Research on the Fault Diagnostic of the Aircraft Cross-Linking Systems

Linlong Ma*  
1Shanghai Aircraft Design & Research Institute, COMAC, Shanghai, 201210, China  
* malinlong@139.com

Abstract. High complexity of modern civil aircraft system leads to a huge difficulty to its trouble-shooting. This paper firstly discussed the two main directions of improving the aircraft fault diagnosis capability, and then analysed the pain points encountered by the model-based troubleshooting method. For the pain points, the Colour Fuzzy Fault Petri Net (CFFPN) model was proposed. The basic principles of the model and the basic process of conducting forward and reverse reasoning diagnosis based on the model were illustrated. Then the application of reasoning process in system design integration and airline maintenance was expounded. Finally, a practical software prototype of the model was developed, and effectiveness of the method and model was demonstrated through applications in engineering practice.

1. Introduction

Modern commercial aircraft are a highly complex and integrated giant system. On the one hand, due to the various working scenarios and complicated operation changes, the control logic of aircraft system are extremely complex [1]. On the other hand, the aircraft system adopts a lot of design of functional redundant due to the high safety requirements, and the existence of hardware and software redundant units and logic of each system composition sharply increases the complexity of the system [2].

This complexity leads to a huge difficulty to the trouble-shooting of modern aircraft. The difficulties of the aircraft system trouble-shooting have become the bottleneck limiting the efficiency of aircraft maintenance and operation [4].

However, the modern civil aviation transport puts forward higher requirements for the operation efficiency and cost of the aircraft. Traditional troubleshooting methods such as manuals query, cases reference or judgment by personal experience, are increasingly difficult to meet the needs of modern commercial aircraft trouble-shooting [5]. Therefore, both the manufacturers and operators are seeking technical means to effectively improve the efficiency of aircraft system fault diagnose.

2. Development of Aircraft Fault Diagnostic Technology

In the past few decades, untiring efforts has been carried out for commercial aircraft fault diagnose in two main directions shown in the following figure 1:

The way to fundamentally improve the fault diagnostic capability of aircraft systems is to introduce more built-in test, condition detection, embedded diagnosis and other means into the lower level of the system, to improve the self-detection and self-diagnosis ability of the underlying product unit [6]. But in thrall to industrial foundation (such as sensors) and objective constraints (such as cost, weight and reliability), the implementation scope of this approach is limited, and it is difficult to achieve significant technical jumps in a short time. In addition, the introduction of fault detection means further aggravates
the complexity of the system. Once the aircraft design is finalized, it is difficult to optimize and improve the design of lower level detection.

Figure 1. Two directions to improve aircraft fault diagnosis capability

Another desirable approach would be to establish logical models at the upper level of the system, to generate certain logic programs and criteria with the help of the computer logic deduction ability, then to judge the possible root cause of the fault with limited information. This approach is based on the idea of system engineering, mainly to further apply the existing information of system design, manufacturing and maintenance in depth. Since these logical models can exist relatively independently of the aircraft system, both manufacturers and operators can build available models based on their own resources, and constantly accumulate knowledge for iterative optimization without restricting the aircraft development cycle. Therefore, this approach has been highly valued. Many manufacturers such as Boeing, Airbus, GE, Honeywell, RR have got lots of technical achievements in this direction [7],[8], and many aircraft operators have also developed some helpful fault diagnosis systems [9].

Focusing on the approach of fault diagnosis models development, it is noticed there are two obvious shortcomings in the existing various technical achievements generally:

- The existing troubleshooting model methods are obviously divided into manufacturer's genres and operator's genres. Aircraft manufacturers' diagnosis models were mainly based on the cognition of the system principle and the fault mechanism, while the operators' were mostly the further mining and utilization of the airline maintenance data and experience. There is no current modelling method that deeply integrates the two.
- The existing fault diagnosis models were unable to effectively solve the fault diagnosis problem of so many cross-linking systems on the aircraft. The fault cascade transmitted crosslinking systems was difficult to be fully described in the mechanistic model, and the data, cases and experience of airline maintenance are also helpless to reproduce the complex fault judgment process.

Therefore, it is urgent to find an effective fault diagnosis modelling method, to combine the knowledge of manufacturers and operators, and to conduct an effective fault diagnosis and isolation on complex crosslinking systems.

3. Colour Fuzzy Fault Petri Net Model

3.1. Modeling method selection

The comparison of the existing technical results shows that the graph theory method including directed graph model, fault tree model and petri net model has many advantages. In particular, the petri network model, which can represent both the structure of the diagnostic object and the fault propagation process, is favoured in engineering applications.

The petri network theoretical method, proposed by Carl Adam Petri in 1962, with both rigorous mathematical expression and intuitive graphical expression, can be used to solve problems in distributed systems and distributed processes [10]. The basic elements of the petri network are place, transition, and token, where the place and transition is connected with connection.

When used for fault modelling, the failure mode of the system is described with place, represented as a circle O; failure mode change is the status variable, described with transition, represented as a
rectangular block ▮; Confidence level for the fault event described with token, represented as a rectangular small black dot●. Where token flow represents the propagation of failure in petri figure.

To apply the petri network to the aircraft system crosslink fault diagnosis, is mainly to solve the complex dynamic propagation path of the aircraft system fault description problem [11]. Therefore, this study combined the existing fuzzy petri network theory and nonferrous petri network, and an extended dyeing fuzzy fault petri network (colour fuzzy fault petri net (CFFPN) model was used to realize the integration of the manufacturer fault mechanism and the operator airline maintenance data experience in fault diagnosis. Figure 2 below gives a graphical representation of the CFFPN model.

![Graphical representation of the CFFPN model](image)

3.2. Knowledge representation of fault propagation

In the aircraft system, the fault propagation relationship is generally manifested in two situations:

- Propagate between adjacent units of the same level (lateral propagation). This situation is mainly in each hardware and software unit with an interface relationship on a functional link, and the downstream unit shows a failure due to the failure of the upstream unit. In aircraft systems, this propagation will evolve complex due to so many redundant.

- Propagate from low-level to high-level (vertical propagation). This situation is mainly caused by the failure of the underlying unit leading to abnormal or even failure of the superior unit. As shown in Figure 3, the PRSOV valve of the engine air bleed adjustment module is blocked, causing its superior subsystem cannot adjust the air bleed, which results in low pressure of the pneumatic system and finally the loss of wing anti-ice of the whole aircraft.

![Fault propagate from low-level to high-level](image)

In the actual aircraft system, the above two propagations occur simultaneously, coupled, and evolve dynamically with the system conditions. In addition, although complex system faults are interlayer propagating, the manifestations of failure modes are different for different modules [12]. Therefore, although the failure of the higher level modules may be caused by the failure of the lower level modules, the faults presented by the two are completely different. Thus, the faults of different levels and different manifestations are treated as an independent fault mode.

Based on the above method, the fault propagation CFFPN model of the crosslink systems (covering flight control, hydraulic, electricity power, navigation and thrust management system) of an aircraft was built.
4. Fault diagnostic based on CFFPN model

4.1. Forward analysis in system development integration

Based on the Failure Mode and Effects Analysis (FMEA) of the underlying unit of the system, the process of the evolution of each underlying failure mode propagation between the systems were analyzed, to find some failure phenomena it may cause. This process mainly includes confidence reasoning, intelligent judgment of transmission fire, and reasoning on fault propagation.

The MYCIN confidence reasoning method has good parallelism and can find all the condition values of the whole space [15]. The confidence of fault event \( p_i \) \( (i = 1, 2, \ldots, n) \) is

\[
\alpha_{k+1} = \alpha_k \oplus \{(O \cdot U) \otimes [I^T \otimes (l_n - \alpha_k)]\}
\]

Where, \( l_n=(1,1,\ldots,1)^T \) is a n-dimensional vector, \( l_n-\alpha_k \) indicates the confidence of the fault \( p_i \) resulted as false in the \( k \)th inference; \( I^T \otimes (l_n - \alpha_k) \) indicates the confidence of the transmission rule \( t_j \) resulted as false in the \( k \)th reasoning.

The reasoning steps are as follows:

Step1: Make \( k=0 \);  
Step2: Get \( \alpha_{k+1} \) according to \( \alpha_k \);  
Step3: If \( \alpha_{k+1} = \alpha_k \), the reasoning ends; otherwise make \( k=k+1 \), return step2 to continue.

Reasoning based on transition fire discriminant matrix: according to the transition fire rule, when transition \( t_j \) is pre-enabled, the vector value of pre-enable \( U(t_j) \) is

\[
U(t_j) = \{1 + e^{-b \sum_{i=1}^{n} a(p_i) \cdot \mu(t_{ij}) \cdot (t_{ij})}\}^{-1}, j = 1, 2, \ldots, m
\]

If the fire condition for the transmission was met, then \( U(t_j)=1 \); otherwise \( U(t_j)=0 \). With the above formula, the fire sequence is

\[
U(t) = (U(t_1), U(t_2), \ldots, U(t_m))^T
\]

According to the fire rules of CFFPN, the fire formula of the place with token is

\[
\begin{align*}
I_k &= I^T \ast M_{k-1} (k = 1) \\
I_k &= I^T \ast (M_{k-1} - M_{k-2}) (k = 2, 3) \\
U_k &= U(t) \land ((I_k \land l_{in})^T \ast \Omega), \quad (k = 1, 2, 3)
\end{align*}
\]

Where \( M_{k-1} - M_{k-2} \) indicates the identify vector of the \( k \)th fire, i.e. condition of fault \( p_i \); \( I_k \) indicates the enable input matrix; \( U_k \) indicates the fire sequence of the \( k \)th fire.

Since the fault propagation characteristics of the CFFPN model are mainly reflected by the flow of token, the fault propagation state matrix reasoning is

\[
M_k = M_{k-1} + (o(I^T_k \otimes M_{k-1}) \ast U_k), \quad k = 1, 2, 3, \ldots
\]

Where \( M_{k-1} \) and \( M_k \) respectively indicate the initial and result identify vectors of the \( k \)th fire, \( I^T_k \otimes M_{k-1} \) indicates the identify vector of transmission (i.e. the number of tokens).

4.2. Reverse delivery in airline operation

The reverse reasoning of CFFPN is to find the fault source when the fault occurs. This paper uses the minimum cut set theory [16] to assist the fault diagnosis. If there are multiple minimum cut sets present, the priority diagnosis order is determined according to the minimum cut set fault-prone rate.

The incidence matrix method, commonly used in petri network, was used to seek minimal cut sets. In this paper, in order to more clearly describe the topology of the petri network, the association
properties of its branches and the junction are represented by the $n \times m$ order matrix $A$. Where its element $a_{ij}$ is defined as

$$a_{ij} = \begin{cases} -1, & p_i \in I(t) \\ 1, & p_i \in O(t) \\ 0, & \text{other} \end{cases}$$

$i=1,2,\ldots,n; j=1,2,\ldots,m$ \hfill (6)

In the CFFPN model, the incidence matrix is used to describe the petri network topology that causes the fault phenomenon. The incidence matrix of fault occurred is

$$A^* = A \cdot (U_i \oplus U_j \oplus \cdots \oplus U_k) \cdot (M_i \oplus M_j \oplus \cdots \oplus M_k)$$ \hfill (7)

5. Engineering Practice
Thanks to petri net's rigorous mathematical logic expression, the model can be easily transformed into practical software tools through computer programming and applied in engineering.

5.1. Development of aircraft system fault diagnostic software
In this study, a prototype software tool for aircraft system fault diagnosis was developed based on the CFFPN method. Individual views of fault diagnosis models were determined in the XML language, and effectively described and constrained by DTD and XML schema.

The core part of the software consists of the following modules:

1) Graphical User Interface and modelling module: to draw and attribute edit the library, change, directed arc, token, text and other elements on a graphical interface.

2) Data management module: to manage the element data of the CFFPN model, import the fault diagnosis related knowledge, check the relevant syntax rules of the model, perform the storage of the model and the maintenance of various data.

3) System diagnostic capability analysis module: For the selected system, to analyse the propagation and evolution of each underlying failure mode in FMEA, analyse some failure phenomena that it may cause, and calculate the failure detection rate of the system.

4) Fault diagnosis and analysis module: to set the analysis conditions according to the actual situation of the studied system, obtain the minimum cut sets according to the correlation matrix, and then realize the analysis results of the accessible map and state space, and give the recommended fault isolation procedure.

5.2. Application effect assessment
The tools developed in this study were used for the test modelling and evaluation of a certain type of aircraft development. After collecting the FMEA and test analysis reports of each aircraft system, cross-system CFFPN models were established based on this. The characterization ability of the fault mode was evaluated for several complex on-flight crosslinking systems. Meanwhile, the model is also used to conduct the cascade impact analysis and evaluation of typical faults such as aircraft IMA (Integrated Modulated Avionics), landing gear WOW (Weight On wheel) signal, RDIU (Remote Data and Interface Units), and bus bar.

In the above process, a number of equipment fault modes were exactly found, which were more influential but difficult to be effectively detected. The problem is feedback to the design and corresponding improvement suggestions are proposed. 8 devices have added the corresponding CMS (Central-Maintenance System) maintenance message logic, 3 devices have added route inspection tasks, and 1 device was configured with airline external testing equipment and procedures.

Another practical application of this study is the software was used in the trouble shooting during the flight test of this aircraft. During the test flight stage, there were much more difficulties have got to be faced in the trouble-shooting of aircraft due to lots of testing-modifications and the un-mature Fault Isolation Manual. During the first 1.8 years of the flight testing, the software were not applied. In the next 2.7 years, the software tools and models developed by this study were provided for flight-test
trouble-shooting. Table 1 below shows fault isolation indexes obtained on the critical systems during the 4.5 years of test flight.

| Aircraft System       | Fault Isolation Rate to 3 LRUs | No-Fault-Found Rate |
|-----------------------|--------------------------------|---------------------|
|                       | First 1.8YRs                   | Next 2.7YRs         |
| ATA21 Air Conditioning| 95.68%                         | 98.46%              |
| ATA24 Electrical Power| 96.06%                         | 97.55%              |
| ATA27 Flight Control  | 92.93%                         | 97.47%              |
| ATA29 Hydraulic       | 93.55%                         | 97.12%              |
| ATA34 Navigation      | 94.92%                         | 99.91%              |

6. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1) It is shown that the CFFPN can realize the fault propagation modelling of the aircraft complex crosslinking system well, and enables the integration of the manufacturer fault mechanism and the operator airline maintenance experience in fault diagnosis.

2) The practice shows that the results of this study could play a role not only in actual fault diagnosis, but also in the aircraft cross-linking system testability design.

3) In the subsequent study, further research should be carried out to integrate the trouble-shooting cases and empirical data from aircraft operators into CFFPN fault diagnostic model.

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