Diagnosis strategy design method based on ant colony algorithm

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Abstract—Diagnosis strategy design is an important step in testability design. In order to be close to the reality, the optimization design of diagnosis strategy is carried out under the condition of unreliable test. Firstly, the changes caused by unreliable test conditions are analyzed, and test cost and error cost are established as optimization objectives. Then the mathematical model of the problem is established. Ant colony algorithm is used to solve the problem, and a new heuristic evaluation function is established. Finally, the effectiveness of the proposed method is verified by an example and compared with other algorithms.

1. Introduction
In today's world, the structure and composition of equipment or equipment are more and more complex, and the function is also improved. However, the over complex system also leads to the difficulty of fault detection and isolation. How to quickly detect the current system status and isolate specific faults has become a hot research topic. In order to solve this problem, testability design came into being, and began to develop rapidly in the late 1990s. Testability, together with reliability, maintainability, supportability and safety, is called "five characteristics", which must be considered at the beginning of equipment development[1]. Good testability design not only takes into account factors such as test cost, but also greatly improves the efficiency of fault diagnosis and greatly reduces the life cycle cost of equipment. When the test sequence is built, the test model can be used to minimize the test cost. In testability, diagnosis strategy mainly refers to test sequence, so the optimization of diagnosis strategy is also called test sequence solving problem.

According to GJB2547A[2] diagnosis strategy is a test step or sequence that is determined by considering the constraints, objectives and related factors. The diagnosis strategy optimization problem is proved to be a NPC problem[3]. There are two kinds of solutions: dynamic programming algorithm and heuristic search algorithm. The most widely used heuristic search algorithm is greedy algorithm, but the algorithm has obvious defects, and the solution is often local optimal solution. Many scholars have improved greedy algorithm. Zhang Rui proposed a diagnosis strategy optimization method based on tabu search algorithm to solve the poor optimization performance of greedy algorithm, which increased the search range of the algorithm and improved the problem that greedy algorithm easily fell into the local optimal solution. However, the i-matrix setting of greedy algorithm has problems, and the effect is not good when applied to complex systems[4]. Johnson proposed an information heuristic search algorithm, which is much better than greedy algorithm, but still easy to fall into local optimumi[5]. Huang Yifeng proposed a diagnosis strategy optimization method based on the rollout algorithm, which essentially introduced an improved greedy algorithm with one-step forward backtracking operator. The effect was greatly improved, but it was still an approximate global optimal solution[6]. Li Deng improved
the rollout algorithm and proposed the rig algorithm to solve the problem of fault diagnosis\cite{7} Sun Meng used the information entropy algorithm to optimize the diagnosis strategy based on the multi feature D matrix\cite{8} Zhang Guohui, Tian Heng and Guo Jiahao have also studied the problem from the perspective of information quantity and information entropy\cite{9,10,11} At present, the most mature solution is adopted by the testability design software teams \textit{AO}$^*$ algorithm\cite{12} The algorithm has good global search ability and good search results, but its essence is a heuristic search algorithm with continuous backtracking. The structure of the algorithm is complex and the storage performance of computing equipment is high, so it is not suitable for complex systems. Most of the existing diagnosis strategy optimization algorithms are based on the premise of test reliability, and do not consider the adaptability of the algorithm under the condition of test unreliability. In fact, the testing process is often not completely reliable, and the cost of unreliability is usually quite heavy. Therefore, the idealized treatment of testing is not correct, and the uncertainty cannot be ignored in the process of diagnosis strategy design. Compared with perfect test conditions, previous studies on the design of diagnosis strategy under unreliable test conditions are less\cite{13,14,15}\textit{The algorithm is still based on search. The search results are optimized by adding backtracking operators and introducing unreliable test factors into the heuristic function. The algorithm has certain practical value, but in the actual operation process, it is difficult to effectively evaluate the cost caused by diagnostic errors, or the evaluation is not completely accurate. After the search, the scheme is returned directly. However, due to the lack of evaluation feedback of the scheme, the final result is not the optimal solution. Improved for unreliable testing, \textit{AO}$^*$ algorithm also has this problem.}

In order to solve the above problems, this paper takes the unreliable test as the premise, comprehensively considers the fault detection rate, test false alarm rate, test cost and the loss caused by the fault diagnosis caused by unreliable test, and proposes a diagnosis strategy optimization method based on the essence ant system. The method adopts the heuristic function including error cost and test cost, and it has the advantages of the original scheme evaluation feedback algorithm. In this paper, the principle and calculation steps of this method are introduced in detail, and the excellent performance of the algorithm is verified by an example of missile borne radio altimeter.

2. **Optimization of diagnosis strategy**

The diagnosis strategy here refers to the test sequence with a certain order. The problem of diagnosis strategy optimization is to establish the test sequence by some method. The test sequence needs to make the test cost, false alarm cost and missed detection cost reach the comprehensive optimization. The related concepts, definitions and problem explanations involved in the optimization of diagnosis strategy under unreliable test conditions are as follows:

Failure set: $F = \{f_0, f_1, ..., f_m\}$ in which $f_l (1 \leq l \leq m)$ indicates the failure mode, $f_0$ indicates no fault state.

Failure probability set: $P = \{p(f_0), p(f_1), ..., p(f_n)\}$

Available test sets: $T = \{t_1, t_2, ..., t_n\}$

Test cost set: $C = \{c_1, c_2, ..., c_n\}$

Test Miss cost set: $MC = \{MC_1, MC_2, ..., MC_n\}$ In which $MC_i$ indicates that the system has failed $f_i$, however, the test did not isolate the fault, instead, it was diagnosed as other fault or no fault due to the fault $f_i$. Continue to exist and cause losses.

Test Miss cost set: $FC = \{FC_1, FC_2, ..., FC_n\}$ In which $FC_j$ Failure or failure of the system is indicated $f_j$ was diagnosed as a failure due to a test error $f_j$. The maintenance cost caused by this.

Fault test correlation matrix: $D = [d_{ij}]$ In which $d_{ij}$ indicates the correlation between fault and test, $d_{ij} = 1$ Represents a test $t_j$ Faults can be detected $f_i$, $d_{ij} = 0$ Represents a test $t_j$ Failure cannot be detected $f_i$. 


Fault detection correlation matrix: \( FD = \{ pd_{ij} \} \) In which \( pd_{ij} \) Represents the detection probability of fault \( f_i \) by test \( t_j \).

\[
pd_{ij} = P(t_j = 1 \mid f_i = 1)
\]

False alarm matrix: \( FA = \{ pf_j \} \) In which \( pf_j \) Represents a test \( t_j \) False alarm probability.

The average test cost of the test sequence is described as follows:

\[
C_{\text{mean}} = \sum_{i=1}^{n} \left( \sum_{j \in \text{MEAS} \{ f_i \}} c_{\text{TEST}(f_j, f_i)} \times P_t \right)
\]

among \( \text{TEST}(f_j) \) Indicates that the fault is isolated in the current diagnostic strategy \( f_i \). The required test sequence. \( c_{\text{TEST}(f_j, f_i)} \) Represents the cost of the jth test in a test sequence.

The average error cost composed of misdiagnosis cost and missed detection cost caused by test sequence is described in formula (2)

\[
EC_{\text{mean}} = \sum_{i=1}^{n} \left( \sum_{j \in \text{MEAS} \{ f_i \}} (1 - P(O = f_j \mid f_i)) \times MC_t + \left( \sum_{j \in X_f} P_{\text{true}}(t_{i-j}) - P_{\text{wrong}}(t_{i-j}) \right) \times FC_t \right)
\]

\[
P(O = f_j \mid f_i) \text{ Indicates that the system is correctly isolated to fault } f_j . \text{ } | \text{TEST}(f_j) \text{ | Indicates that the fault is isolated in the current diagnostic strategy } f_i . \text{ } \text{The number of tests in the test sequence of. } P(t_j = \text{wrong} \mid t_{i-j} = \text{true}) \text{ Represents the probability that the j-th test diagnosis in a fault isolation test sequence has an error, while the previous tests have diagnosed correctly. } x_j \text{ The current test represents the current test } t_j \text{ Diagnostic error, the fault set to which the fault is isolated.}

Diagnosis strategy optimization is a constrained optimization problem, that is, under the condition of satisfying the constraint conditions, the diagnosis strategy is calculated by some method, which makes the average test cost and average error cost reach the minimum. The individual fitness function is calculated as formula (3)

\[
Ts = f(\text{TEST}) = C_{\text{mean}} \ast EC_{\text{mean}}
\]

Where test represents the complete test sequence.

Therefore, under the condition of unreliable test, the mathematical model of multi-objective optimization selection problem is as follows:

\[
\min (C_{\text{mean}} \ast EC_{\text{mean}})
\]

3. Elite ant system algorithm for unreliable testing

The essence ant system algorithm is an ant colony optimization algorithm. The idea of the algorithm comes from the ant colony foraging phenomenon in nature. It has been found that in nature, ant colony can realize indirect communication through a substance called pheromone, and find the shortest path through cooperation. In 1992, Dorigo proposed ant colony optimization algorithm by modeling and abstracting this phenomenon\[15\]. At present, the algorithm has become a mature and reliable optimization algorithm, and successfully solved a variety of optimization problems. The essence ant system is an improved ant system algorithm. Based on the original ant system algorithm, it strengthens the optimal path so far. This improvement also makes the algorithm have faster evolution speed and higher precision than the traditional ant system. The construction method of the essence ant system and diagnosis strategy is described as follows:

3.1. Construction of heuristic function

In this paper, the optimal design of diagnosis strategy is carried out under the condition of unreliable test. Therefore, the heuristic function of the algorithm should not only consider the test cost, but also introduce the cost of missed detection and misdiagnosis caused by unreliable testing.
Given by historical data or expert experience. The test can be calculated by the cost of missed detection and misdiagnosis $t_j$. The estimated error cost is as follows:

$$EC(X; t_j) = \sum_{f \in X} \left( \frac{P(f_i)}{P(X)} \left( d_{ij}^f (1 - pd_{ij})MC_i + \right) \right)$$

Where $x$ is the fault set consisting of the currently UN isolated faults.

According to the theory of information entropy, the information contained in the test is as follows:

$$IG(X, t_j) = -\left( \frac{p(x_j^f) \log_2 p(x_j^f) +}{p(x_j^f) \log_2 p(x_j^f)} \right)$$

among $X_{jp}$, $X_{jf}$ Indicates that the test is complete $t_j$. After that, the original fault set is divided into test independent fault subsets $X_{jp}$ And test related subsets $X_{jf}$.

Test the heuristic function under unreliable condition

$$k^*(t_j) = \arg \max_{j} \left( \frac{IG(X, t_j)}{c_j + EC(X; t_j)} \right)$$

3.2. Pheromone update

This paper introduces two basic concepts: (1) node: in this paper, it mainly refers to each test, and ants are isolated to the smallest fault fuzzy group through each node. (2) path: in this paper, the path refers to the direction that ants choose from the specified node. Here, the path mainly refers to the two results corresponding to the test -- pass and alarm, which are expressed as $R_{i0}$, $R_{i1}$.

For example, the ant selects the node first $t_i$ The result is pass, then select test $t_j$, then this path uses $R_{ij0}$ express.

$\tau_{ij0}$, $\tau_{ij1}$ From the test $t_i$ Through the path $R_{ij0}$, $R_{ij1}$ To test $t_j$ The pheromone concentration of. At first, the pheromone concentration of all paths is the same, which is a constant value $\tau_{i0} = \tau_0$, $\tau_{i1} = \tau_0$. After an iteration, all ants in the ant colony release pheromones in the corresponding path. Pheromones are updated as follows.

$$\tau_{ij0}(t + 1) = (1 - \rho) * \tau_{ij0}(t) + \sum_{k=1}^{m} \Delta \tau_{ij0}(t + 1) + \sigma * \Delta \tau_{ij0}^h$$

$$\tau_{ij1}(t + 1) = (1 - \rho) * \tau_{ij1}(t) + \sum_{k=1}^{m} \Delta \tau_{ij1}(t + 1) + \sigma * \Delta \tau_{ij1}^h$$

$$\Delta \tau_{ij0}(t + 1) = \begin{cases} \frac{1}{|Ts^0|}, & \text{Ant K goes through this path} \\ 0, & \text{otherwise} \end{cases}$$

$$\Delta \tau_{ij1}(t + 1) = \begin{cases} \frac{1}{|Ts^1|}, & \text{Ant K goes through this path} \\ 0, & \text{otherwise} \end{cases}$$

$$\Delta \tau_{ij0}^h = \begin{cases} \frac{1}{|Ts^0|}, & \text{The optimal path contains this path} \\ 0, & \text{otherwise} \end{cases}$$

$$\Delta \tau_{ij1}^h = \begin{cases} \frac{1}{|Ts^1|}, & \text{The optimal path contains this path} \\ 0, & \text{otherwise} \end{cases}$$

$\rho$ Represents the evaporation rate of pheromone. $\Delta \tau_{ij0}^h(t + 1)$ Represents the ant colony's $t + 1$ iteration path $R_{ij0}$ from $t_i$ To test $t_j$ The pheromone released. $\Delta \tau_{ij0}^h T$ represents the current iteration of the best
pheromone, $\Delta \tau_{ij}$. The introduction of the essence ant system is the improvement of the ant system. It helps to guide the ants to search better and accelerate the convergence speed of the algorithm.

At first, each ant randomly selects a test as the initial test, and then selects the subsequent tests according to the test selection rules, until all fault fuzzy groups are isolated finally.

3.3. Design of diagnosis strategy

Ants determine the next test according to the test selection rules, and the test selection rules follow two paths $R_{ij-0}$, $R_{ij-1}$. It is divided into two parts, i.e., concentration function and pheromone value

\[ p_{ij-0}^k = \begin{cases} \sum_{t_j \in J_k} [\tau_{ij-0}(t)^\alpha (k(t_j))^\beta], & j \notin J_k \\ 0, & \text{otherwise} \end{cases} \]  

\[ p_{ij-1}^k = \begin{cases} \sum_{t_j \in J_k} [\tau_{ij-1}(t)^\alpha (k(t_j))^\beta], & j \notin J_k \\ 0, & \text{otherwise} \end{cases} \]  

$J_k$ represents the test set to be selected. The test selection rule is that ants pass the probability value and choose to go to the next test according to the random proportion principle.

3.4. Transfer process

Taking ant K in random initial test $i_t$ as an example, the probability of passing through $R_{ij-0}$ and $R_{ij-1}$ paths to all other tests is calculated according to the above formula. Firstly, it is clear that ant K moves according to the principle of $R_{ij-0}$ path priority. In other words, ants search for subsequent tests along $R_{ij-0}$ first, and then consider searching along $R_{ij-1}$ when they can’t follow $R_{ij-0}$. For the path $R_{ij-0}$, ant K chooses the next test according to the probability using the principle of random proportion. This is called tabu table, which is used to store the test data in the subsequent test.

Taboo list and transfer process are described as follows:

1. Ant K searches from test $i_t$, and puts test $i_t$ into the tabu list, then determines the subsequent tests according to the test selection rules and path priority principle, and puts these test sequences into the tabu list. In the process, the tests in the tabu list cannot be repeatedly selected until ant K isolates a fault through this branch and ends the search of the branch;

2. After ant K completes the search of the front branch, its position is in the last test of the tabu list. At this time, the ant chooses path $R_{ij-1}$ to start the search. The search process is the same as before until a fault is isolated. Note that after the search starts, the follow-up path still follows the principle of path $R_{ij-0}$ first;

3. When the branches corresponding to the two paths of the last test in the tabu list are isolated to the fault, the last test is deleted from the tabu list. The ant starts with the last test of the new tabu table, and repeats steps (1) ~ (3) to search until all faults are isolated.
3.5. Algorithm flow

Figure 1. algorithm flow chart

4. CASE ANALYSIS

Taking the radio altimeter of a certain missile as the object, the diagnosis strategy is optimized by using the method in this paper. The failure test matrix of radio altimeter under unreliable test conditions is shown in table (1). The failure rate, false alarm probability, test cost, misdiagnosis cost and missed detection cost are included in the table. The correlation matrix information has been integrated into the matrix, and the correlation value corresponding to the uncorrelated fault and test is directly set to 0.

According to the correlation matrix of fault test in table (1), assuming that the system is a single fault, the diagnosis strategy is designed by using the essence ant system algorithm in this paper. The algorithm parameter settings are shown in table (2).

Table 1 Fault test matrix

| Fault | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | $T_9$ | $T_{10}$ | $T_{11}$ | $T_{12}$ | $T_{13}$ | $T_{14}$ | $T_{15}$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Test cost | 1 | 2 | 1 | 1 | 2 | 5 | 3 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 4 |
| Test false alarm rate | 0.02 | 0.01 | 0.04 | 0.03 | 0.02 | 0.01 | 0.05 | 0.03 | 0.03 | 0.04 | 0.02 | 0.03 | 0.04 | 0.04 | 0.05 |
| failure rate | $f_0$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.781 |
| MC | 3 | 5 |
| FC | |
| $f_1$ | 0.97 | 0 | 0 | 0 | 0.94 | 0.93 | 0.92 | 0.93 | 0.94 | 0.91 | 0.99 | 0.93 | 0 | 0 | 0.003 |
| | |
| $f_2$ | 0.92 | 0 | 0 | 0 | 0.9 | 0.93 | 0.93 | 0.97 | 0.97 | 0.98 | 0.98 | 0 | 0 | 0 | 0.019 |
| | |

End
The test sequence obtained by the algorithm is represented in the form of fault diagnosis tree, as shown in figure (2).

In order to verify the effectiveness of the algorithm, greedy algorithm and common ant colony algorithm are used to design the diagnosis strategy for the object, and the results are compared with the method in this paper.

The evaluation information and calculation time of the diagnosis strategy obtained by the three algorithms are shown in table (3).
Figure (3) shows the fitness function change curve of the best individual in the past generations obtained by the elite ant system algorithm and the ordinary ant colony algorithm. It can be seen that the essence ant system algorithm has faster convergence speed and excellent performance.

5. Conclusion
In this paper, the essence ant system algorithm is proposed to solve the optimization problem of diagnosis strategy under the condition of unreliable test. The simulation results show that the essence ant system can solve the problem well. By comparing with the mature greedy algorithm and common ant colony algorithm, it is found that the algorithm in this paper has better calculation effect and faster calculation speed. Therefore, the algorithm has the ability of application in the design process.

Of course, some disadvantages of the algorithm are also exposed in the process of verification, such as the advantage of computing time is not obvious, multi-objective needs to be integrated into a single objective to optimize, and so on.

In engineering application, because the optimization process of diagnosis strategy is in the stage of equipment design and development, calculation time is not a factor that must be considered, and better optimization effect is the main goal to be pursued, and the essence ant system algorithm has the possibility of continuous improvement and Optimization for multi-objective situation. Greedy algorithm or other search algorithms terminate the algorithm after solving an optimal diagnosis strategy, and there is no process of feedback results, so it is difficult to improve for multi-objective situation. The ant colony algorithm has this feedback process, which can be improved by introducing the non dominated optimal solution or E-dominant optimal solution, and the subsequent upgrading space of the algorithm is broad.

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