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An analytical model of electronic fault diagnosis on extension of the dependency theory

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ABSTRACT

Based on the D-matrix model, the dependency theory is widely used in the field of fault diagnosis to model the fault flows in complex electronic systems. However, the traditional dependency model can only handle a single fault; it fails to recognize and diagnose multiple faults. In addition, it is not tolerant with system structural or functional changes. These inherent weaknesses of the traditional dependency theory may lead to unsatisfactory acquisition of the diagnosis results. To solve the problem, an improved dependency model is invented as novel analytic diagnosis model to better describe the relationships between faults and tests. The system fault diagnosis based on the improved dependency model is formulated as an optimization problem with binary logic operations where all the fault hypotheses are tested. The calculation process consists of three steps: establishment of the objective function, determination of the nominal states, and determination of the expected states. Finally, the proposed method is demonstrated via an avionic processor case using the improved dependency model. The optimization-based fault diagnosis problem is formulated and the optimal solution is obtained. The diagnosis result demonstrates that the proposed method is successful on performance assessment and fault diagnosis.

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1. Introduction and related works

Technological advances have improved structural complexity and functional versatility in electronic systems. Now, a system may comprise a large number of components, and efficient diagnosis is required to improve the reliability of relevant functions [1] and to reduce high maintenance cost [2]. Fault diagnosis includes fault detection and isolation, which aims at determining which fault is the most likely to have occurred [3]. In modern electronic systems, multiple components can sometimes interact in complicated manners, which may lead to cross-linked or dependent faults. Detecting and isolating such interacting faults is a challenging problem [4].

It is noted that there can be a significant number of dependencies among components or faults. Built-in tests (BITs) are widely used in electronic systems to find whether system faults occur [5], and the concept of dependency can extend to the relation between faults and BITs (and other types of test points) [6]. It is necessary to abstract the system configurations and depict the dependencies before the fault diagnosis process.

The testability model based dependency identification and fault diagnosis methods are widely used in recent years. There are several popular testability models, including dependency matrix (D-matrix) [7], multi-signal flow graph [8], information flow model [9], and quantitative directed graph [10]. Among these models, the dependency model is perhaps the most important and applicable method, which uses the directed graph to describe the dependency between components (or functional modules) and the tests [11]. The relationships among failure modes and symptoms should be interpreted as causal, that is failure modes “cause” symptoms [4]. Using the D-matrix generated in the dependency model, one can develop intelligent diagnostic engines to solve the root cause problem.

For the purpose of fault diagnosis, Sheppard et al. [12] provide a theoretical analysis of the D-matrix and prove that a Boolean D-matrix with single fault assumption is linearly separable. Song et al. [13] present a selected test points set and corresponding diagnosis strategy. Shi et al. [14] propose the diagnosis fault tree generation method based on the D-matrix. The dependency model applications are presented in Yamada et al. [15], Azam et al.[16], Temple et al. [17], etc. There are commercial tools such as TEAMS [18] and eXpress [19] which employ D-matrix-based models for system-level diagnosis. IEEE also published the “diagnostic inference model” as a standard based on the D-matrix in IEEE Std 1232-2002 [20]. The D-matrix-based framework is also defined in IEEE Std 1522-2004 [21].

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Nomenclature

R_i	The ith component or module
S_i	The ith switch (SW)
T_i	The ith test point (TP)
U_k	The kth unit that is divided by TPs.
d_i	Hypothesized normal or faulty state of R_i
m_i	Hypothesized tripping state of S_i
f_i	Hypothesized operating state of T_i
H_s	The sth fault hypothesis (FH)
$E(H_s)$	Expected value of objective function corresponding to H_s
t_k	Actual alarm of T_k
s_l	Actual action of S_l
$a_{tk}(H_s)$	Expected state of t_k under H_s
$a_{sl}(H_s)$	Expected state of s_l under H_s
$\mathbf{Z}_k^{(f)}$	Set of forward units connected directly to U_k
$\mathbf{R}_k^{(f)}$	Set of forward components or modules connected directly to R_k
$\mathbf{p}(R_i, T_k)$	Set of SWs in the fault path form the location of R_i to the location of T_k
$\sigma(\mathbf{p}(R_i, T_k))$	Number of critical paths from R_i to T_k,
$\mathbf{p}(R_i, S_l)$	Set of SWs in the fault path from the location of R_i to the location of
$\sigma(\mathbf{p}(R_i, S_l))$	Number of critical paths from R_i to S_l
$t_k^*(H_s)$	Final state of t_k considering the malfunction of T_k under H_s
$s_l^*(H)$	Final state of s_l considering the malfunction of T_k under H_s

The D-matrix-based diagnosis model is straightforward and can be explained easily, yet it has some disadvantages due to its oversimplification. Firstly, the primary assumption of the dependency model is the single fault assumption, which may sometimes not be suitable for the complex electronic systems. Shi et al. [22,23] attempt to analyze the feasibility to use the dependency model to represent sequential faults, but the results are proved not optimistic. Secondly, the dependency model only considers a propagated fault with global effect (causing the breakdown of the whole system) [24], yet a trigger fault event is not considered, which will probably affect other components [25].

Another case in point is the dynamic reconfiguration designs in modern electronic systems. Dynamic reconfiguration involves upgrading/altering a system's functionality and topology at runtime via addition, deletion, and replacement of components and connections [26]. A system can change its structure or function relations with the given operation logics so as to be more flexible and fault-tolerant [27,28]. However, a static dependency model fails to allow for the possibility of dynamic reconfigurations.

The dilemma of the dependency model and the D-matrix-based diagnosis method is derived partially from its pursuit for a definite answer of the fault diagnosis results [29]. However, in most of the cases, fault diagnosis should be seen as a classification problem [30] where the diagnosis results are “most likely” but not “deterministic.” Some improvements should be made to incorporate more possibilities and lower the strict assumptions of the dependency model in order to facilitate a practical (rather than theoretical) diagnosis. The forward fault assertion is then be transformed to the backward reasoning or inference.

The fault diagnosis issue has been transformed as a binary programming problem (the special form of the integer programming problem where all the variables are either 0 or 1) with a criterion that could reflect the discrepancy between the actual and the expected states [31–33]. The best solutions can be obtained at the minimum (or maximum) point of the objective function, representing the fault causes that have happened most likely. With respect to the fault diagnosis of electronic systems, some common algorithms used for solving the optimization problem are adopted, such as the genetic algorithm (GA) and binary particle swarm (BPS) [29].

Our work is to provide an analytic model for electronic fault diagnosis on the basis of the improved dependency model, where we follow the main principles of the traditional dependency model and formulated the fault diagnosis issue as a binary programming problem. The main contribution of this paper is, at least three unacceptable situations in a traditional dependency model are now available and accessible in our model; they are:

1) Not only single fault but also multiple faults can be disposed;
2) The dynamic reconfiguration concepts are realized in the model;
3) The malfunctions of the tests and the reconfigurations are considered in the model.

Some relevant researches have also focused on multiple fault diagnosis. For example, the dynamic multiple fault diagnosis (DMFD) problem based on the HMM model is discussed in Refs. [34–36], where the inference involves computing the posterior probabilities of multiple hidden layers (or states). A beforehand training process is needed, and the fault diagnosis process can be treated as finding the maximum probability corresponding to a predetermined fault mode. It is a data-driven method and the fault diagnosis does not consider the structure of the product under test. Compared with the method, our proposed method is structure dependent, and the formulated optimization problem is characterized by the structural or combinational relationship of the components. For our method, the potential fault modes are not predefined, and a training process is not needed. The fault isolation is done by solving the optimization problem: we obtain the information which component(s) are susceptible to be faulty, and in what manner the faults occurred.

This paper is structured as follows. Section 2 briefly introduces the D-matrix-based diagnosis principles and its limitations. Section 3 illustrates the improved dependency model with considerations of dynamic reconfiguration. Section 4 introduces fault hypothesis and formulates the objective function. Sections 5 and 6 propose the determination methods of the expected states without and with considering the malfunctions, respectively. Section 7 gives a case study in which the aforementioned method is put into real practices. Finally, Section 8 concludes this paper.

2. Dependency model

The primary assumption of traditional dependency theory is the single fault assumption, meaning that two or more faults will not occur in the system at the same time and only one fault can lead to the breakdown of the system. The D-matrix model is derived from a dependency graphical model (DGM). A DGM of a system is a graphical description of the dependency relationships between the faults (marked as rectangles) and test points (marked as circles); see Fig. 1(a) where F2 constitutes as a feedback loop.

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