Chapter 4

Reliability Evaluation for Mechanical Systems by Petri Nets

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Additional information is available at the end of the chapter

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Abstract

The current trend in mechanical engineering is to design mechanical systems with higher stability, reliability, availability and operability. In order to meet the requirement of high reliability for a machine, it is of great importance for designers to seek the weak links in the system and learn the state of the key subsystems, carrying out the remedial measures when necessary. Hence, behavior modeling and failure analysis are the two aspects seriously concerned in the reliability evaluation in mechanical systems. This chapter will introduce new methodologies that use the fuzzy reasoning Petri net (FRPN) models to evaluate the reliability of mechanical systems in reliability prediction, reliability apportionment and reliability analysis. Cases are proposed by analyzing a spacecraft solar array system using the proposed method. Results indicate that the Petri nets models can contribute to a higher accuracy in reliability evaluation for mechanical systems.

Keywords: reliability evaluation, mechanical system, Petri nets

1. Introduction

Some mechanical systems experience complicated environment which may continuously influence the reliability and availability. For instance, the spacecraft solar arrays are one of the most vital links to satellite mission success because providing reliable power over the anticipated mission life is critical to all satellites [1–3]. Although the faults have been reduced in the last few years by some measures, it still affects the longevity of the satellite severely, and faults of mechanical system occupy a large proportion of all the anomalies [3]. As a result, it is necessary for mechanical systems to evaluate reliability in different stages, including conceptual design of mechanical system, initial design and system improvement. The tasks of reliability evaluation in these stages are defined as reliability prediction, reliability apportionment and reliability analysis, respectively. Many methodologies such as reliability block diagram (RBD), failure mode effect analysis (FMEA) and fault tree analysis (FTA) are widely used in reliability evaluation for electronic systems [4–6]. Recently, a number of papers reported the methodologies that use these models to evaluate reliability of the mechanical systems [7–9]. However, there still has some obstacles needed to be overcome for reliability evaluation of mechanical systems. Generally, three tasks should be accomplished, including reliability prediction, reliability apportionment and reliability analysis. We summarize the defects of previous research from the three aspects mentioned above.

For reliability prediction, there are currently four main ways of reliability prediction for mechanical systems [10–12], including the similar product method (SPM), correction coefficient method (CCM), analysis of physics reliability method (APR) and parts count reliability prediction (PCRP). However, in the phase of conceptual design stage for one complex mechanical system, there has no enough experimental data or field record because the machine is not physically built. Moreover, APR is based on the physical failure mechanism which cannot be clearly identified in the conceptual design stage.

For reliability apportionment, there are two important issues needed to be addressed, i.e. how to describe the relationship among the different components and how to overcome data deficiency problem in the early stage of design [13–16]. It is usually hard to describe the factors of one mechanical system by the binary logic because the state cannot be simply classified into function or failure. Further, since the lack of system reliability data is a commonly encountered case in the initial stage of design, the reliability apportionment merely based on mathematics may not be feasible.

For reliability analysis, the FTA model has been widely employed as a powerful technique to evaluate the safety and reliability of complex systems by many scholars [17–19]. However, FTA has some limitations in reliability analysis. Firstly, in FTA, the probabilities of basic events must be known before analysis, but the designers can hardly obtain the probability of each fault because the conventional reliability test of the solar array mechanical system is difficult to carry out [19]. Secondly, it is not easy for FTA to conduct further quantitative analysis automatically due to the lack of effective means of mathematical expression. Thirdly, FTA cannot find the weak links of the system precisely, describe the propagation of fault and represent the characteristics of the system before and after improvement. In the literature, fuzzy reasoning is an effective method to solve the above problems [20].

The Petri net is one of the mathematical modeling approaches for the description of distributed systems, which consists of places, transitions, and directed arcs [21–23]. Many extensions to the Petri nets have been successfully applied in analyzing reliability of mechanical systems [24]. The fuzzy reasoning Petri net is a mathematical and graphical combined tool that can build a complex system with a variety of logical connections by using fuzzy reasoning, which may fit for building the reliability model for mechanical systems and evaluating reliability of them [20]. As a result, the primary objective of this chapter is to introduce the FRPN based models to evaluate the reliability of mechanical systems, including reliability prediction,

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reliability apportionment and reliability analysis. Some cases are included to illustrate the effectiveness of the methods.

2. Fuzzy reasoning Petri net

A great volume of literature combines fuzzy reasoning and Petri net to accomplish the fault diagnosis and reliability analysis [25–27]. Gao presented an FRPN model and proposed a fuzzy reasoning algorithm based on matrix equation expression [19]. An FRPN model can be defined as an 8-tuple model instead of the basic 5-tuple Petri net model [19].

1. Places, namely, a set of propositions,

$$P = \{p_1, p_2 \ldots p_n\}, 1 \times n; \tag{1}$$

2. Transitions,

$$R = \{r_1, r_2 \ldots r_{\mathrm{m}}\}, 1 \times m; \tag{2}$$

3. Directed arcs propositions to rules,

$$I : P \times R \to \{0, 1\}, n \times m \tag{3}$$

4. Directed arcs from rules to propositions,

$$O : P \times R \to \{0, 1\}, n \times m \tag{4}$$

5. Complementary arcs from positions to rules,

$$H : P \times R \to \{0, 1\}, n \times m \tag{5}$$

6. Truth degree vector:

$$\theta = (\theta_1, \theta_2, \cdots \theta_n)^T, \theta_i \in [0, 1], n \times 1 \tag{6}$$

7. Marking vector:

$$\gamma : P \to \{0, 1\}, \gamma = (\gamma_1, \gamma_2 \ldots \gamma_n)^T, n \times 1 \tag{7}$$

8. Confidence of

$$r_j : C = diag\{c_1, c_2 \ldots c_{25}\}, 1 \times m. \tag{8}$$

On the basis of algorithm provided by Gao [19], the simulation can be operated automatically. The following are the main rules:

1. If one transition is fired, the token will be sent to the upper place.
2. If there are many places to one transition like AND gate in FTA model, the upper truth value will be the minimum; if there are many places to many transitions like OR gate in FTA model, the upper truth value will be the maximum.
3. The vector $\gamma = \left(\gamma_1, \gamma_2 \cdots \gamma_{\mathrm{i}} \cdots \gamma_{\mathrm{n}}\right)^T, n \times 1$ shows the propagation of the faults in model. If the element $\gamma_{\mathrm{i}} = 1$, the place p_{i} will get the token.
4. The truth degree vector $\theta = (\theta_1, \theta_2, \cdots \theta_n)^T$ shows the fuzzy possibility of the faults.

The PRPN model takes advantage of the following maximum algebra

1. $\oplus : A \oplus B = D$, where A, B and D are all $m \times n$ dimensional matrices, such that

$$d_{ij} = \max\left\{a_{\mathrm{ij}}, b_{\mathrm{ij}}\right\} \tag{9}$$

2. $\otimes : A \otimes B = D$, where A, B and D are $m \times p$, $p \times n$ and $m \times n$-dimensional matrices respectively, such that

$$d_{ij} = \max_{1 \le k \le p} \left\{a_{ik} \cdot b_{kj}\right\} \tag{10}$$

The firing and control vectors are stated as follows [19]:

$$\begin{cases} \mu^k_{m\times 1} = 1_{m\times 1} - (I + H)^T \otimes \overline{\gamma}^k \\ \rho^k_{m\times 1} = 1_{m\times 1} - \left(I^T \otimes \left(\overline{\gamma}^k \oplus \overline{\theta}^k\right)\right) \oplus \left(H^T \otimes \left(\overline{\gamma}^k \oplus \theta^k\right)\right) \end{cases} \tag{11}$$

in which

$$\begin{cases} \overline{\theta}^k = 1_{\mathrm{m}\times 1} - \theta^k \\ \overline{\gamma}^k = 1_{\mathrm{m}\times 1} - \gamma^k \end{cases} \tag{12}$$

The marking and truth degree vectors can be obtained by

$$\begin{cases} \gamma^{k+1} = \gamma^k \oplus \left[O \otimes \mu\right] \\ \theta^{k+1} = \theta^k \oplus \left[(O \cdot C) \otimes \rho\right] \end{cases} \tag{13}$$

which reflects the status of the components in the mechanical system. The FRPN model is suitable to describe the status transition in a mechanical system because

1. The FRPN model is constructed by the places and logical connections which match the properties of mechanical systems with multiple components.

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2. The FRPN model can describe the fault propagation in mechanical system by fuzzy reasoning, which can describe the properties of mechanical systems accurately.
3. The FRPN model is based on an iteration algorithm, so the status transition can be easily tracked, which may be useful for examining the fault propagation and fault severity in the system.

3. Reliability evaluation by FRPN

For evaluating the reliability of a mechanical system, one should complete a series of work including reliability prediction in the stage of conceptual design, reliability apportionment in the stage of initial design, and reliability analysis in the stage of system improvement. The following subsections will illustrate the method of how to evaluate reliability by FRPN models.

3.1. Reliability prediction by FRPN

3.1.1. Method

Reliability prediction acts when a product is in the stage of conceptual design. Here we introduce a method of reliability prediction of mechanical systems. This method includes the following steps (**Figure 1**). First, we will build an FRPN model of the mechanical system by its working principle and the logical connections among the components. Second, we get three key values which characterize quantity, importance and quality of the components in the mechanical system. Third, we will arrive at the reliability prediction result by parts count reliability prediction (PCRP). Finally, the reliability prediction formula of mechanical system denotes to

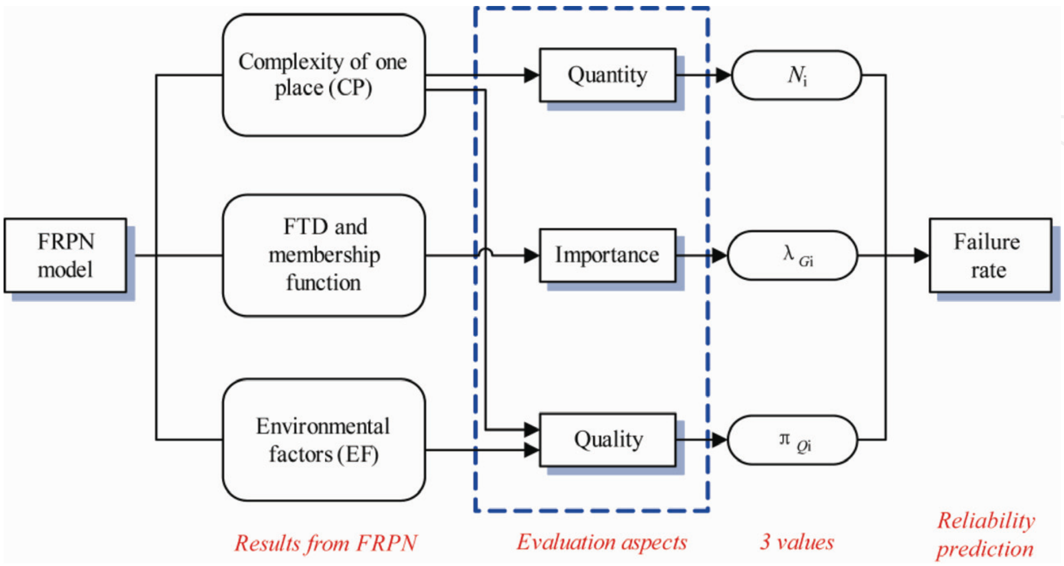

Figure 1. Main process of reliability prediction.

$$\lambda_p = \sum_{i=1}^{T} N_i \cdot \lambda_{\mathrm{Gi}} \pi_{\mathrm{Qi}} \tag{14}$$

where λ_p is the final predicted failure rate, λ_{Gi} and π_{Qi} are the indexes which indicate importance and quality of the components [28].

3.1.2. Case study

We take the deployable solar array used in spacecraft as an example. The running process of a typical deployable solar array is shown in **Figure 2**, which is widely used for power supply in the spacecraft nowadays. In general, the entire running process includes three stages, i.e. the deployable solar array is first folded, then deployed in the orbit and finally oriented to the sun to generate power for satellite.

In general, the mechanical system of the solar array consists of seven kinds of mechanisms [29–31], i.e. the hold-down and release mechanism, the solar panel, the driving mechanism, the deployable mechanism, the locking mechanism, the synchronization mechanism, and the orientation mechanism, as shown in **Figure 3**. Torsion spring is often chosen to drive the solar array, the closed cable loop (CCL) is used as the synchronization mechanism, and the stepping motor or servo motor is carried to orient to the sun. The driving mechanism, the deployable mechanism and the locking mechanism are always integrated into the hinge. Therefore the five main mechanisms of the solar array include hold-down and release mechanism, the solar panel, the hinge, the synchronization mechanism and the orientation mechanism.

We use R_1 to R_5 to represent the reliability of the five mechanisms, respectively. Then the reliability of the mechanical system can be calculated as follows:

$$R = R_1 R_2 R_3 R_4 R_5 \tag{15}$$

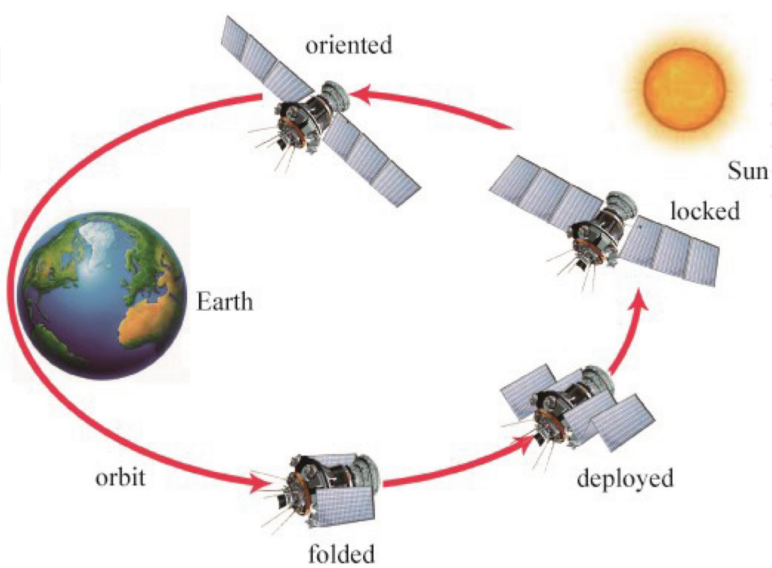

Figure 2. Operating principle of a deployable solar array.

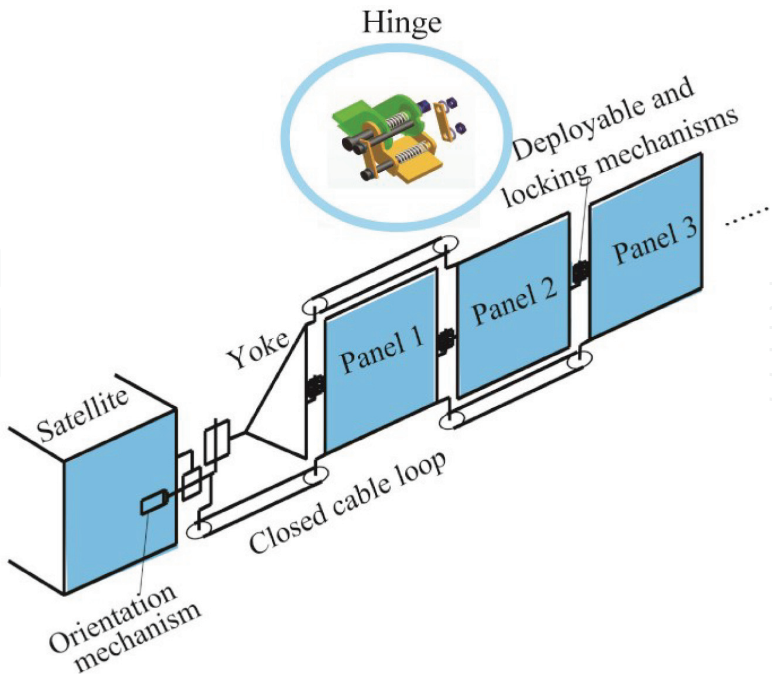

Figure 3. Mechanisms in a spacecraft solar array.

In the phase of conceptual design, designers should divide the reliability of the system into the five main parts. The following section introduces a new method of reliability apportionment which focuses on how to get the predicted values of $R_i(i = 1, 2, 3, 4, 5)$ to meet the requirement of the design standard. We build an FRPN model for the mechanical system of the solar array (**Figure 4**). **Table 1** shows the markers and events of FRPN model [32, 33].

By the method shown in **Figure 1**, we can measure the complexity of the ith place (CP) as a number of N_i, the final truth degree of the ith place (FTD) as λ_{Gi}, and the environmental factor

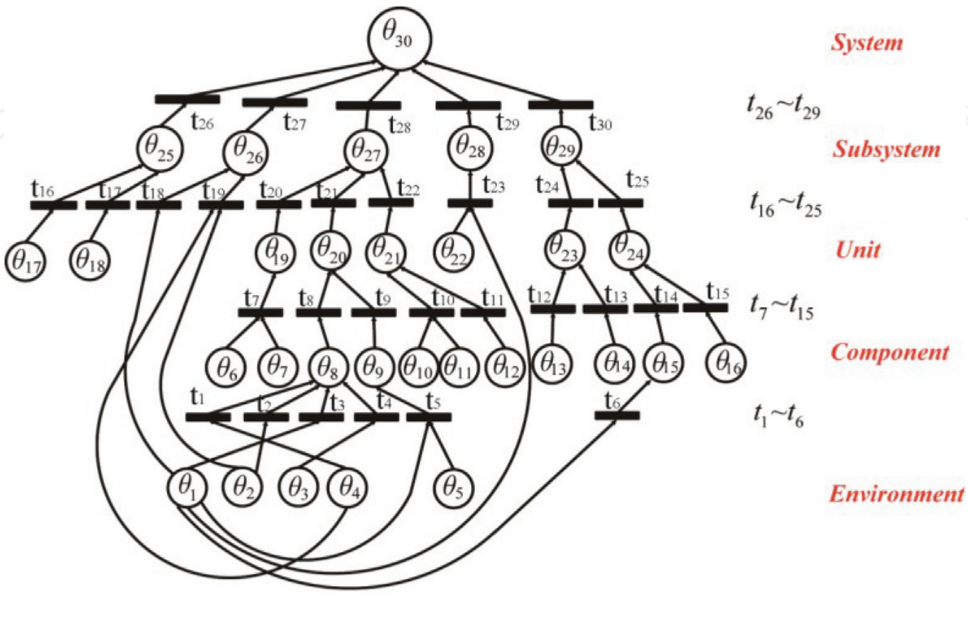

Figure 4. The FRPN model of the solar array for reliability prediction.

Marker	Event	Truth degree	Marker	Event	Truth degree
P_1	Harsh thermal environment in space	0.9	P_{16}	Fault of the bearing in the reducer	0.4
P_2	Vacuum and micro-gravity environment in space	0.6	P_{17}	Fault of the electronic arcing of the hold-down and release mechanism	0.7
P_3	Fault of the grease used in hinges between panels	0.4	P_{18}	Fault of the cutter of the hold-down and release mechanism	0.7
P_4	Impact caused by particles in space	0.7	P_{19}	Fault of the driving mechanism	_
P_5	Fault of the brass gasket	0.5	P_{20}	Fault of the deployable mechanism	_
P_6	Fault of the main driving torsion spring	0.6	P_{21}	Fault of the locking mechanism	_
P_7	Fault of the reserved driving torsion spring	0.6	P_{22}	Fault of the steel wire	0.7
P_8	Fault of the driving pin in the hinge	_	P_{23}	Fault of the stepping motor	_
P_9	Fault of the side wall of the hinge	_	P_{24}	Fault of the transmission system	_
P_{10}	Fault of the main locking spring	0.8	P_{25}	Fault of the hold-down and release mechanism	_
P_{11}	Fault of the reserved locking spring	0.5	P_{26}	Fault of the solar panels	_
P_{12}	Fault of the locking pin of the hinge	0.5	P_{27}	Fault of the hinges	_
P_{13}	Fault in the mechanical part of the stepping motor	0.3	P_{28}	Fault of the synchronization mechanism	_
P_{14}	Fault in the electronic part of the stepping motor	0.2	P_{29}	Fault of the orientation mechanism	_
P_{15}	Fault of the gear in the reducer	_	P_{30}	Fault of the mechanical system of the solar array	_

Table 1. Markers and events of FRPN model for reliability prediction.

(EF) of the *i*th place as π_{Qi}. Some details can be checked in [32]. We collected the actual reliability data (lifetime of mechanical systems) of the solar arrays in a group of satellites from 1950s to 2000s provided by [34]. The results show that all of the predicted reliability lies in the interval of the operation data, which demonstrates the correctness of FRPN-based model for reliability prediction. **Figure 5** validates the predicted reliability by using the four selected time: 0.025×10^6 h, 0.05×10^6 h, 0.075×10^6 h and 0.1×10^6 h. Some more details can be checked in [34].

3.2. Reliability apportionment by FRPN

3.2.1. Method

After reliability prediction in the conceptual design phase, the engineer should start reliability apportionment that acts when a product is in the stage of initial design. The conventional

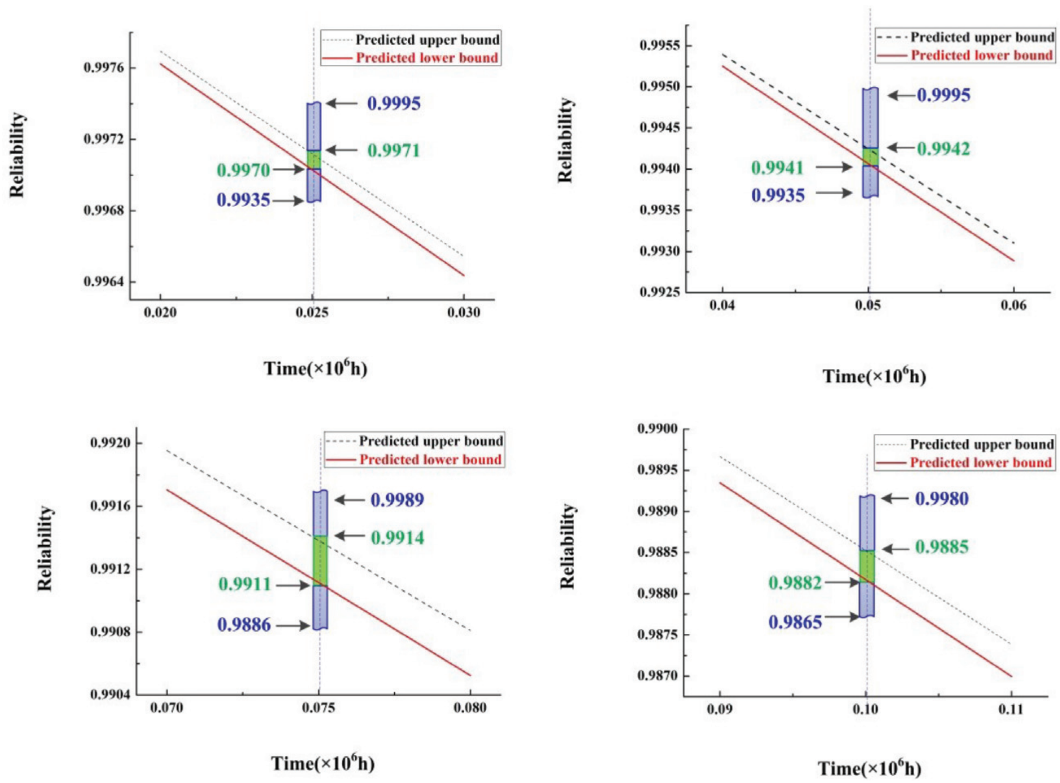

Figure 5. Comparison between the predicted reliability and real reliability at selected phases.

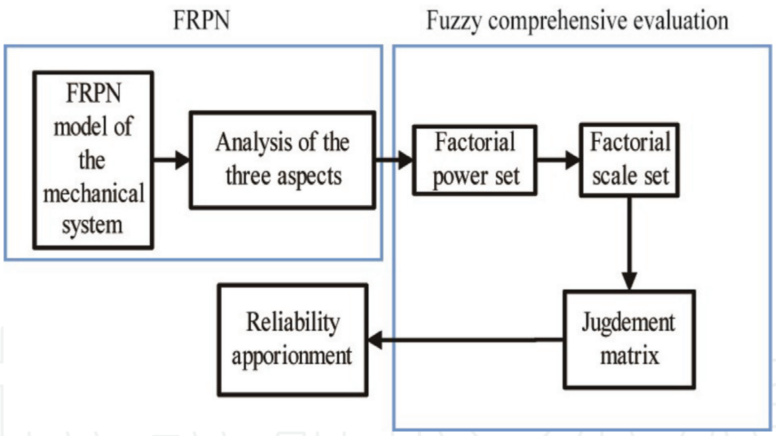

Figure 6. Procedures for reliability apportionment by FRPN. The FRPN model is used in the first and second steps and the following two steps use the fuzzy comprehensive evaluation.

reliability apportionment approaches including equal distribution method, Alins distribution method and algebra distribution method are widely used in the early stage of the reliability design [35, 36]. However, these methods have some limitations. It is obvious that dividing the system reliability into those of the subsystems equally may ignore the diversity of the components. Although the Alins distribution method and the algebra distribution method involve the importance or complexity of the different units, they are heavily dependent on the existing data and engineering experience which are scare in the early stage of the reliability design. Here we propose an FRPN-based method for reliability apportionment to solve the problems discussed above. This method includes the following steps (**Figure 6**):

1. Decompose the mechanical system;
2. Build the FRPN model of the mechanical system;
3. Analyze the three aspects including the complexity of one component during propagation of the faults, the importance of one component and the working environment;
4. Fuzzy comprehensive evaluation;
5. Reliability apportionment.

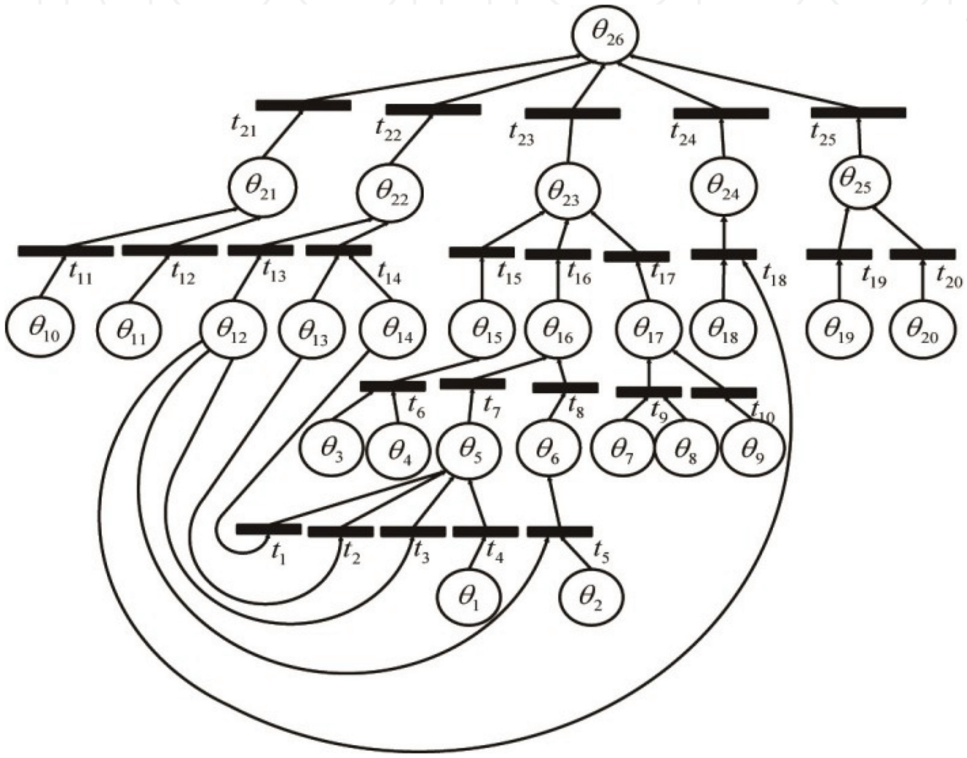

Figure 7. The FRPN model of the solar array for reliability apportionment.

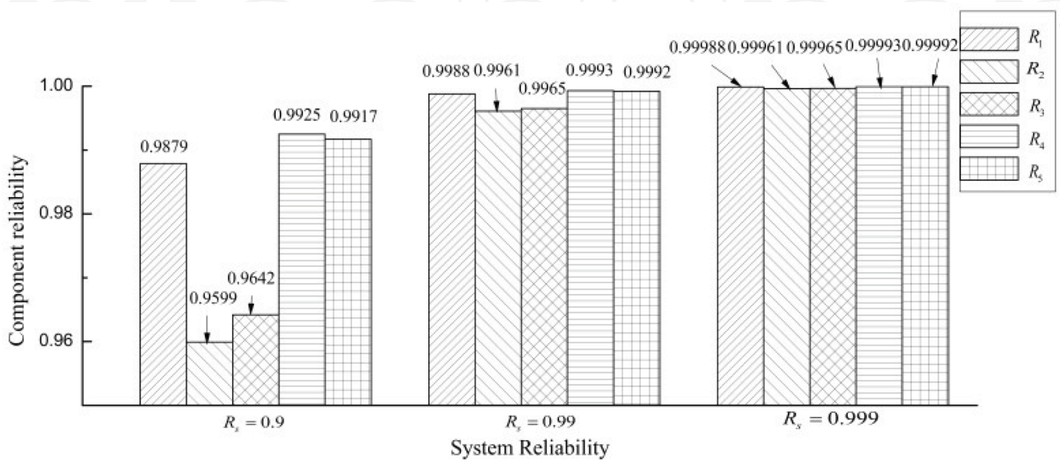

Figure 8. The reliability apportionment of the five key components of solar array. The reliability system is equal to 0.9, 0.99 and 0.999 respectively.

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Marker	Event	Truth degree	Marker	Event	Truth degree
P_1	Grease used in hinges between panels	0.4	P_{14}	Particles in space	—
P_2	Brass gasket	0.5	P_{15}	Driving mechanism	—
P_3	Main deriving torsion spring	0.6	P_{16}	Deployable mechanism	—
P_4	Reserved driving torsion spring	0.6	P_{17}	Locking mechanism	—
P_5	Driving pin in the hinge	—	P_{18}	Steel wire	0.7
P_6	Side wall of the hinge	—	P_{19}	Stepping motor	0.2
P_7	Main locking spring	0.8	P_{20}	Transmission system	0.6
P_8	Reserved locking spring	0.5	P_{21}	Hold-down and release mechanism	—
P_9	Locking pin of the hinge	0.5	P_{22}	Solar panels	—
P_{10}	Electronic arcing of the hold-down and release mechanism	0.7	P_{23}	Hinges	—
P_{11}	Cutter of the of the hold-down and release mechanism	0.7	P_{24}	Synchronization mechanism	—
P_{12}	Harsh thermal environment in space	0.9	P_{25}	Orientation mechanism	—
P_{13}	Vacuum and micro-gravity environment in space	—	P_{26}	Mechanical system of the solar array	—

Table 2. Markers and events of FRPN model for reliability apportionment.

3.2.2. Case study

We take the spacecraft solar array as an example to conduct the reliability apportionment by using the FRPN model (**Figure 3**). According to the operational principle of array mechanical systems of a solar array, we build an FRPN model for reliability apportionment of spacecraft solar array. The graphical representation of this model is shown in **Figure 7**. **Table 2** shows the markers and events of the FRPN model [32].

From **Figure 7**, the FRPN model of solar array includes 13 bottom places- P_1, P_2, P_3, P_4, P_7, P_8, P_9, P_{10}, P_{11}, P_{12}, P_{18}, P_{19} and P_{20}. And P_{21}, P_{22}, P_{23}, P_{24}, and P_{25} represent the subsystems (**Table 2**). The final reliability apportionment results are illustrated in **Figure 8** under the system reliability of 0.9, 0.99 and 0.999. In this figure, R_S represents the reliability of the system and $R_i(i = 21, 22, 23, 24, 25)$ expresses the reliability of the five key subsystems. The reliability apportionments are shown in **Figure 8**. By using the FRPN based model, the system reliability can be allocated considering the environmental factors and the intrinsic connection in the mechanical system itself [33].

3.3. Reliability analysis by FRPN

3.3.1. Method

Reliability analysis happens in the stage that the mechanical system has been built physically. By using the FRPN model, we can analyze the reliability of the system with the following steps:

1. Decompose the mechanical system.
2. Build the FRPN model of the mechanical system.
3. Get the truth degrees of the bottom places according to the characteristics of the faults in the system, operation data and engineering experience
4. Calculate the truth degree of top place.
5. Use the cosine matching function (CMF) to analyze reliability of the system.

3.3.2. Case study

We also take the spacecraft solar array as a case for reliability analysis. **Figure 9** shows the FRPN model of the spacecraft solar array for reliability analysis and **Table 3** represents markers and events [37].

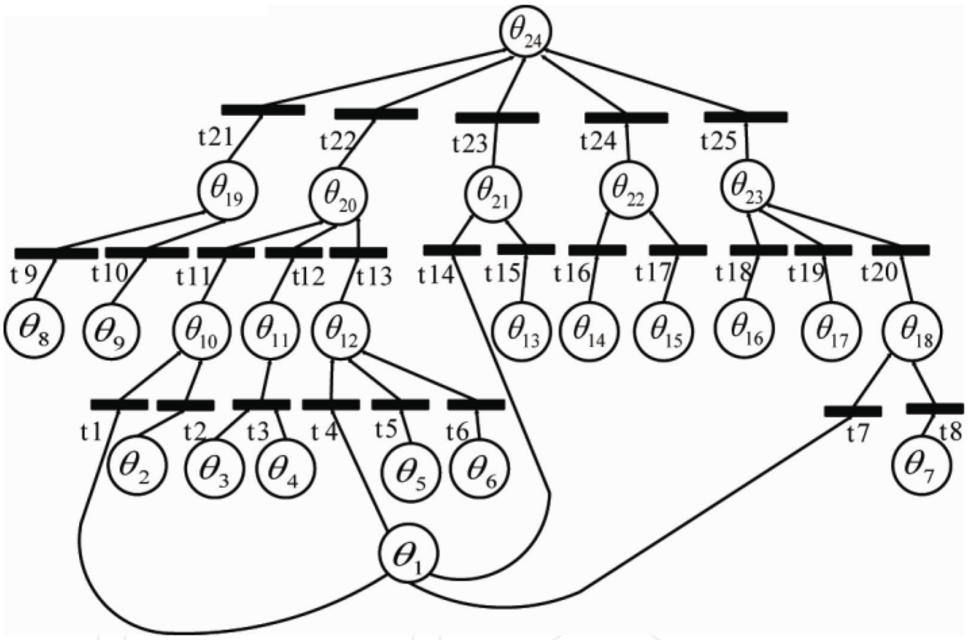

Figure 9. The FRPN model of solar array for reliability analysis.

Marker	Event	Marker	Event
P_{24}	Failure of the solar array system	P_1	Harsh thermal environment in space
P_{19}	Fault of the unlock-mechanism	P_2	Fault of the grease used in hinges between panels
P_{20}	Faults during deployment process	P_3	Insufficient torque of the main torsion spring
P_{21}	Faults during locking process	P_4	Insufficient torque of the reserved torsion spring
P_{22}	Fault of orientation to the sun	P_5	Insufficient preload of the cable
P_{23}	Other faults of mechanical system	P_6	Poor thermal characteristic of the cable
P_{10}	Deadlocking in hinges	P_{13}	Inappropriate driving torque of the locking torsion spring
P_{11}	Insufficient preload of the torsion spring	P_{14}	Fault of the motor

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Marker	Event	Marker	Event
P_{12}	Fault of CCL	P_{15}	Fault of the transmission unit
P_{18}	Vibration of panels induced by thermal deformation	P_{16}	Impact caused by particles in space
P_8	Electronic arcing is out of service	P_{17}	Vibration caused by clearances of hinges
P_9	Fault of the cutters	P_7	Bad thermal characteristic of honeycomb materials

Table 3. Markers and events of FRPN for reliability analysis.

Define θ_i as the truth degree of the bottom place p_i, $\theta_i \in [0, 1]$. A higher value indicates that the possibility of the event is higher, which means the fault occurs much easier. **Table 4** demonstrates the ranks, occurrence, and truth degrees of the bottom places. According to the characteristics of

Rank	I	II	III	IV	V	VI	VII
Occurrence	Very low	Low	Fairly low	Moderate	Fairly high	High	Very high
Truth degree	0.1	0.3	0.4	0.5	0.6	0.8	1.0

Table 4. Solar array classification ranks of the fault model.

Marker of bottom places	P_1	P_2	P_3	P_4	P_5	P_6	P_7
Rank	VII	III	V	V	VI	V	VI
Truth degree	1.0	0.4	0.6	0.4	0.8	0.6	0.8
Marker of bottom places	P_8	P_9	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}
Rank	V	V	V	II	IV	VI	VI
Truth degree	0.4	0.6	0.8	0.3	0.5	0.8	0.8

Table 5. Fault rank of the bottom places and their truth degree.

Bottom place	Improvement measures
P_1	The thermal environment in space is the crucial factor of the failure. Some approaches to improve the reliability of the system. (1) Investigate the temperature in space precisely where the solar array works and sum the rules; (2) use new material that is fit for the change of the temperature in space; (3) research the temperature impact on the structure, and optimize the structure of the crucial part of the system
P_{13}	(1) Test the torsion spring on the ground, then find the torque-angle curve to know the characteristics of the torsion spring more deeply; (2) test the performance of the whole system, using torsion springs with different characters, like stiffness
P_{16}	That happens occasionally. There is no effective measure to avoid particles in space, maybe only two ways: (1) make the structure stronger; (2) make the system more agile to detect the vibration caused by the impact of particles, and make adjustment with expedition

Table 6. Improvement measures.

the faults in the system, operation data and engineering experience [9]. **Table 5** represents the fault rank of the bottom places and their truth degrees.

We can get the results of reliability analysis by using the method in Section 3.3.1. According to the results, we can evaluate the importance of bottom places in the FRPN model. Some details can be checked in [37]. To improve the system reliability, we should propose some approaches to enhance the weak links. **Table 6** shows some improvement measures for the mechanical system of a spacecraft solar array.

4. Conclusion

With the ever-increased high requirement of reliability and safety for critical equipment, accurately performing the reliability evaluation of the mechanical systems, such as solar arrays, gains much attention in recent years. The proposed method for reliability evaluation by FRPN can be used to solve the problem on how to describe the relationship among the different components and how to overcome data deficiency. The FRPN based models may open up a new way for evaluating complex mechanical systems with multi-state operation in variable working environment.

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Conflict of interest

There has no conflict of interests.

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