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Methods of sequential test optimization in dynamic environment

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ABSTRACT

In this paper, sequential test problem with assumption of varying test cost and failure rate is considered. Due to varied operation environment and maintain history of electronic equipment, the cost of measurement and/or failure rate of fault source may change throughout the life cycle. Under these circumstances, instead of rerunning the whole AO∗ algorithm thoroughly, we make trivial adjustments on previous decision tree to accommodate the new circumstance. This method is much more efficient than the traditional AO∗ algorithm. Besides, the decision tree can evolve with varying environment and maintain history. Without loss of accuracy, the time efficiency is improved. The effectiveness of the proposed approach is proved by simulation and comparison with other methods.

1. Introduction

1.1. Motivation

Due to the lack of consideration of testability requirements, it is difficult to detect fault components/modes in large complex systems. Actual costs of system maintenance may greatly exceed the expected ones. Therefore, the design for testability [1] (DFT) is badly needed to decrease the test cost. Sequential test problem is a vital respect of DFT. Any measurement, observation and signal can be considered as an available test. Since every test has cost, one can avoid unnecessary costs by carefully choosing the tests and the order to execute these tests to figure out the failure state of system under test (SUT). In general, the next test to be executed depends on the results obtained from previously executed tests. The goal of sequential test optimization is to develop an algorithm that uses the (a priori) failure probabilities and test costs to construct effective diagnostic procedures, to minimize the expected cost of diagnosis. Usually, the test cost and failure rate are assumed to be constant. In such case, one can generate the diagnostic procedure off line and then use the same strategy over and over. However, the test cost, especially the failure rate, may vary with the system operating circumstance and maintain history. We propose some methods to quickly obtain the new optimal decision tree after the change of circumstance. The main idea is to utilize the existing information and modify the original decision tree efficiently. By using the proposed method, the optimal decision tree can evolve in dynamic circumstance.

1.2. Previous works

The problem of sequential test was first introduced in [2]. It was proven to be a NP-complete problem [3]. There are several different traditional optimization solutions to this problem: The dynamic programming (DP) algorithm was first proposed in [4] to solve the test sequential problem. The DP algorithm builds the decision tree from the leaves up according to the test matrix until the entire tree from the initial node of complete ambiguity is generated. The storage and computational requirements of DP algorithm is $O(3^n)$, where n denotes the number of tests, as a result, it is impractical for systems with $n \geq 12$. Kundakcioglu and Unluyurt [5] put forward a method based on the ideas of Huffman coding [6] by binding two system states together until all the states are solved, while its computational requirements grow exponentially as n increases and may cause combinatorial explosion. AO* algorithm (AND/OR graph search method) was proposed in [7] and it generated fault decision tree in an AND/OR graph and provided a minimal expected test cost. An approach based on integrating concepts from the information theory and the heuristic AND/OR graph search method was developed [8]. It used HEF (Heuristic evaluation function) to estimate nodes in AND/OR graph to decrease the number of expanded nodes. The HEF choosing for AO* will influence the accuracy and computational requirement of this algorithm. The HEF based on Huffman coding provides an accurate result while the HEF based on entropy+1 provides a tradeoff between optimality and computational complexity [9].

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In recent years, as the evolution algorithms became increasingly popular, the combination of sequential test problem and evolution algorithms has been attempted by a few researchers [10–13]. An adaptive simulated annealing genetic algorithm was proposed in [14] to select test and minimize the test cost for PHM systems. The genetic algorithm can also optimize the data for least squares support vector regression to improve the prediction accuracy for fault prognosis [15]. A heuristic particle swarm optimization algorithm is proposed to solve the problem of test point selection with unreliable test [16].

Sequential test problem belongs to the general class of binary classification problem that arise in a wide area of applications, including telecommunication network topology [17], computer vision texture classification [18], action recognition [19] and disease prediction [20]. The approach in [21] invokes a naive Bayes classifier to reduce test costs while maintaining the prediction accuracy of a classifier. The authors present an integrated algorithm for simultaneous feature selection (FS) and designing of diverse classifiers using genetic programming in [22]. Though sequential test problem has more restrictions than the general classification problem, the methods can be used for the sequential test problem.

Methods mentioned above to solve test sequential problem are all static, viz., the parameters for test sequential problem are unchangeable. In fact, the test cost, especially the failure rate, may vary because of unstable environmental conditions, aging components and other reasons. To the best of our knowledge, this problem has not yet been discussed so far. Hence, it is essential to find a dynamic optimal method for this problem. Several solutions are discussed in this paper.

1.3. Organization of this paper

The paper is organized as follows. In Section 2, we formulate the sequential problem in detail and describe the AND/OR graph search method. Different solutions to different parameter varying scenarios are proposed in Section 3. Several examples and the results found by the proposed methods are presented in Section 4. Finally, summary and future extension is presented in Section 5.

2. Test sequential problem

The test sequential problem belongs to the class of identification problem containing five basic elements:

1. A finite set of system fault states S={ $s_0, s_1,\ldots, s_m$}, in which s_0 denotes the fault-free state of system, while s_i denote different fault state;
2. P={ $p_0, p_1,\ldots, p_m$} means the prior probability vector of system states. It is assumed that at most one fault state occurs. The probability vector is normalized and $\sum_{i=0}^{m} p_i = 1$;
3. T={$t_1,t_2,\ldots,t_n$} represents available tests set;
4. c={$c_1,c_2,\ldots,c_n$} is a user defined test costs vector. It is the weighted sum of any test related factor, such as money, time;
5. D is a (m+1) × n binary test matrix, where d_{ij}=1 if the fault state s_i can be detected by test t_j, and 0 otherwise.

The problem is to devise a procedure to decide which test to be performed based on the outcomes of tests used before such that the expected test cost J is minimal. The expected test cost J is given by formula (1).

$$J = P^T AC = \sum_{i=0}^{m}\sum_{j=1}^{n} a_{ij} p_i c_j \tag{1}$$

Table 1
Test matrix, failure probabilities and test costs.

Fault state	t_1	2	t_3	t_4	t_5	Probability $p(s_i)$
s_0	0	0	0	0	0	0.7
s_1	0	1	0	0	1	0.01
s_2	0	0	1	1	0	0.02
s_3	1	0	0	1	1	0.1
s_4	1	1	0	0	0	0.05
s_5	1	1	1	1	0	0.12
Test cost c_j	1	1	1	1	1	

where A=(a_{ij}) is a (m+1) × n binary matrix. a_{ij}=1 if test t_j is used in the path of identifying the system state s_j, and 0 otherwise.

Here a small example from literature [2] is given to illustrate our methods. In this system, there are five fault states $s_1,s_2,\ldots,s_5$ and one fault-free state s_0. Six available tests and their test costs are given in Table 1. The optimal decision tree is shown in Fig. 1. Take s_2 for example, three tests, viz., t_2, t_4, and t_1, are needed to locate this fault state. It can be seen from Table 1 that the test cost of these three tests is 3. The failure rate of s_2 is 0.02 as shown in Table 1. Hence, the cost of isolating s_2 is 0.02 × 3. The total cost J is computed as follows:

$$J = P^T AC = \sum_{i=0}^{5}\sum_{j=1}^{5} a_{ij} p_i c_j = 0.7 \times 2 + 0.01 \times 3 + 0.02 \times 3 + 0.1 \times 3 + 0.05 \times 3 + 0.12 \times 2 = 2.18$$

The tree shown in Fig. 1 is an AND/OR binary decision tree. It is a feasible optimal solution to test sequential problem. The OR node denoted by circle contains the ambiguity groups of fault states. It is also named as fault node in this paper. The rectangle shows the AND node. It represents the used test. The weighted average length of the

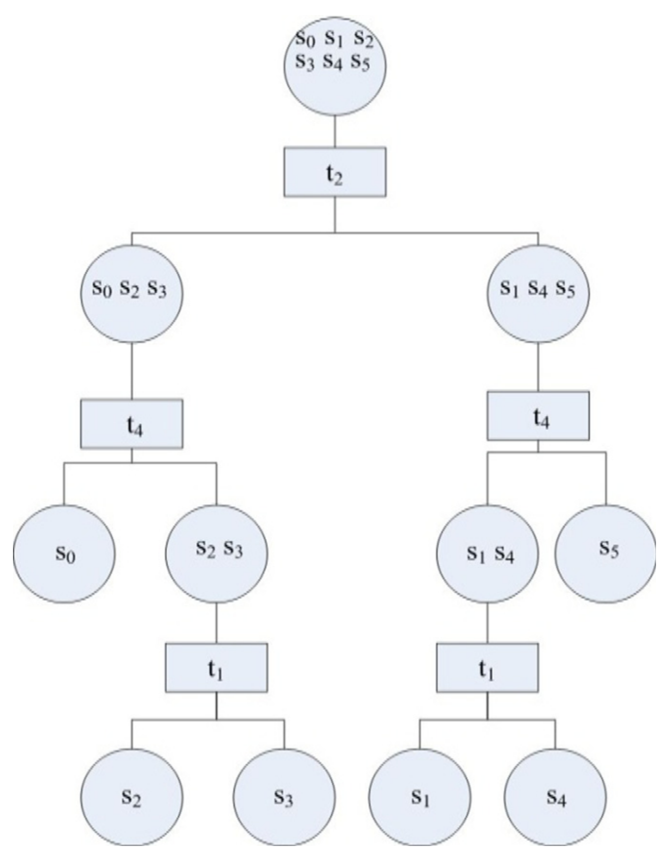

Fig. 1. The optimal decision tree of example 1.