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A novel test optimizing algorithm for sequential fault diagnosis

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ABSTRACT

Once all available measurements are determined, the highest testability index of a complex system is determined. To achieve such highest index with the lowest test cost, AND/OR graph search algorithms were developed for years to determine an optimal or near-optimal test sequence. However, in most cases, achieving the highest testability index induces extremely high test cost. The purpose of this paper is to optimize test set and test sequence so as to cut down the test cost while keeping the required, not necessarily the highest, FIR (Fault Isolation Rate) satisfied. Traditionally, this is an NP-Complete problem, which makes the computation of optimal test set impractical for even the moderate-sized model. In this paper, a greedy method is proposed to get the optimized test set. Then, we combine the greedy method with discrete binary particle swarm optimization (DPSO) to construct a test sequential tree. With the specified FIR requirement satisfied, the lowest test cost is achieved. The proposed algorithms are illustrated and tested in a range of real-world systems. The effectiveness and accurateness of the proposed algorithm is verified by computational results.

1. Introduction

Complex systems with high safety and mission criticality requirements, such as the space shuttle or commercial aircraft, consume high maintenance expenditures annually. The cost of life-cycle maintenance of a complex system may exceed the original purchase cost by a factor of three to ten. The high maintenance cost can often be attributed to the lack of consideration of testability requirements at the initial design stage and inefficiencies in test strategy. An important issue that arises in design for testability is constructing a test sequence that achieves high fault isolation accuracy and yet consumes low expected test cost and fault isolation time [1].

1.1. Motivation

The problem of generating the optimum test sequence has been studied for more than three decades [12–17]. A framework for sequential testing problem was described and analyzed in [9]. A class of one-step look-ahead near optimized algorithm was studied earliest [12,13]. In these approaches, the information heuristic algorithm [12] and the separation heuristic algorithm [13] were proposed. Then, an approach based on integrating concepts from the information theory and the heuristic AND/OR graph search method [14–16] was developed. This approach is widely applied in system testability analysis [18]. In 2003, the use of Lagrangian relaxation and sub-optimal gradient to solve the optimal tests problem is studied [19] and computing efficiency is further improved when the scale of system is not large. To get the global optimal solution, a bottom-up test sequencing generation method is proposed [20]. Although this method can overcome the vulnerability to the local optimality of the original AO* algorithm, its iterations to search a global optimal solution are sharply increased and may cause combinatorial explosion. Then intelligent algorithms such as the genetic algorithm [21], discrete binary particle swarm optimization (DPSO) [23] applied in the optimal diagnostic test strategies were suggested to effectively reduce the testing cost for large-scale system.

Since developed by Kennedy and Eberhart in 1995 [22], Particle Swarm Optimization (PSO) is a concise evolutionary algorithm which is widely employed in optimization. PSO's local and global search ability was improved by the introduction of inertia weight and constriction factor [24,25]. Qiu [26] indicated that the swarm behavior is determined by the previous velocity, the own experience, the others experience and the adventure factor or the random factor. This idea can improve the particle's diversity and is fit for the swarm behavior compatibly [23]. In 2010, DPSO was applied in test selection in [27] and test techniques for specific system were developed in [3–8].

The constrained test optimization problem is discussed in literatures [10,11]. Bülent [10] studied the problem of minimum cost sequential testing of a series system under precedence constraints. But still they focused on test precedence constraints and did not concern about the constraints on the flexible testability index. Zhang

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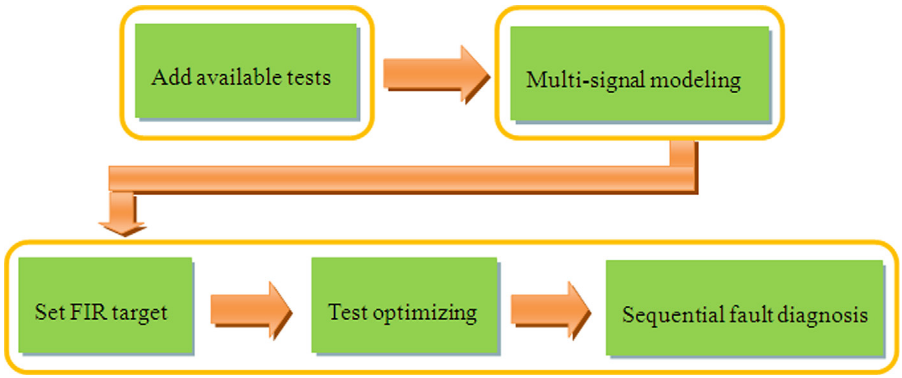

Fig. 1. Test optimizing system framework.

[11] proposed a new formulation for the problem of test selection of imperfect tests in order to minimize the total cost of selected tests subject to lower bound constraints on fault detection and fault isolation. But it cannot generate an optimal diagnosis tree with lowest expected test cost subject to a required FIR.

All the mentioned algorithms tried to seek an optimal test sequence to achieve the highest FIR. But the pursuit may make the expected test cost soar when some expensive tests are added to a complex system. Hence, we prefer to find an optimum set of tests and optimize the test sequence which has the lowest expected test cost, meanwhile the required, not necessarily the highest, FIR is achieved. To the best of our knowledge, this problem has not yet been discussed so far. To solve the constrained test sequential optimization problem, a DPSO based algorithm is proposed in this paper. To keep the FIR requirement satisfied and test cost as low as possible, a binary vector is used as DPSO particle to represent the tests selected from the original test group. An efficient greedy method is proposed to estimate the expected test cost of test sequence, which is used as fitness function of DPSO to lead to obtain the optimal test set. The significance of the proposed method is proven by extensive experiments. At the same time, the exhaustive search method, viz. enumerating all possible combinations of test group, is executed as a reference to the proposed algorithms in Section 4.

1.2. System framework

An overview of diagnostic system framework which uses the proposed test optimizing algorithm is shown in Fig. 1. First, a multi-signal model of the system under test (SUT) is built to obtain the dependence matrix. In this model, all available tests are taken into account. Then a FIR target is set and redundant tests are abandoned by the algorithm. Finally, the algorithm calculates an optimal diagnosis tree which meets the FIR requirement.

In Section 2 we formulate the problem with a small-scale example. In Section 3, a greedy method is given to solve the problem. Then the test optimizing algorithm is introduced in detail, flow charts are given to show how the algorithm works in this section. The effectiveness of the proposed algorithm is shown by several data sheets in Section 4. Section 5 is summary of the algorithm.

2. Problem formulation

First, the traditional test sequencing problem is introduced. Then test optimizing problem is formulated and a small example is given to explain the problem.

Table 1
Dependence matrix of small scale example

State	Test					Rate
	T1	T2	T3	T4	T5	
Sys OK	0	0	0	0	0	0.01
S1	0	1	0	0	1	0.08
S2	0	0	1	1	0	0.28
S3	1	0	0	1	1	0.20
S4	1	1	0	0	0	0.30
S5	1	1	1	1	0	0.13
Cost	1.0	4.0	3.0	2.0	5.0	

2.1. Test sequencing problem

Test sequencing problem (also known as test planning issue) can be defined as the five-tuple (S, P, T, C, and D), where

(1) $S=\{s_0, s_1,\ldots, s_m\}$ is a set of statistically independent failure states associated with the system, where s_0 represents “no fault” state, s_i $(0<i<m+1)$ is the ith fault condition.
(2) $P=[p(s_0), p(s_1),\ldots, p(s_m)]$ is a priori probability vector associated with the set of failure states S.
(3) $T=\{t_1, t_2, \ldots t_n\}$ is a finite set of n reliable binary outcome tests, where each test t_j checks a subset of S.
(4) $C=\{c_1, c_2,\ldots, c_n\}$ is a set of test cost measured in terms of time, manpower requirements, or other economic factors, where c_j is the cost of applying test t_j.
(5) $D=[d_{ij}]$ is a binary matrix of dimension $m\times n$ which represents the relationship between the failure state set S and test set T, where $d_{ij}=1$ if test t_j monitors failure state s_i; Otherwise $d_{ij}=0$.

Test sequencing problem is to find the optimal test sequence, and the FIR is required as high as possible with minimum expected test cost. Formally, the expected test cost is

$$J=P^TAC=\sum_{i=0}^{m}\sum_{j=1}^{n} a_{ij}p(s_i)c_j \tag{1}$$

where $A=(a_{ij})$ is a binary matrix with dimension of $(m+1)n$. $a_{ij}=1$ if the test t_j is used in the identification of failure state s_i, otherwise $a_{ij}=0$. Assumes that there is only one system failure state occurs in this paper.

2.2. Test optimizing problem

In contrast with the traditional test sequencing problem, the proposed test optimizing problem is to select a test set with which