lidar measurement information is used to display relative distance and velocity information for astronaut instruments. Astronaut manual docking is mainly based on television cameras and target images to determine the relative position and posture.

(2) Display equipments

After receiving the information from the measuring devices, the display equipments display the attitude and related information to the astronaut in the form of audio, video and images. Display instruments are generally installed in the spacecraft where the astronauts are located, commonly shared by the instrument display units in the spacecraft where the astronauts are located, or installed independently. Their main function is to display the video images captured by the television camera on the instrument screen in real time. In order to facilitate observation and confirmation by astronauts in engineering, grids and lines are added during video display, and astronauts can send corresponding control commands, Superposition the observation and control parameters you need on the display unit to timely and accurately grasp the changes in navigation parameters.

(3) Control equipments

The control equipments receive the astronaut's control actions or instructions and converts them into control signals. The control equipments mainly include GNC system human control circuit, attitude control handle, position control handle, and instrument system control panel. The astronaut manual control process mainly uses position handles, attitude handles, and control panels.

(4) Execution equipments

The execution equipments complete deceleration, rotation, and other actions based on the control signal of the operating equipment. The execution equipments mainly include equipment such as attitude and orbit control engines and docking mechanisms.

(5) Astronauts

Astronauts, as the core and interactive hub of the manual rendezvous and docking mission process, have an indispensable importance in the entire mission system. The manual interactive docking task requires astronauts to have high operational skills and reaction speed, accurately capture important reference information from the display in a very short time, adjust personal attention and other mental resources, and achieve consistent observation, judgment, and operation. Astronauts should have sufficient parameter information about the relative motion of target spacecraft and tracking spacecraft.

3. Comprehensive Modelling Method for Manual Complex Mission Process Based on Petri Nets

3.1. Modelling method for manipulation process based on CPN

The basic elements of the control process are the control status, control resources, and logical relationships between operation steps. The following is the definition of the basic elements.

(1) Control status

The control status represents the completion status of each operation step, represented by the library. When a state library contains a token, it indicates that all previous steps in the library have been completed, and subsequent steps have not been completed. Set $P_C = \{p_{c1}, p_{c2}, \cdots, p_{cn}\}$ as the set of control state libraries and the number of state libraries. Due to the fact that the tokens in the state library only represent the status of whether the task has been completed, there is only one color token, and each state library can only have at most one token. The identification and capacity function of the state library can be represented by equation (1).

$$\begin{cases} M(p_c) = m_c \times c_c, \ m_c = 0 \ \text{or} \ 1 \\ K(p_c) = c_c \end{cases} \tag{1}$$

where c_c is the color of the state library's tokens, and m_c is the number of tokens in the state library.

(2) Manipulate resources

Manipulation resources refer to the resources required for the manipulation process, including personnel resources and equipment resources. Human resources refer to human cognitive functional resources, which can be divided into perceptual resources, cognitive resources, and executive resources. There are various types of equipment resources, including measuring devices, display equipments, control equipments, execution equipments.

The resource status reflects the system's ability to complete operational steps. At the same time, the total amount of available resources in the system is limited. If the required resources for executing operational steps are higher than the available resources of the human-machine system, conflicts will arise and the predetermined control tasks cannot be completed.

If $P_S = \{p_s\}$ represents the collection of human cognitive function resources, its identification and capacity function expression is:

$$\begin{cases} M(p_s) = m_{s1}c_{s1} + m_{s2}c_{s2} + \cdots + m_{sp}c_{sp} \\ K(p_s) = k_{s1}c_{s1} + k_{s2}c_{s2} + \cdots + k_{sp}c_{sp} \end{cases} \tag{2}$$

where $c_{si}(i = 1, 2, \cdots, p)$ is the color of the token in the *i*-class cognitive function resource pool p_s; m_{si} is the number of cognitive functional resources available in place s_s in a certain state; k_{si} is the maximum value of the *i*-class category of cognitive functional resources in the place.

Similarly, the identification and capacity function expressions of device resources are:

$$\begin{cases} M(p_m) = m_{m1}c_{m1} + m_{m2}c_{m2} + \cdots + m_{mq}c_{mq} \\ K(p_m) = k_{m1}c_{m1} + k_{2}c_{m2} + \cdots + k_{mq}c_{mq} \end{cases} \tag{3}$$

where $c_{mj}(j = 1, 2, \cdots, q)$ represents the color of the *j*-class device resource token; k_{mi} is the maximum value of the *j*-class device resource in the place.

(3) Logical relationship of operation steps

The logical relationship between operation steps is represented as $R \subseteq T \times T$, and $r_{ij} \in R$ represents the logical relationship between t_i and t_j. The logical relationships between operational steps mainly include serial relationships, parallel relationships, and selection relationships. Due to the fact that personnel resources and equipment resources do not have an impact on the logical relationship of operational steps, when describing the logical relationship of operational steps based on CPN, each resource place is not considered, and only the logical relationship between the manipulation state place and the transition is described.

The serial relationship represents the sequential dependency relationship of the operation steps, and the completion of the previous operation step is a necessary condition for the start of the next operation step. The serial relationship of the operation steps based on CPN is shown in Fig. 2, that is, if $t_i \in \bullet p_c \cap t_j \in p_c \bullet$, then r_{ij} is the serial relationship.

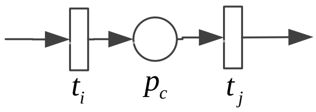

Fig. 2: Serial relationship

The parallel relationship indicates that two or more operational steps can start simultaneously, and only after all of these operational steps are completed can the next operational step proceed. The parallel relationship of operation steps based on CPN is shown in Fig. 3, that is, $\forall t \in T$, if $p_{ci} \in \bullet t_i$, $p_{cj} \in \bullet t_j$ and $\{p_{ci}, p_{cj}\} \subseteq t_k \bullet$, or $p_{ci} \in \bullet t_i$, $p_{cj} \in \bullet t_j$ and $\{p_{ci}, p_{cj}\} \subseteq \bullet t_k$, then r_{ij} is a parallel relationship.

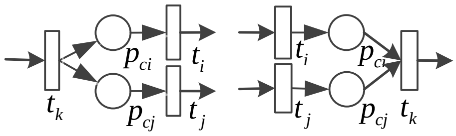

Fig. 3: Parallel relationship

The selection relationship indicates that in a certain state, one of multiple operation steps can be executed, and the completion of any one operation step can achieve a change in a certain state. The selection relationship usually occurs after astronaut judgment or decision completion. The selection relationship of operation steps based on CPN is shown in Fig. 4, that is, $\forall t \in T$, if $\{t_i, t_j\} \subseteq \bullet p_{ci}$ or $\{t_i, t_j\} \subseteq p_{ci}\bullet$, then r_{ij} is the selection relationship.

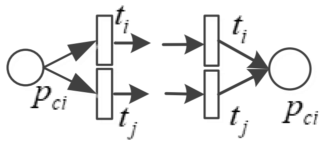

Fig. 4: Selection relationship

3.2. Modelling method for equipment resource reliability based on GSPN

Assume the reliability of equipment resources as follows:

(1) A mission is composed of p independent functional units, which are connected in series and do not consider maintainability;

(2) Each functional unit has a redundant backup structure, and each functional unit contains multiple basic units. At any given moment, each basic unit is in any of the three states of working, reserve, and failure. The system state is the sum of the states of each basic unit;

(3) For the functional units of the cold backup structure, the backup unit will only work if the main unit fails. When the main unit fails, the backup unit will immediately transition from the backup state to the working state, and the failure rate of the backup unit during the backup period is considered to be 0. For the functional units of the warm backup structure, the backup unit will only work if the main unit fails. When the main unit fails, the backup unit will immediately transition from the backup state to the active state. The backup unit has a low failure rate during the backup period and may fail during the backup period. For the functional units of the hot backup structure, the main unit and backup unit only have two states of activation and failure, which is equivalent to a parallel structure.

(4) The lifespan distribution of system resources follows an exponential distribution.

Based on the above assumptions, the steps for modeling equipment resource reliability are:

(a) Identify the system equipment functional units required for the task and determine the elements of the GSPN model;

(b) Based on the backup mechanism of each functional unit, define the state of the basic work unit node (including activation state, backup state, and failure state) and the dynamic transformation logic between each state, thereby establishing a reliability model for each functional unit;

(c) Determine the logical relationship of device resource failure based on the logical relationship of system functional unit nodes, and establish a system task reliability model.

4. Case Study

Taking the spacecraft manual rendezvous and docking mission system as an example, reliability modeling and analysis are conducted.

4.1. Modelling the manipulation process of manual rendezvous and docking based on CPN

Based on the analysis of manual rendezvous and docking mission scenarios, a CPN-based control process model is constructed as shown in Fig. 5, where S_C represents a resource place in a controlled state, and each resource place has only one color token C_C, and when there is a token, it indicates that it is in that state. The weight functions between the transition and control resource state databases are all expressed as w_k. The astronaut cognitive function database includes sensory resources c_{h1}, cognitive resources c_{h2}, and executive resources c_{h3}. The equipment function resource library includes a display as c_{m1}, a translation handle as c_{m2}, a posture handle as c_{m3}, a wide and narrow field of view switch button as c_{m4}, a human control and automatic control line switch button as c_{m5}, a wide field of view TV camera as c_{m6}, a narrow field of view TV camera as c_{m7}, a human control inertial measurement unit as c_{m8}, a manual control line as c_{m9}, an attitude control engine as c_{m10}, and a track control engine as c_{m11}. The S_{cij} control state place is an intermediate state place between the S_{ci} control state repositories and the S_{ci+1} control state repositories; from

t_1 to t_{11} are operational transitions, which can only be triggered when the Tokens in the resource place associated with each operational transition meet the requirements of the on-arc weight function; from t_{12} to t_{14} is a logical transition that has no practical significance, and is used for merging operation states after parallel operations.

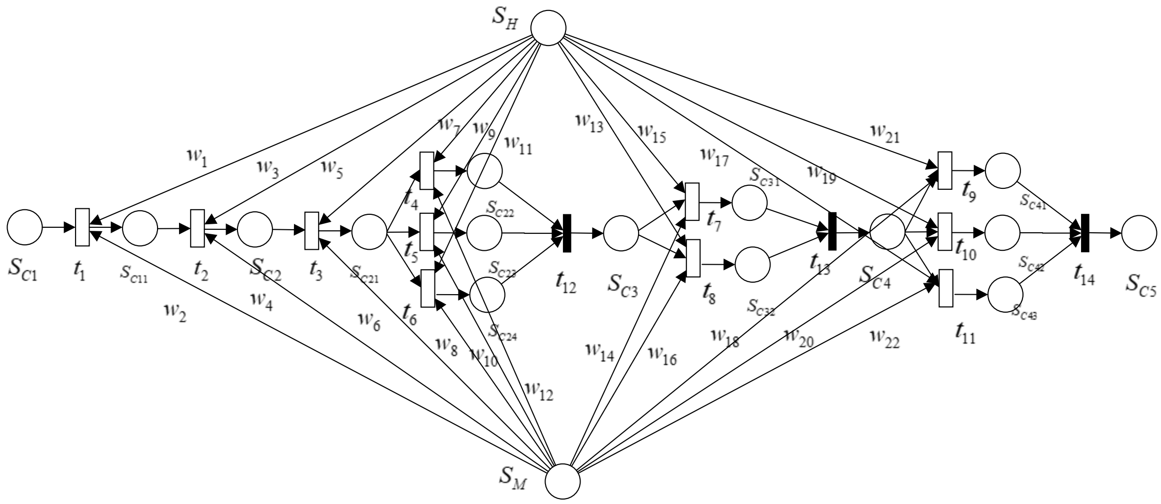

Fig. 5: A CPN-based manipulation process model for manual rendezvous and docking

4.2. Modelling the manual rendezvous and docking equipment resources based on GSPN

The resource analysis model of manual docking equipment based on GSPN[6] was established, as shown in Fig. 6. Among them, the TV camera, human-controlled IMUs and engines are dual-redundancy hot backup devices, the manual control line and controller are dual-redundancy warm backup devices, and the LCD screen is dual-redundancy cold backup devices.

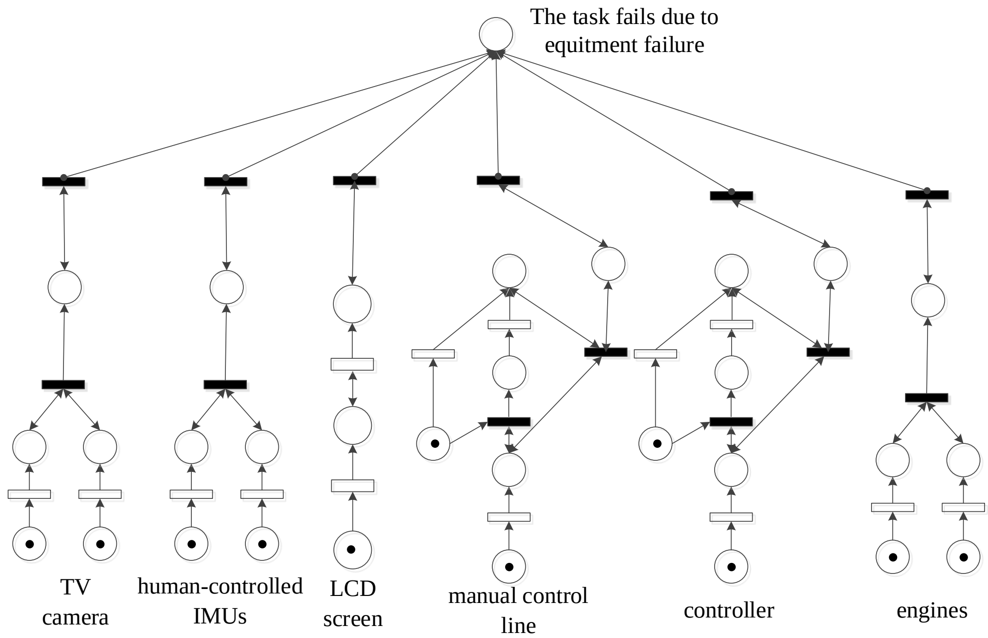

Fig. 6: Equipment resources model for manual docking mission based on GSPN

4.3. Failure probability analysis of operation steps

The human error of astronauts is divided into perceptual error, cognitive function error, and executive function error. Assuming that the probabilities of the three failure modes (incomplete, inaccurate, and untimely) corresponding to each human error are equal, the failure probability of each operation transition in the CPN model during the manual rendezvous and docking operation process can be obtained as shown in Table 1.

Table 1: Failure probability of operation transition during manual docking

Subtask	Transition	Meaning	Specific errors	Error Mode Type	CFP
Preparation before docking T1	t_1	Observe and diagnose the current state	Incomplete information diagnosis	Incomplete knowledge based cognition	0.065
	t_2	Connect the manual control line	Manual control line not connected	Skilled execution is not comprehensive	0.0011
Remote docking operation T2	t_3	Specify the operation strategy after locking the docking target	Operational strategy formulation error	Rule based cognitive inaccuracy	0.013
	t_4	Eliminate position deviation based on target image	Incorrect operation force and direction	Inaccurate skilled execution	0.0011
	t_5	Eliminating Attitude Adjustment Based on Target Images	Incorrect operation force and direction	Inaccurate skilled execution	0.0011
	t_6	Establish initial docking speed	Incorrect operation force and direction	Inaccurate skilled execution	0.0011
Docking and holding T3	t_7	Shut down the engine and keep it in state	Failure to shut down the engine in time	Skilled execution is not timely	0.0011
	t_8	Toggle narrow field of view	Narrow field of view not switched	Skilled execution is not comprehensive	0.0011
Final approach operation T4	t_9	Eliminate position deviation based on target image	Incorrect operation force and direction	Inaccurate skilled execution	0.0011
	t_{10}	Eliminate attitude adjustment based on target image	Incorrect operation force and direction	Inaccurate skilled execution	0.0011
	t_{11}	Establish final approximation speed	Incorrect operation force and direction	Inaccurate skilled execution	0.0011

The analysis of the logical relationship between operation tasks and steps is as follows: The manual docking task is divided into four stages of subtasks, each of which consists of multiple operational steps. In the pre docking preparation task T1, t_1 and t_2 are in a serial operational relationship, and only when t_1 is completed can t_2 operations be performed; The t_3 and {t_4, t_5, and t_6} in the docking operation task T2 are in a serial relationship. The operations in { t_4, t_5, and t_6} can only be performed after the t3 operation is completed. The t_4, t_5, and t_6 operations can be performed simultaneously, which is a parallel operation relationship; In the docking hold task T3, t_7 and t_8 are parallel operations, while in the final approximation operation T4, t_9, t_{10}, and t_{11} are parallel operations.

According to the analysis results of the logical relationship between the above operation tasks and operation steps, the failure probability of the operation steps of the manual docking task is

$$F_T = 1 - \prod_{i=1}^{4}(1 - CFP_{Ti}) \tag{4}$$

$$CFP_{T1} = CFP_{t1} \cdot CFP_{t2} \tag{5}$$

$$CFP_{T2} = CFP_{t3} \cdot \max(CFP_{t4}, CFP_{t5}, CFP_{t6}) \tag{6}$$

$$CFP_{T3} = \max(CFP_{t7}, CFP_{t8}) \tag{7}$$

$$CFP_{T4} = \max(CFP_{t9}, CFP_{t10}, CFP_{t11}) \tag{8}$$

where CFP_{Ti} represents the operational failure probability of the ith subtask, and CFP_{ti} represents the operational transition failure probability of the jth subtask.

The transition failure probability value in Table 3 is brought into the above calculation formula, and the failure probability of the operation step is 0.002.

4.4. Operation response time analysis based on monte carlo method

In different scenarios of manual rendezvous and docking missions, the individual endurance of astronauts is different, and the time spent on each control action varies within a certain range. Using the operation response time prediction model, the time distribution function for each operation step can be obtained, as shown in Table 2.

Table 2: Time distribution of various transitions in manual rendezvous and docking tasks

Transition	Time distribution	Transition	Time distribution
t_1	N(5,0.5)	t_7	N(100,0.5)
t_2	N(1,0.4)	t_8	N(0.15,0.01)
t_3	N(5,0.5)	t_9	N(62,0.04)
t_4	N(62,0.4)	t_{10}	N(62.5,0.04)
t_5	N(62,0.4)	t_{11}	N(2,0.101)
t_6	N(2,0.4)		

Assuming that astronauts need to complete the final 80m manual rendezvous and docking task within T=310s, the starting time for automatic control equipment failure to turn into a human controlled docking event is at t=0. Monte Carlo method[7] is used to simulate the human operation response time, and a response failure probability with an initial available operation time of 310s is obtained as shown in Fig. 7. As can be seen from the figure, as the number of simulations increases, the response failure probability stabilizes in the range. When the available operation time is 310 seconds, the probability of response failure is high.

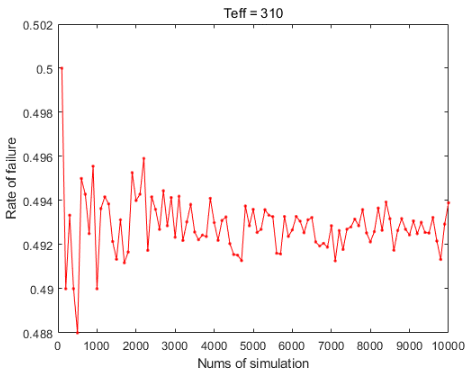

Fig. 7: Change process of response failure probability at initial time Teff=310s

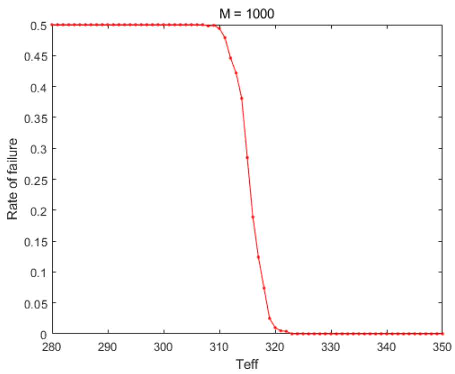

Fig. 8: Change process of response failure probability with initial available time

Assuming that the number of simulation cycles is 1000 and the available operating time Teff value at the initial time is 280~350 seconds, using Monte Carlo method for simulation, we can obtain the change process of the response failure probability with the available operating time Teff at the initial time, as shown in Fig. 8. As can be seen from the figure, when the available operation time is greater than 300 seconds, the response failure probability continuously decreases as the available operation time increases, and the response failure probability approaches zero at 323 seconds.

4.5. Failure probability analysis of equipment resources

The failure rates of each equipment in the GSPN model for manually controlled rendezvous and docking equipment resources are shown in Table 3.

Table 3: Equipment resource failure rate

Equipment category	Constituent unit	Failure rate $\lambda / 10^{-6}$
Measuring devices	Wide field TV camera	1.76
	Narrow field TV camera	1.76
	Human-controlled IMU	1.56
Display equipments	LCD display	1.82
Control equipments	Manual control line	1.96/0.7
	Translation handle and line	1.8/0.48
	Attitude handle and line	1.8/0.48
Execution equipments	Attitude control engine	2.73
	Rail controlled engine	2.73

Set the simulation time to 50000 hours, and the failure probability of the equipment resources can be obtained as shown in Fig. 9.

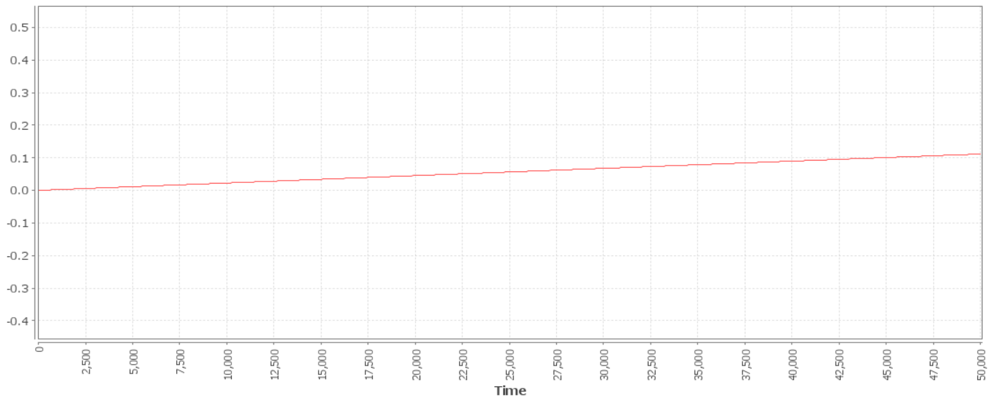

Fig. 9: Equipment resource failure probability Diagram

It can be seen from the above figure that the failure probability of system equipment resources increases with task time. When the task time is 50000 hours, the failure probability of system equipment resources is 0.1117.

4.6. Reliability calculation of manual rendezvous and docking mission

The reliability of manual rendezvous and docking mission mainly consists of three parts: operational step reliability, operational response reliability, and equipment resource reliability. The reliability calculation formula is shown in Equation (9).

$$R = (1 - F_T)(1 - F_t)(1 - F_M) \tag{9}$$

where F_T is the failure probability of the operation step; F_t is the probability of operation response time failure; F_M is the probability of device resource failure.

According to the failure probability analysis of operational steps, the failure probability of astronauts' operational steps is:

$$F_T = \prod_{i=1}^{4} (1 - CFP_{Ti}) = 0.002 \tag{10}$$

Assuming an initial available operating time of 320 seconds, the Monte Carlo simulation results show that the operational response failure probability of astronauts under the 320 seconds available operating time constraint is F_t =0.002.

Assuming that the manual docking task requires equipment resources to be available within T=10000 hours, the equipment resource failure probability within 10000 hours can be seen from the equipment resource failure rate chart, F_M =0.023.

Substituting F_T, F_t, and F_M into equation (9), it can be obtained that the reliability of manual rendezvous and docking mission considering human factor related failures and equipment effectiveness is 0.973, and the calculated result meets the general engineering requirements.

5. Conclusion

This paper proposes a reliability analysis method for manual rendezvous and docking mission based on Petri nets. Based on the analysis of the mission phases, mission resources, and astronaut operation steps of the manual rendezvous and docking mission, a CPN model for the manual rendezvous and docking operation process and a GSPN model for the manual rendezvous and docking equipment resources are constructed. Quantitative analysis was conducted on the failure probability of operational steps affected by three potential human errors by astronauts; Based on Monte Carlo method, the failure probability of operation response is simulated and analyzed; The failure probability of equipment resources is evaluated based on the GSPN model of manual rendezvous and docking equipment resources. Based on the analysis results of the above three dimensions, the reliability of manual rendezvous and docking tasks considering human factor related failures and equipment effectiveness is calculated.

The mannual rendezvous and docking mission is a complex mission system with multiple factors that are cross coupled. In practical situations, the coupling effect between multiple failure factors on mission reliability cannot be ignored. Therefore, future research work will focus on the reliability analysis method of manual rendezvous and docking missions under the influence of human-machine- environment coupling.

6. References

[1] Alam M , Al-Saggaf U M. Quantitative Reliability Evaluation of Repairable Phased-Mission Systems Using Markov Approach. IEEE Transactions on Reliability, 1986, 35(5):498-503.

[2] Yong O , Dugan J B. Approximate sensitivity analysis for acyclic Markov reliability models. IEEE Transactions on Reliability, 2003, 52(2):220-230.

[3] S.P.Chew, S.J.Dunnett, J.D.Andrews.Phased mission modeling of systems with maintenance free operating period using simulated Petri nets. Reliability Engineering&System Safety,2008,93(7):980-994.

[4] H X Hu, Y C Xie, J Hu. Shenzhou spacecraft rendezvous & docking manual control system design. Sci Sin Tech, 2014, 44: 34–40(in Chinese), doi: 10.1360/092013-1262

[5] Nanhua Wang, Zugui Chen,Yifeng Zhang. "Shenzhou" spacecraft astronaut manual motion control system. 2005(02):10-13+26(in Chinese).

[6] Jingbin Wang, Surong Dai, Yun Zhou, Minjie Gu, Research on GSPN-based Mission Reliability Modeling of Complexed Avionics System. 2020,51(02):1-5(in Chinese).DOI:10.12175/j.issn.1006-141X.2020.02.01

[7] Liexiang Hu, Lei Wang, Mingfeng Dong. Operational Optimization and Reliability Evaluation of Integrated Energy Systems Based on Improved Time Constrained Petri Nets. China Electric Power, 2020,53(10):123-132+139(in Chinese).