Multiple Fault Diagnostic Strategy for Redundant System

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ABSTRACT

It is difficult to diagnose the faults, especially multiple faults, in redundant systems by traditional diagnostic strategies. So the problem of multiple fault diagnostic strategy for redundant system was researched in this paper. Firstly, the typical characters of multiple faults (minimal faults) were analyzed, and the problem was formulated. Secondly, a pair of two-tuples were applied to denote the possible and impossible diagnostic conclusion at different diagnostic stages respectively, and a multiple fault diagnostic inference engine was constructed based on Boolean logic. The inference engine can determine the system diagnostic conclusions after executing each test, and determine whether a repair action was needed, and further determine whether a next test was needed. Thirdly, a method determining the next best test was presented. Based on the proposed inference engine and test determining method, a multiple fault diagnostic strategy was constructed. Finally, a simulation case and a certain flight control system were applied to illustrate the proposed diagnostic strategy. The simulation and practical data computational results show that the presented diagnostic strategy can diagnose multiple faults in redundant systems effectively and it is of certain application value.

1. INTRODUCTION

With the rapid development of aviation projects, the designers have attached more importance to system reliability and safety. In the aviation domain, redundant techniques are usually adopted to improve system reliability. At the same time, as technology advances, there is a significant increase in the complexity and sophistication of aviation systems, which can easily induce multiple faults in all probability. Hence, studying the problem of multiple fault diagnosis in redundant systems is very important and significant. Unfortunately, there are little literatures referring to the problem at present.

A great variety of aviation systems with redundancy and with little or no opportunity for repair or maintenance during the operation may induce multiple faults, thus, a single failure assumption does not hold for this situation. Furthermore, the combinations of multiple faults may be of great multiplicity, and different fault combinations likely take on the same failure omen due to non-linearity, coupling and time-variance among the system components, and especially due to the redundant design in some systems. Thus, it becomes a difficult problem to diagnose multiple faults in redundant systems.

In the literature in the recent years, many scholars show great interesting on the multiple fault diagnostic problems [1-6]. Nevertheless, the premise of multiple fault diagnosis is enough sensor data acquired by executing multiple tests simultaneously. In practical application, tests are executed sequentially rather than simultaneously in most cases, so it is imperative important to study multiple fault sequential diagnostic strategy problem. Shakeri et al [7,8] have studied the problem based on sequential test and presented a multiple fault diagnostic optimization generation method, known as Sure strategies. The paper mainly considers the problem of multi-fault sequential diagnosis in redundant systems.

2. PROBLEM FORMULATION

The diagnostic strategy problem is defined by the five-tuple (**F**,**P**,**T**,**C**,**B**), where $\mathbf{F}=\{f_1,\ldots,f_m\}$ is a set of independent failure sources, $\mathbf{P}=[P(f_1),\ \ldots,\ P(f_m)]$ is the a priori probability vector associated with the set of failure sources **F**, $\mathbf{T}=\{t_1,\ t_2,\ldots,\ t_n\}$ is a finite set of n available binary outcome tests, $\mathbf{C}=\{c_1,\ c_2,\ldots,\ c_n\}$ is a set of test costs and $\mathbf{B}=[b_{ij}]_{m\times n}$ is fault-test dependency matrix where $b_{ij}=1$ if test t_j detects f_i, otherwise $b_{ij}=0$.

The form of multiple faults are of great diversity, moreover, multiple faults refer to complex fault mechanism and relate closely to the practical application environment and the specific objects. In order to simply the problem, the paper mainly considers the multiple faults with additivity. Let's define $\mathbf{FS}(f_i)=\{t_j|\ b_{ij}=1,\ 1\le j\le n\}$ to denote the signature of failure state f_i, it indicates all the tests that monitor failure state f_i, $\mathbf{FS}(f_i, f_j)$ denotes the failure signature of the multiple faults, f_i and f_j. If they both satisfy additivity, then

$$\mathbf{FS}(f_i, f_j)=\mathbf{FS}(f_i)\cup\mathbf{FS}(f_j) \tag{1}$$

Nevertheless, there exist many multiple faults which don't satisfy Eq.(1), especially in systems with redundancy. Consider the digraph model in Figure1. The AND nodes α_1 and α_2 show the system is redundant. If only f_3 or f_4 occurs individually, t_2 will not detect them, yet if they both occur, t_2 can detect them, hence $\mathbf{FS}(f_3)\cup\mathbf{FS}(f_3)$ $\mathbf{FS}(f_3,f_4)$.The fault combination $\{f_3,\ f_4\}$ related to the AND node α_2 is usually termed minimal fault, which can be considered as a special fault state in multiple fault redundant analysis. The minimal faults for the example are $s_5=\{f_3,f_4\}$ and $s_6=\{f_1,f_2,f_3\}$.

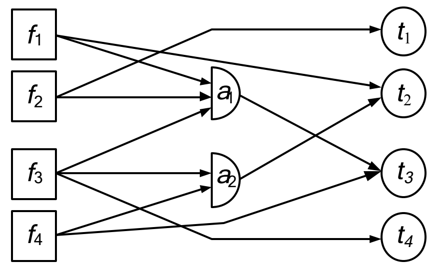

Figure 1. An example system with redundancy

In fault-tolerant systems, the failure sources **S** can be derived by adding minimal faults to the single fault set, i.e., $\mathbf{S}=\{s_1,s_2,\ldots,s_z\}$, where $s_i=\{f_i\}$ for $1\le i\le m$ corresponds to each single failure source respectively, and $s_{m+1}\sim s_z$ corresponds to minimal fault of the system respectively.

In Figure1, $\mathbf{S}=\{\{f_1\},\{f_2\},\{f_3\},\{f_4\},\{f_3,f_4\},\{f_1,f_2,f_3\}\}$, The corresponding fault-test dependency matrix $\mathbf{D}=[w_{ij}]_{n\times z}$ is shown in Table 1.

Table1. The extended dependency matrix of the example

	Tests			
Failure sources	t_1	t_2	t_3	t_4
$s_1=\{f_1\}$	0	1	0	0
$s_2=\{f_2\}$	1	0	0	0
$s_3=\{f_3\}$	0	0	0	1
$s_4=\{f_4\}$	0	0	1	0
$s_5=\{f_3,f_4\}$	0	1	1	1
$s_6=\{f_1,f_2,f_3\}$	1	1	1	1

Through the previous analysis, the multiple fault diagnostic strategy problem in redundant systems can be defined by the five-tuple ($\mathbf{S},\mathbf{P}^*,\mathbf{T},\mathbf{C},\mathbf{D}$), where **S** denotes the extended fault states, $\mathbf{P}^*$ denotes the fault probability vector, $\mathbf{P}^*(s_i)=P(f_i)$ for $1\le i\le m$, $\mathbf{P}^*(s_i)$ for $m+1\le i\le z$ equals the product of correlation single fault sets. **D** denotes the extended dependency matrix. **T** and **C** have the same meaning as defined before.

3. BOOLEAN LOGICAL INFERENCE ENGINE

Usually, a test is not enough to unambiguously isolate failure sources. However, according to the outcomes of the test, faults can be divided into possible diagnostic conclusion and impossible diagnostic conclusion. Based on the ideal and using the compact set conception provided by Shakeri, let the two-tuple(**X**,**G**) describes diagnostic conclusion of the system at different time, where $\mathbf{X}=\{x_k|\ x_k\subset\mathbf{S}^*\}$ and $\mathbf{G}(\mathbf{G}\subseteq\mathbf{S}^*)$ denote possible and impossible diagnostic conclusion at present time epoch respectively, and $\mathbf{S}^* = \mathbf{S} \cup \{s_0\}$, s_0 denotes fault-free conclusion. Set $\mathbf{X}$ is complete and is a set cluster consisting of compact sets. Compact set x ($x \in \mathbf{X}$) denotes the possible diagnostic conclusion, which is consistent to the known test outcomes and composed of minimal faults. If there is given($\mathbf{X}$,$\mathbf{G}$), where $\mathbf{X}=\{x_1,x_2,\ldots,x_q\}$, then $x_k \in \mathbf{X}$, $(x_k \cap \mathbf{G})=\emptyset$. Denote diagnostic conclusion corresponding to PASS and FAIL outcomes of the test t_j by ($\mathbf{X}_{jp}$, $\mathbf{G}_{jp}$) and ($\mathbf{X}_{jf}$, $\mathbf{G}_{jf}$) respectively.

The impossible diagnostic conclusion, $\mathbf{G}_{jp}$ and $\mathbf{G}_{jf}$, can be calculated by:

$$\begin{aligned} \mathbf{G}_{jp} &= \left\{ s_i \mid s_k \subseteq s_i, \forall s_k \in \mathbf{G} \cup \mathbf{TS}(t_j) \right\} \\ \mathbf{G}_{jf} &= \mathbf{G} \cup \{s_0\} \end{aligned} \tag{2}$$

Where $\mathbf{TS}(t_j)=\{s_i | w_{ij}=1, \text{for} 1 \le i \le z\}$ denotes the signatures of test t_j, indicating all the failure states detectable by test.

The possible diagnostic conclusion, $\mathbf{X}_{jp}$ and $\mathbf{X}_{jf}$, can be get through the following steps.

First, $\mathbf{X}_{jp}$ and $\mathbf{X}_{jf}$ can be expressed by:

$$\begin{aligned} \mathbf{X}_{jp} &= \sum_{x_k \cap G_{jp} = \emptyset} x_k \cdot \sum_{s_i \notin G_{jp}} (1 - w_{ij}) s_i \\ \mathbf{X}_{jf} &= \sum_{x_k \cap G_{jf} = \emptyset} x_k \cdot \sum_{s_i \notin G_{jf}} w_{ij} s_i \end{aligned} \tag{3}$$

Then, let (3) expand to and/or expressions, and simply them based on the following logical rules.

$$\begin{aligned} & s_k \cdot s_k = s_k, s_i + s_i = s_i \\ & s_0 \cdot s_i = s_i, s_k + s_k \cdot s_i = s_k \end{aligned} \tag{4}$$

where sign "·" denotes logical multiplication operation, $s_1 \cdot s_2$ denotes that the two faults occur simultaneously; sign "+" denotes logical add operation, and shows that at least one of the two faults occurs.

The further simplification of (3) can be based on the rule 1.

Rule1: If $s_i \subset s_k$, then $s_i \cdot s_k = s_k$; if $s_i \cup s_j = s_k$, then $s_i \cdot s_j = s_k$. For example, in table I, $s_3 \cdot s_5 = s_4 \cdot s_5 = s_5$, and $s_3 \cdot s_4 = s_5$ due to s_3, $s_4 \subset s_5$ and $s_3 \cup s_4 = s_5$

At last, eliminate compact sets which include elements of $\mathbf{G}$, and get possible diagnostic conclusion, $\mathbf{X}_{jp}$ and $\mathbf{X}_{jf}$.

Consider the data in Table1. Initially, the diagnostic conclusion ($\mathbf{X}$,$\mathbf{G}$) is ($\mathbf{F}^*$,$\emptyset$), where $\mathbf{F}^*=\{\{s_0\},\{s_1\},\ldots,\{s_6\}\}$. Provided four test are executed, and t_1 PASS, t_2, t_3, t_4 FAIL. First, derive the impossible diagnostic conclusion $\mathbf{G}=\{s_0,s_2,s_6\}$ according to (2); then get the possible diagnostic conclusion based on (3) (4), $\mathbf{X}=s_1s_3s_4+s_5$; simply it to $\mathbf{X}=s_5$ according to rule 1. In the form of set, the possible diagnostic conclusion is $\mathbf{X}=\{\{s_5\}\}$.

After getting the diagnostic conclusion ($\mathbf{X}$,$\mathbf{G}$), use the rule 2 to determine whether the repair operations are needed.

Rule2: If $|\mathbf{X}|=1$, all the faults in $\mathbf{X}$ should be repaired; if no test gives any information gain, i.e., $\mathbf{X}_{jp}=\emptyset$ or $\mathbf{X}_{jf}=\emptyset$ for $t_j \in \mathbf{T}$, then all the faults in $\mathbf{X}$ should be repaired too.

Refresh the diagnostic conclusion after repair operations based on rule 3.

Rule3: If fault state s_i has been repaired, then refresh the diagnostic conclusion according to (5).

$$\begin{aligned} & \mathbf{G}' \leftarrow \mathbf{G} \cup \{s_k \in \mathbf{S} \mid s_k \cap s_i \neq \emptyset\} - \{s_0\} \\ & \mathbf{X}' \leftarrow \mathbf{S}^* - \mathbf{G}' \end{aligned} \tag{5}$$

4. MULTI-FAULT DIAGNOSTIC STRATEGY

Multi-fault diagnostic strategy is constructed as follows: first, judge whether the candidate tests can provide information at the present diagnostic conclusion ($\mathbf{X}$,$\mathbf{G}$). If not, replace all the candidate fault components; otherwise, select the best test according to the heuristic function, then, judge the system states according to outcomes of the test. The heuristic function used to guide test selection is given by:

$$j^* = \arg\max_{t_j \in T} \left\{ \frac{IG(\mathbf{X}; t_j)}{c_j} \right\} \tag{6}$$

where c_j corresponds cost of t_j, $IG(\mathbf{X};t_j)$ denotes average mutual information between test t_j and possible diagnostic conclusion $\mathbf{X}$. The (6) means that the test with maximal diagnostic information per cost should be selected with a priority.

$IG(\mathbf{X};t_j)$is calculated by:

$$IG(\mathbf{X};t_j) = -\left\{\frac{P(\mathbf{X}_{jp})}{P(\mathbf{X})}\ln\frac{P(\mathbf{X}_{jp})}{P(\mathbf{X})} + \frac{P(\mathbf{X}_{jf})}{P(\mathbf{X})}\ln\frac{P(\mathbf{X}_{jf})}{P(\mathbf{X})}\right\} \quad (7)$$

Given $\mathbf{X}=\{x_1,x_2,\ldots,x_z\}$ and $x_k=\{s_{k1},\ldots,s_{kq}\}$, so P(**X**) can be calculated by:

$$P(\mathbf{X}) = 1-\prod_{k=1}^{z}\left(1-\left(\prod_{j=1}^{q}P(s_{k_j})\right)\right) \quad (8)$$

Especially, if $\mathbf{X}_{jp}$=Ø or $\mathbf{X}_{jf}$= Ø, then IG(X;t_j)=0.

If there exist more than one (≥2) compact sets after executing the test t_j, then, do further according to rule 4.

Rule4: Given the dimensions of the possible diagnostic conclusion satisfies |**X**|≥2**.** If t_j **T**, $IG(\mathbf{X};t_j)$=0， then repair all the faults in **X**, refresh diagnostic conclusion after repair according to (5)otherwise, select the next best test according to (6).

Multi-Fault Diagnostic Strategy Generation Algorithm

Step1: Input the basic data (**S**,**P***,**T**,**C**,**D**), and create ψ used to store diagnostic nodes. Initially, ψ={(**F***,Ø)}, create an empty set D used to store the decision tree.

Step2: Repeat the following steps until ψ= Ø, output D.

2.1: Select a diagnostic node from ψ, denoting it by(**X**,**G**),and put it in D, analyze dimension of **X**.

2.2: **IF** |**X**|=1, THEN

IF x ∪ **G=S***, (x ∈ **X**), THEN

-Action: remove **X** from ψ to D.

Return.

IF x ∪ **G** **S***, (x ∈ **X**), THEN

-repair all the faults in x,

-generate a new diagnostic node (**X**',**G**') under the node (**X**,**G**) and store it in ψ

Return.

ELSE IF |**X**|>1, THEN, calculate possible conclusion set after each candidate test, e.g., after test t_j, denote the possible conclusion set by $\mathbf{X}_{jp}$ and $\mathbf{X}_{jf}$. Calculate diagnostic information of each candidate test.

IF no test **give** any information, viz., $\mathbf{X}_{jp}$ (or $\mathbf{X}_{jf}$)=Ø for $t_j\in\mathbf{T}$, THEN

-repair all the faults in **X,**

-remove **X** from ψ.

Return.

IF there exist some tests giving diagnostic information, THEN

-select the best test according Eq.(6), denoting it by t_k, store the new diagnostic conclusion ($\mathbf{X}_{kp}$, $\mathbf{G}_{kp}$) and ($\mathbf{X}_{kf}$, $\mathbf{G}_{kf}$) produced by t_k in ψ and the test t_k in D.

Return.

5. APPLICATION STUDY

A simulation example with five failure nodes, five test nodes and an AND node is used to verify the presented algorithm. The multi-signal flow model of the system is shown in Figure2. The minimal fault is {f_1, f_3}, and the extended dependency matrix with failure state probability is shown in Table2. The minimal fault probability equals to the product of the correlation single faults.

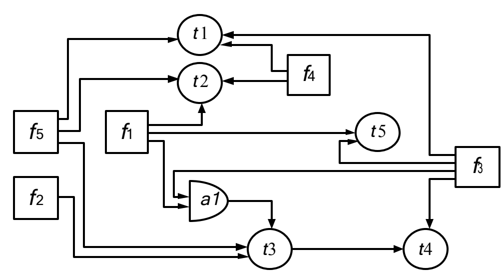

Figure 2. A simulation example with redundancy

Table2. The Extended dependency matrix with fault probability of the simulation example

Fault sources	tests					Fault probability
	t_1	t_2	t_3	t_4	t_5	
$s_1=\{f_1\}$	0	1	0	0	1	0.014
$s_2=\{f_2\}$	0	0	1	1	0	0.027
$s_3=\{f_3\}$	1	0	0	1	1	0.125
$s_4=\{f_4\}$	1	1	0	0	0	0.068
$s_5=\{f_5\}$	1	1	1	1	0	0.146
$s_6=\{f_1,f_3\}$	1	1	1	1	1	0.002

The corresponding fault diagnostic tree applying the proposed algorithm is shown in Figure3.

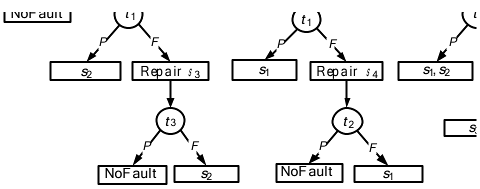

Figure 3. The multi-fault diagnostic tree

The fault tree has 11 leaf nodes, number the nodes sequentially from left to right, and analyze the masking false failures and hidden failures of each leaf node. The results are shown in Table3.

Form the results in Table3, obviously, there are no hidden failures and masking false failures in all diagnostic conclusions. Hence, realize multiple fault diagnosis for systems with redundancy effectively and accurately.

Note that there exist two shaded nodes in Figure3, x_{10} and x_{11}. Let denote the diagnostic conclusions of the two nodes by $(\mathbf{X}_{10},\mathbf{G}_{10})$ and $(\mathbf{X}_{11},\mathbf{G}_{11})$ respectively, it can be referred that: $\mathbf{G}_{10}=\{s_0,s_1,s_3,s_6\}$, $\mathbf{G}_{11}=\{s_0\}$, $\mathbf{X}_{10}=\{\{s_5\}, \{s_2,s_4\}\}$ and $\mathbf{X}_{11}=\{\{s_1,s_5\},\{s_3,s_5\},\{s_6\},\{s_1,s_2,s_4\},\{s_2,s_3,s_4\}\}$ respectively. It is obvious that the possible diagnostic conclusions are not unique, yet, all the tests have been selected, and no test can provide diagnostic information any more, so all the faults in $\mathbf{X}$ should be repaired according rule 4. When the union of possible diagnostic conclusion and impossible diagnostic conclusion equals to $\mathbf{S}^*$, terminate the diagnostic process.

Table3. The hidden failures and masking false failures for each leaf node

Leaf nodes	Passed tests	Repaired faults	Hidden failures	Masking false failures
$x_1=\{s_0\}$	$D_{P(1)}=\{t_2,t_4\}$	Ø	Ø	Ø
$x_2=\{s_2\}$	$D_{P(2)}=\{t_1,t_2\}$	Ø	Ø	Ø
$x_3=\{s_0\}$	$D_{P(3)}=\{t_2,t_3\}$	$\{s_3\}$	Ø	Ø
$x_4=\{s_2\}$	$D_{P(4)}=\{t_2\}$	$\{s_3\}$	Ø	Ø
$x_5=\{s_1\}$	$D_{P(5)}=\{t_1,t_4\}$	Ø	Ø	Ø
$x_6=\{s_0\}$	$D_{P(6)}=\{t_2,t_4\}$	$\{s_4\}$	Ø	Ø
$x_7=\{s_1\}$	$D_{P(7)}=\{t_4\}$	$\{s_4\}$	Ø	Ø
$x_8=\{s_1,s_2\}$	$D_{P(8)}=\{t_1\}$	Ø	Ø	Ø
$x_9=\{s_3,s_4\}$	$D_{P(9)}=\{t_3\}$	Ø	Ø	Ø
$x_{10}=\{s_2,s_4,s_5\}$	$D_{P(10)}=\{t_5\}$	Ø	Ø	Ø
$x_{11}=\{s_2,s_4,s_5,s_6\}$	$D_{P(11)}=$ Ø	Ø	Ø	Ø

Consider the digraph model of F18 Flight Control System (FCS) for the left Leading Edge Flap (LEF) in Figure4, which was used as an example in [9]. The minimal faults for the example are {FCCA,FCCB}, {FCCA,CHNL3}, {FCCB,CHNL2}, and {CHNL2,CHNL3}. The extended dependency matrix is shown in table 4.

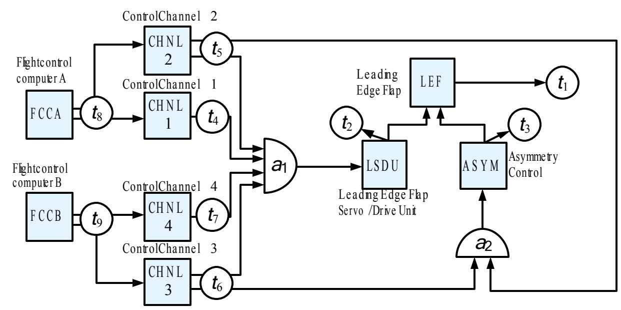

Figure 4. Diagraph model of subsystem LEF

Table4. The extended dependency matrix of subsystem LEF

Failure sources	Tests									Probability
	t1	t2	t3	t4	t5	t6	t7	t8	t9	
s0={f0}	0	0	0	0	0	0	0	0	0	0.9906
s1={LEF}	1	0	0	0	0	0	0	0	0	0.001
s2={LSDU}	1	1	0	0	0	0	0	0	0	0.001
s3={ASYM}	1	0	1	0	0	0	0	0	0	0.001
s4={FCCA}	0	0	0	1	1	0	0	1	0	0.001
s5={FCCB}	0	0	0	0	0	1	1	0	1	0.001
s6={CHNL1}	0	0	0	1	0	0	0	0	0	0.001
s7={CHNL2}	0	0	0	0	1	0	0	0	0	0.001
s8={CHNL3}	0	0	0	0	0	1	0	0	0	0.001
s9={CHNL4}	0	0	0	0	0	0	1	0	0	0.001
s10={FCCA,FCCB}	1	1	1	0	0	0	0	0	0	0.0001
s11={FCCA,CHNL3}	1	0	1	0	0	0	0	0	0	0.0001
s12={FCCB,CHNL2}	1	0	1	0	0	0	0	0	0	0.0001
s13={CHNL2,CHNL3}	1	0	1	0	0	0	0	0	0	0.0001

The diagnostic tree of subsystem LEF adopting the proposed reference engine and diagnostic strategy is shown in Figure5.

Obviously, the presented diagnostic strategy can diagnose multiple fault of the LEF correctly. The diagnostic tree is very complex due to many types of multiple faults. The traditional diagnostic strategies based on single fault assumption can't diagnose the multiple faults in redundant systems. For example, in the daily maintenance action of the LEF, if FCCA occurs fault, the single assumption-based diagnostic strategy can't diagnose it due to the existing AND node α_1, but if CHNL3 also occurs fault during next flight mission, it will result in severe accident. The proposed diagnostic strategy can efficiently and correctly diagnose these faults in subsystem LEF, so with higher application value in practical engineering.

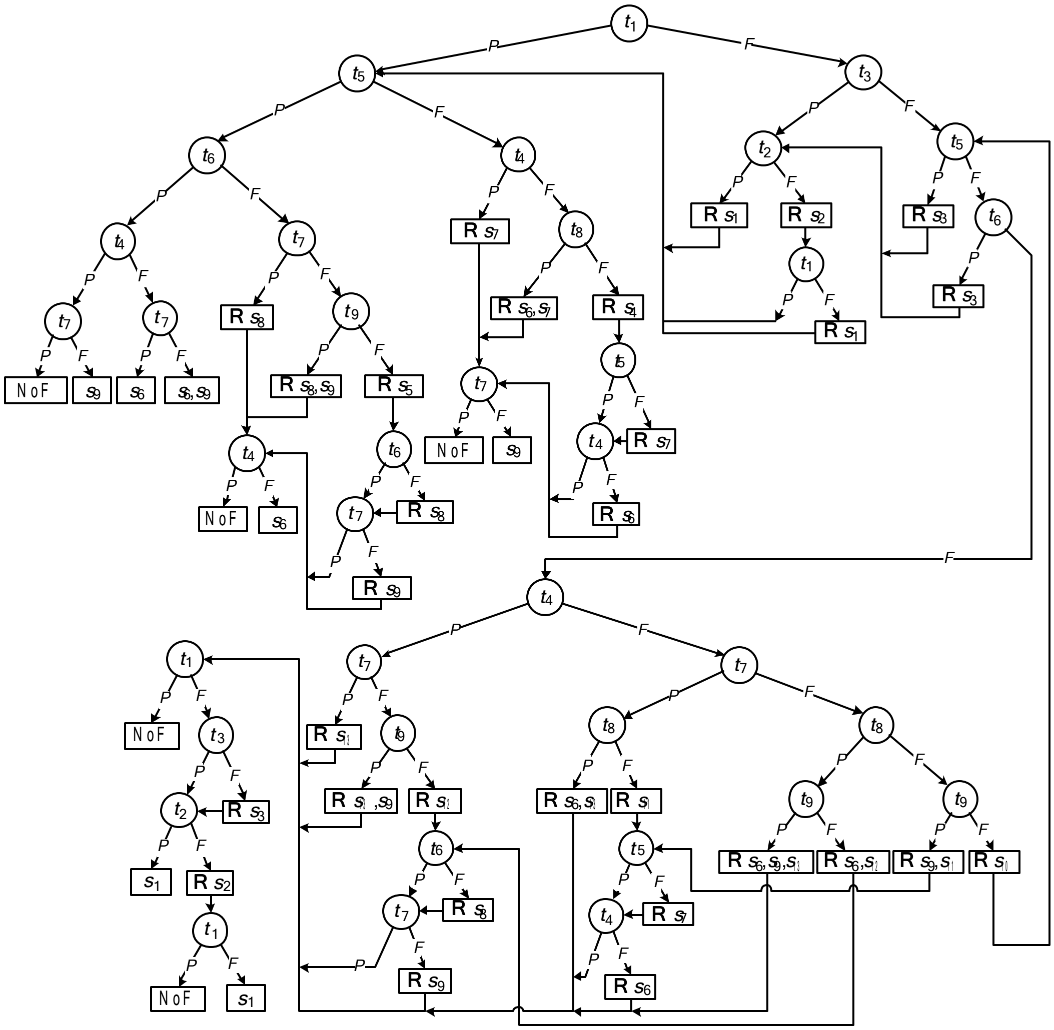

Figure 5. Diagnostic tree of subsystem LEF

6. CONCLUSIONS

The paper mainly considers the multiple fault diagnostic strategy problem arising in systems with redundancy. The paper first formulates the problem, then presents multiple fault inference engine based on Boolean logic and three additional inference rules. The inference engine can be applied to determine the possible diagnostic conclusion and impossible diagnostic conclusion accurately after executing each test. Based on the knowledge, an efficient multiple fault diagnostic strategy for redundant systems is constructed. An efficient multiple fault diagnostic strategy for the F18 FCS is constructed by the proposed method. The analysis results show that the strategy can diagnose multiple faults in the FCS, and can avoid missed diagnosis and false diagnosis. Hence, the proposed multiple fault diagnostic strategy can be applied to practical engineering.

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