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Testability Analysis Method of Radar Equipment Based on Dependency Model

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Testability Analysis Method of Radar Equipment Based on Dependency Model

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Abstract. In order to improve the testability design level of radar equipment, achieve rapid detection and isolation of faults, and reduce the life cycle cost of the system, a testability analysis method of radar equipment based on correlation model is proposed. The basic process of correlation model modeling is introduced. On this basis, the optimization method of test points for fault detection and isolation and the generation method of fault diagnosis strategy are analyzed. The effectiveness of the proposed method is verified by applying it to radar transmitting subsystem.

1. Introduction

In the increasingly complex battlefield situation, the performance of radar equipment is constantly improved, and its structure and function are increasingly complex, which brings severe challenges to the fault detection and isolation of equipment. To solve this problem, it is necessary to design the radar equipment for testability. Testability is a design feature that enables a product to accurately determine its state and isolate its internal failures[1]. Good testability design can shorten the time of equipment fault detection and isolation, which is of great significance to improve the reliability and safety of tasks and reduce the life cycle cost[2].

Establishing a testability model in the process of equipment development and using the model to analyse and evaluate the testability design of equipment is not only conducive to timely find and solve the existing testability problems in the early stage of equipment development and avoid substituting the problems into the next stage of development, but also conducive to the control of testability design in the process of equipment development, so as to improve the testability level of equipment.

The dependency model uses the form of directed graph and matrix to describe the fault-test dependence relationship and causal reasoning relationship between modules[3]. The model is widely used in testability and diagnostic design, system engineering, maintainability and reliability[4]. Based on the analysis of dependency model, a dependency model of radar transmitting subsystem is established in this paper. By analysing the model, the fault test dependency matrix of radar transmitting subsystem is obtained. Through the analysis of dependency matrix and qualitative analysis and quantitative calculation of testability index, the testability of radar equipment can meet the requirements of relevant maintenance and testing, and improve the fault detection and isolation efficiency of radar equipment.

2. Dependency model

2.1. Modeling analysis process

Dependency model is a model that express the logical relationship between equipment fault and test correlation, including graphical model and mathematical model[7]. Firstly, Failure Modes and Effects Analysis (FMECA) is carried out for equipment, that is, through system analysis, all possible failure modes of components, parts, equipment and software in the design and manufacturing process, as well as the causes and effects of each failure mode are determined. After FMECA, each failure mode is obtained in order of probability and severity. Based on this, the function and structure of Unit Under Test (UUT) are divided, the correlation graph model is established based on available Test points, and then the first-order correlation relationship is analyzed. The fault-test dependency matrix is obtained by the reachability algorithm. After the dependency matrix model is established, optimization calculation of test points can be carried out to establish a diagnosis tree. At this time, the generated diagnosis strategy can be used to predict the fault detection rate and fault isolation rate. The modeling and analysis process of correlation model is shown in figure 1.

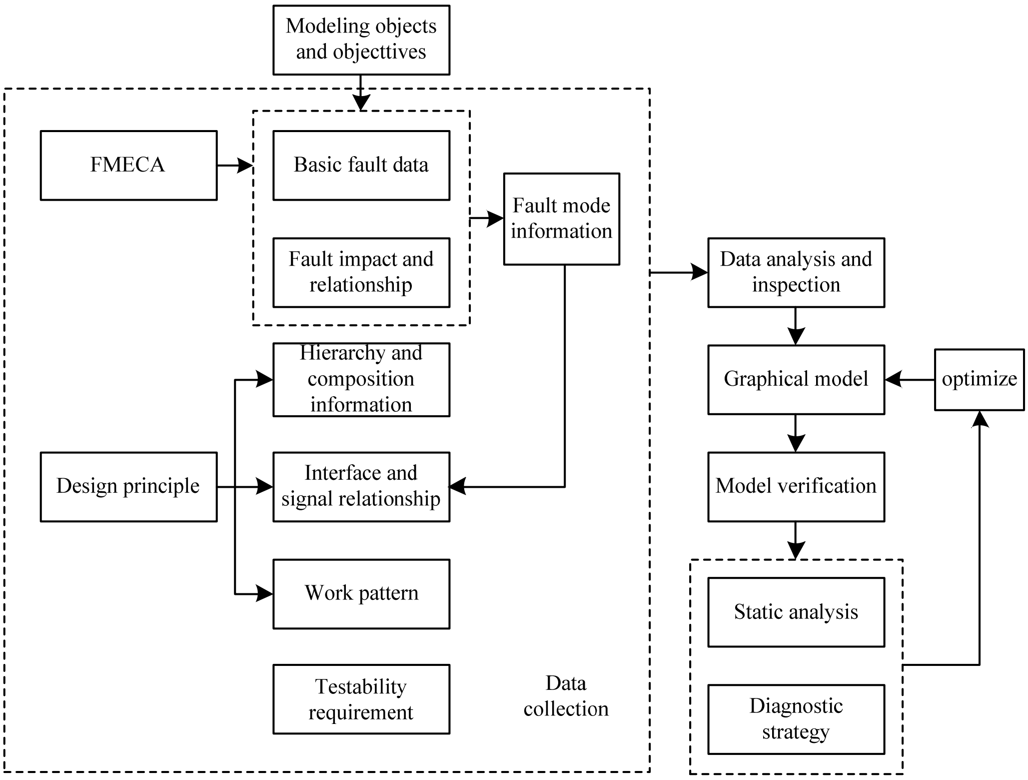

Figure 1. Modeling and analysis process.

2.2. Dependency mathematical model

The dependency mathematical model describes the relationship between faults and tests, which is represented by matrix $\boldsymbol{D}_{m\times n}$, called $\boldsymbol{D}$ matrix. On the basis of the dependency graphical model, the line vector method can be used to solve the dependency mathematical model[7]. Firstly, the first-order dependency is analysed according to the graphical model, and the first-order dependency logic equations of each test point are listed. Then solve the equations and get the $\boldsymbol{D}$ matrix model. The form of the first-order dependency logic equation is as follows.

$$T_j = F_x + F_y + F_z + \cdots + T_k + T_l + T_h + \cdots \tag{1}$$

On the right side of the equation are the features and test points that have first-order dependency with test point T_j, with "+" indicating logical "or". The value of subscript x or y is a positive integer less than or equal to m, and the value of k and l is a positive integer less than or equal to n, but not equal to *j*. Let $F_i = 1$, and the rest $F_x = 0 (x \neq i)$, solve the equations to obtain the values of each d_{ij}, so as to obtain the i row of the dependency matrix.

$$F_i = [d_{i1}\ d_{i2}\ \cdots\ d_{in}] \tag{2}$$

Take $i = 1, 2, \cdots, m$. Repeat the above process to obtain m row vectors, which together form the matrix ***D.***

For large, complex systems, the dependency matrix is large, and some tests do not provide useful information. Therefore, the dependency matrix needs to be simplified. If a column of the matrix is all zero, the test is useless and the column is deleted during optimization. If $t_i = t_j$, $i \neq j$ that is, the two columns of the matrix are identical, the two tests are redundant and only the tests with lower cost or easy implementation are retained. If $f_x = f_y$, $x \neq y$, means that the two rows of the matrix are identical, and the fault sources f_x and f_y form a fuzzy group, that is, they cannot be isolated by existing tests, then they can be combined into a line in the dependency matrix. If they need to be separated, appropriate test points need to be added.

3. Test point optimization method

3.1. The selection of detection test points

For matrix $\boldsymbol{D} = [d_{ij}]_{m \times n}$, the fault detection weight W_{FD} of the *j* test point can be calculated by the following formula:

$$W_{\mathrm{FD}j} = \sum_{i=1}^{m} d_{ij} \tag{3}$$

After calculating the W_{FD} of each test point, the one with the largest W_{FD} value is selected as the first test point. The corresponding column matrix is $\boldsymbol{T}_j = [d_{1j}\ d_{2j} \cdots d_{mj}]^{\mathrm{T}}$. Divide the matrix $\boldsymbol{D}$ into two parts by $\boldsymbol{T}_j$ to obtain two sub-matrices.

$$\boldsymbol{D}_P^0 = [d]_{a \times n} \tag{4}$$

$$\boldsymbol{D}_P^1 = [d]_{(m-a) \times n} \tag{5}$$

Where, $\boldsymbol{D}_P^0$ is the sub-matrix formed by the rows corresponding to elements equal to 0 in $\boldsymbol{T}_j$; $\boldsymbol{D}_P^1$ is the sub-matrix formed by the rows corresponding to elements equal to 1 in $\boldsymbol{T}_j$; *a* is the number of elements in $\boldsymbol{T}_j$ that are equal to 0; *P* is the number of tests that have been selected.

After selecting the first test point for detection $P = 1$. If $a \neq 0$, W_{FD} value of $\boldsymbol{D}_P^0$ is calculated again, the test point with the maximum value of W_{FD} is selected as the second test point, and the corresponding column matrix is used to segment again. Repeat the above process until the column matrix corresponding to the selected test point no longer contains the element of 1.

3.2. The selection of test points for fault isolation

For the *j* test point, its fault isolation weight W_{FI} can be calculated by the following formula:

$$W_{\mathrm{FI}j} = \sum_{i=1}^{m} d_{ij} \sum_{i=1}^{m} (1 - d_{ij}) \tag{6}$$

After selecting the first test point, divide the matrix, recalculate the W_{FI} of the sub-matrix, repeat the above process until each sub-matrix becomes only one line, and then the selection process of test points for fault isolation is completed.

3.3. Consider the impact of reliability and cost

For radar equipment, components with low reliability are more likely to fail, so priority should be given to detection and isolation. In addition, the failure detection and isolation process will incur corresponding test costs, so the test site with low comprehensive cost should be selected first. Therefore, test points should be selected, diagnostic strategies formulated, and W_{FD} and W_{FI} calculated based on dependency as well as the relative failure rate and test cost.

$$W_{\mathrm{FD}j}=\frac{1}{a_{cj}}\sum_{i=1}^{m}a_i d_{ij} \tag{7}$$

$$W_{\mathrm{FI}j}=\frac{1}{a_{cj}}\sum_{i=1}^{m}a_i d_{ij}\left[\sum_{i=1}^{m}a_i(1-d_{ij})\right] \tag{8}$$

$$a_i=\lambda_i\Big/\sum_{i=1}^{m}\lambda_i \tag{9}$$

$$a_{cj}=c_j\Big/\sum_{j=1}^{n}c_j \tag{10}$$

Where, a_i is the failure frequency ratio of component unit i ; λ_i is the failure rate of the component unit i ; c_j is the sum of related costs of test j ; a_{cj} is the relative cost ratio for the test j .

4. Diagnosis tree and diagnostic capabilities

The diagnosis tree represents the test sequence for fault detection and isolation. It is the basis for detailed design of the UUT testability and provides technical support for external diagnosis testing of the UUT. It can be used not only in product design stage, but also in the practical stage of maintenance fault diagnosis. The establishment of diagnosis tree is based on the optimization results of test points, detect first and then isolate, and the diagnosis tree is formulated according to the sequence of test points[8].

After constructing the diagnosis tree, the fault diagnosis ability can be calculated as follows:

$$N_D=\sum_{i=0}^{m}p_i k_i \tag{11}$$

$$p_0=\frac{\sum_{k=1}^{m}(1-\lambda_k)}{\sum_{k=1}^{m}(1-\lambda_k)+\sum_{k=1}^{m}\left(\lambda_k\prod_{k=1,k\neq i}^{m}(1-\lambda_k)\right)}=\frac{1}{1+\sum_{k=1}^{m}\lambda_k(1-\lambda_k)} \tag{12}$$

$$p_i=\frac{\lambda_i\prod_{k=1,k\neq 1}^{m}(1-\lambda_k)}{\prod_{k=1}^{m}(1-\lambda_k)+\sum_{i=1}^{m}\left(\lambda_i\prod_{k=1,k\neq i}^{m}(1-\lambda_k)\right)}=\frac{\lambda_i(1-\lambda_i)}{1+\sum_{k=1}^{m}\lambda_i(1-\lambda_i)},\quad i\neq 0 \tag{13}$$

Where, N_D is the average number of test steps, p_i is the probability of failure i , and k_i is the number of test steps of failure i .

FDR and FIR are[9]:

$$\gamma_{\mathrm{FD}} = \sum \lambda_{\mathrm{FD}i} \Big/ \sum \lambda_i \tag{14}$$

$$\gamma_{\mathrm{FI}} = \sum \lambda_{\mathrm{FI}i} \Big/ \sum \lambda_{\mathrm{FD}i} \tag{15}$$

Where, $\lambda_{\mathrm{FD}i}$ is the failure rate of detected component unit i ; $\lambda_{\mathrm{FI}i}$ is the failure rate of isolated component unit i .

5. Example analysis and verification

A radar transmitting subsystem includes power amplifier extension, multi-beam klystron, directional coupler, titanium pump power supply, magnetic field power supply, filament power supply, bias power supply, high voltage power supply, charging control extension, artificial line, high power pulse transformer and 11 corresponding test points. Thus, dependency graphical model can be established, as shown in figure 2.

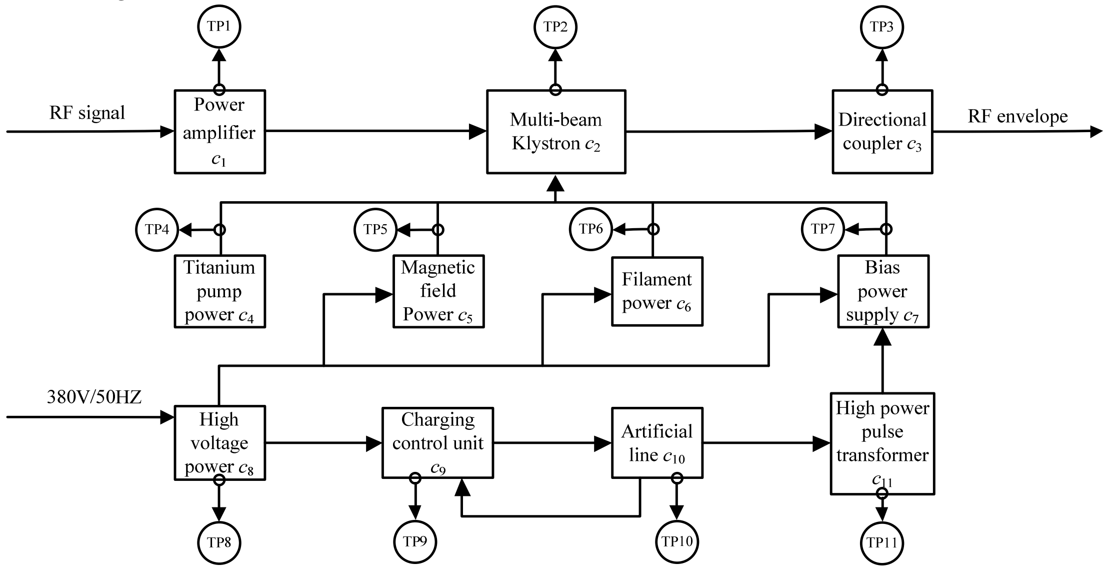

Figure 2. Radar transmitting subsystem.

The first-order correlation relationship in the model is analyzed, and the equations are solved by using Equation (1), and the correlation mathematical model of radar transmitting subsystem is obtained, as shown in table 1.

Table 1. Dependency matrix of Radar transmitting subsystem.

Fault	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}
F_1	1	1	1	0	0	0	0	0	0	0	0
F_2	0	1	1	0	0	0	0	0	0	0	0
F_3	0	0	1	0	0	0	0	0	0	0	0
F_4	0	1	1	1	0	0	0	0	0	0	0
F_5	0	1	1	0	1	0	0	0	0	0	0
F_6	0	1	1	0	0	1	0	0	0	0	0
F_7	0	1	1	0	0	0	1	0	0	0	0
F_8	0	1	1	0	1	1	1	1	1	1	1
F_9	0	1	1	0	0	0	1	0	1	1	1
F_{10}	0	1	1	0	0	0	1	0	1	1	1
F_{11}	0	1	1	0	0	0	1	0	0	0	1

Where, F_9 and F_{10} are a fuzzy group, and tests t_9 and t_{10} are mutually redundant tests. F_9 and F_{10} are combined and t_{10} is removed to complete the simplification of dependency matrix. If the failure rate a of each component unit is known, formula (9) and Formula (13) can be used to calculate the failure frequency ratio and failure probability of each component unit respectively, and the results are shown in table 2.

Table 2. Failure frequency ratio and failure probability.

UUT	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	$F_9 F_{10}$	F_{11}
$\lambda_i \times 10^{-2}$/h	4	3	5	3	4	5	2	3	5	6
a_i	0.100	0.075	0.125	0.075	0.100	0.125	0.050	0.075	0.125	0.150
p_i	0.028	0.021	0.034	0.021	0.028	0.034	0.014	0.021	0.034	0.041

According to Formula (12), it can be concluded that the probability of no failure F_0 is 0.724. According to Equation (14), it can be concluded that the fault detection rate FDR is 100%. Since F_9 and F_{10} are a fuzzy group, it can be obtained from Equation (15) that the FIR of fault isolation rate isolated to a single component is 75%, and that isolated to two components is 25%.

Combined with the reliability data, the simplified dependency matrix is analyzed, and the diagnosis tree was obtained as shown in figure 3.

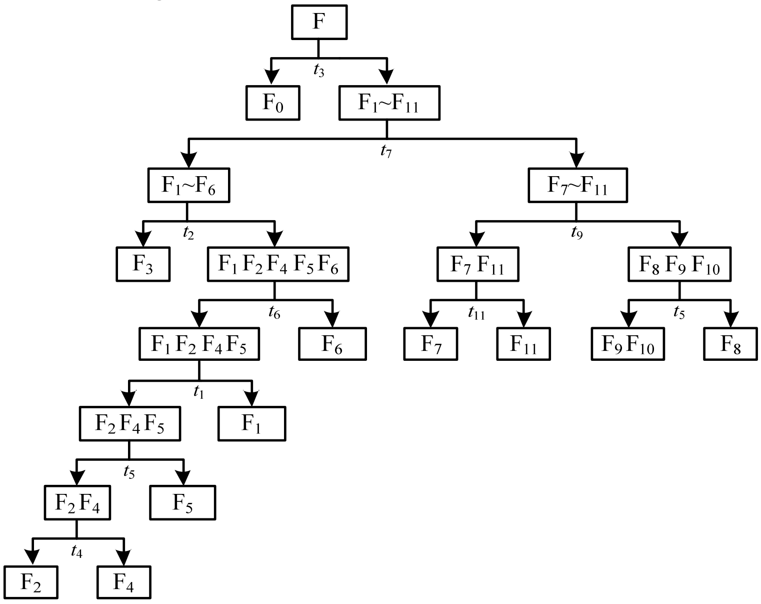

Figure 3. Diagnosis tree.

In the figure, t_3 is the test point for fault detection, and the rest are the test points for fault isolation. According to Equation (11), the average test step N_D of the diagnosis tree is 2.004.

6. Conclusions

Testability modeling and analysis is the basis of equipment testability design. Based on the theory of dependency modeling, the testability analysis method of radar equipment based on dependency model is proposed in this paper. Based on the analysis object of radar equipment transmitting subsystem, the dependency model is established, and the test points for fault detection and fault isolation are optimized, and the fault diagnosis tree is constructed. This method provides a new idea for modeling and analyzing the testability of radar equipment and has certain theoretical and practical application value.

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