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A Unified Diagnosability Evaluation Framework for Complex Systems

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A unified diagnosability evaluation framework for complex systems is presented. In this framework, four elements are used to define the diagnosability evaluation problem: fault space, indication space, fault-indication relation, and metrics. In different stages of product life cycle, the information source for diagnosability analysis may be different. But the evaluation procedure, information integration method and relation models are similar and can be unified into a framework to provide guidelines for system design and analysis. This paper is focused on the extraction of the principle rules of diagnosability evaluation and the selection of information for analysis in different stages of system life cycle. Ambiguity analysis based evaluation measures are also proposed as a complement of previous works. Both system level evaluation and component level evaluation metrics are introduced.

1. Introduction

High technology and high integration of modern systems result in increased complexity and bring many difficulties to system diagnosis. Designing systems with optimized diagnosability is becoming increasing important (Mocko and Paasch, 2002). Diagnosability is one of the design characteristics of the system and defined as a measure of the ease degree for fault isolation, and diagnosability evaluation is the procedure to provide this measure so as to access the diagnosis related performance of systems. It can be carried out for either new or existing systems. Proper diagnosability evaluation method not only helps to increase diagnosis efficiency and fault isolation rate, but also helps to improve system design scheme and maintainability.

In previous work, different methods are applied to evaluate the diagnosability of a system in different stages of product life cycle, such as design, analysis, operation and maintainability. During our research, it is found out that these works are essentially related and can be unified into a general framework. In this framework, all the diagnosability evaluation methods can be viewed as different combinations of following four elements: fault space, indication space, fault-indication relation, and metrics. This framework is useful for understanding of the diagnosability analysis procedure and relationship between existing methods and also helpful for assisting in the selection of the most suitable technique for specific situation.

The organization of the paper is as follows. A brief introduction of previous related work is given in section 2. Section 3 is the main part of the paper, in which framework construction, information extraction for different stages of design and ambiguity feature based evaluation methods are presented. Conclusions are given in section 4.

2. Related works

Diagnosability analysis is an important theme to ensure a system’s reliability. Many methods have been developed for specific systems and systems in different stages of product life cycle.

The initial diagnosability evaluation is a kind of “after the fact” method and mostly based on the design check lists (DOD, 1984). Evaluation objects are existing systems and scores are subjectively given to those systems by experts under maintainability consideration. It is apparent that this kind of methods is based on experience. For different experts, the results and quality of the analysis may vary greatly.

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Under this circumstance, model based analysis methods and evaluation metrics are needed to improve the reliability of the diagnosability analysis results. In Ishida(1985)'s work, a binary incidence matrix is adopted to represent relations between faulty units and measurements, based on which, topological geometry is used to evaluate the diagnosability of large-scale systems. This matrix laid a foundation of mathematical model for diagnosability analysis. Chang (1990) develops Ishida's model and gives a graphical representation of action-error-feature data to analyze manufacturing systems. Diagnosability of a system is indicated by the number of errors that can be discriminated from the others. Clark (1996) and Paasch (1997) give a symmetric analysis on diagnosability problem for mechanical systems. They use the relationship between function hierarchy and physical hierarchy to analyze the diagnosability of a system. LRU metrics and system metrics for diagnosability evaluation are both proposed and four evaluation metrics are given. But for large scale systems, it is not convenient to use these graph based models. Wani tries to solve this problem and provides a bipartite graph and matrix model to represent the relationship between performance parameters and physical objects (Wani and Gandhi, 2000). In his another work (Wani and Ummar, 2006), the model is developed to fuzzy relationship. Provan (2001) presents a directed-cyclic graph based diagnosability analysis method, in which multi-valued relation is considered and simulation can be carried out. From all above works, we can conclude that diagnosability analysis is a process to distinguish the fault-indication relationship of the system. All these works address the basic requirements of evaluation problem for different kinds of systems and using different kinds of information. But general modelling metric is not provided to designers. In our work, we want to find the essential principles behind the methods and give a unified and general modelling framework for diagnosability analysis.

Since diagnosability directly affects the value of a system, it should be incorporated in every stages of product life cycle. However, most above works are more suitable for fully defined or existing systems, for the measurements, physical and action information can only be available in late design stage. Henning (2000) and Mocko (2002) propose FMEA based diagnosability models to consider the inherent diagnosability of a system in early design stage. Though FMEA has the potential for application in the conceptual design stage, the failure modes information is always clear when physical details of the system are known. In our work, through analyzing all the information related to diagnosis, a proper information distribution strategy is introduced to make sure the proposed diagnosability framework can be applied to whole product life cycle. To complete the framework, ambiguity analysis based evaluation metrics are introduced to access the component level and system level diagnosability.

3. Diagnosability evaluation framework

A unified framework for diagnosability evaluation is proposed for the whole product life cycle. In different stages, the elements in the framework may be different. But the analysis procedure, information integration method and relation models are similar. This framework is important for understanding of the diagnosability problem and the application of relative methods.

From section 2, it is concluded that the key factor of diagnosability analysis is a relation distinguishing process. Given a system or system requirement, we should first gather the **information** for analysis, and then construct the **relation** between them, at last, assess the relation and give a quantity **measure** to evaluate system ability for diagnosis. So, four elements can be used to define the diagnosability evaluation problem: fault space, indication space, fault-indication relation, and metrics.

- Fault space: a set of possible failure sources information in a given stage, represented as $\{f_1, f_2, f_3, \cdots\}$.
- Indication space: a set of symptom information related to the faults, represented as $\{i_1, i_2, i_3, \cdots\}$. The indication can be quantitative or qualitative.
- Fault-indication relation: represents whether or not a fault is related to a symptom.
- Metric: a quantity measurement of the distinguishability of the fault-indication relation.

Next we will introduce how to obtain these four elements for diagnosability analysis.

3.1 Fault and indication Information

In different stages of product life cycle, the content of fault and indication space can be varied. We will give a brief analysis on how to choose proper information for diagnosability analysis in different stages.

1) Conceptual design

Conceptual design is a function-driven design. The main work for designers is:

a. Transfer customer requirements into functions.

b. Decompose functions into subfunctions.

c. Find components to fulfill those subfunctions.

All work above is function related and physical information of components is not involved. So fault space here includes conceptual components and indication space includes subfunctions. Figure 1 is an information structure of conceptual design process and “Comp” represents conceptual “component”. The part in dashed frame is the information and relations we consider in this stage. At this conceptual stage, designers have great freedom to change the design scheme with minimal cost. So it is absolutely necessary for designers to perform diagnosability analysis in conceptual design stage.

2) Partly designed system

With the evolvement of system design, performance parameters are available to measure functional performance. Performance parameters are observations of subfunctions. One subfunction can have more than one performance parameters, which makes the fault-indication relation more complex.

In this stage, fault space includes components, the same with conceptual design. But indication space includes performance parameters, represented by “P” in Figure 2.

3) Fully designed system

When system is fully defined, FMEA reports are available and can provide failure modes information for each component. So in this stage, analysis model is expanded again. Fault space includes failure modes and indication space includes performance parameters (see dashed frame).

Figure 3 is an illustration of fully defined system and “m” here is used for “failure mode”.

4) Other stages

In test, operation or maintenance stage, if other sensors or test equipments are added in the system, the indication space should be expanded larger in the same way.

As the design matures, the complexity of the diagnosability analysis information structure is increased. But the analysis procedure is the same. So the diagnosability evaluation framework will work for the whole product life cycle.

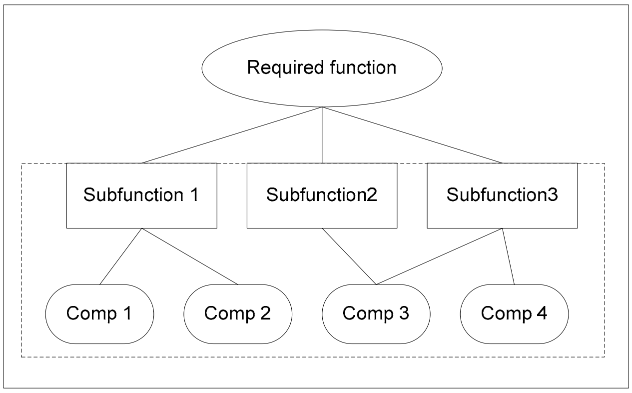

Figure 1: Information structure of conceptual design

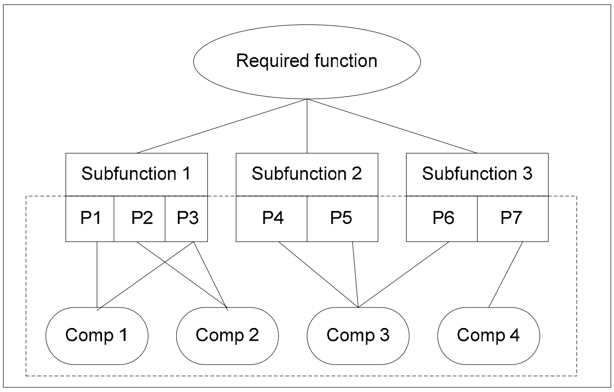

Figure 2: Information structure of partly designed system

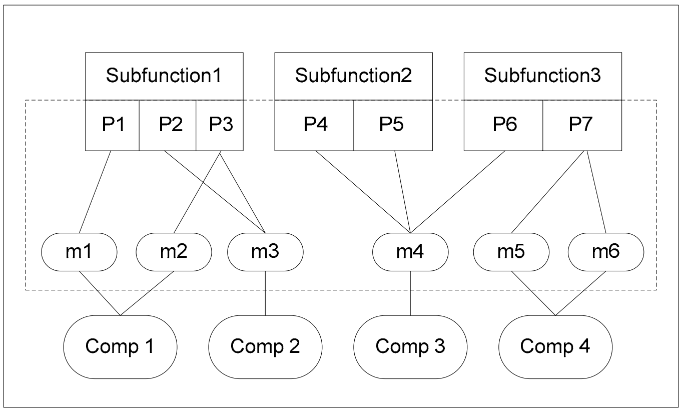

Figure 3: Information structure of fully designed system

3.2 Fault-indication relation

Fault-indication is a classical casual relation and matrix is one of the best candidates for casual description. So matrix is adopted to model a fault-indication relation. The matrix can be binary, fuzzy or uncertain for different circumstances and

- binary matrix: represents the existence (1) or non-existence (0) of the relation;
- fuzzy matrix: represents undefined relationship between fault and indication;
- probability matrix: represents the uncertainty of existent relations.

Table. 1 is a binary matrix example. If fault i is causally related with indication j, then $FI(i,j)=1$, otherwise $FI(i,j)=0$. The fault with unique indication combinations can be diagnosed from the other. This model is convenient for large-scale system diagnosability analysis through matrix computation.

Graph is an intuitional representation of the fault-indication relation and is convenient when system scale is small or the analysis is for system level (see Figure 4). Solid line in the graph represents the existence of a causal relation. It can be easily extended to directed graph and networks.

Table 1: Fault-indication binary matrix

FI	i_1	i_2	i_3	i_4	$\cdots$
f_1	0	1	1	0	$\cdots$
f_2	1	0	0	0	$\cdots$
f_3	0	0	0	1	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	

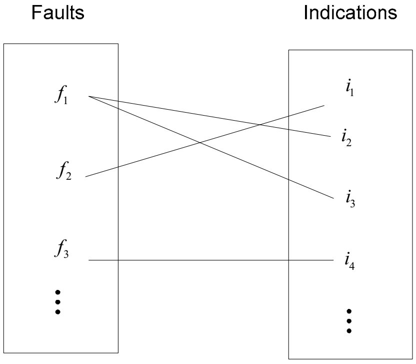

Figure4: Graphical representation of fault-indication relation

3.3 Evaluation metrics

There are many measures associated with the ability to diagnose failures (Simpson and Sheppard, 1998). For different purpose, different measures can be selected. In this part, ambiguity analysis based distinguishability measures are defined to provide principle rules for metrics selection and design.

As we all know, faults with same indications can form an ambiguity group. The fault in an ambiguity group can not be uniquely isolated from the others with given indications. From diagnosability consideration, we hope the system under design has few multi-faults ambiguity groups. If ambiguity is inevitable, we hope the size of ambiguity groups could be small. So ambiguity features can be used as measures of diagnosability of components and systems.

1) For conceptual and partly defined systems

In real application, it is important to point out which part of the system should be changed or redesigned to improve system diagnosability. Component level evaluation measure can provide such information.

In Eq.n(1), C_i is defined as the measure of the component level diagnosability.

$$C_i = \frac{1}{d_i} \tag{1}$$

d_i is the size of the ambiguity group that component i belongs to. If component i can be uniquely isolated, then corresponding ambiguity group have only one fault candidate, that is $d_i = 1$ and evaluation metric C_i get its maximum value $C_i = 1$.

When system level evaluation is considered, we always want all the ambiguity groups have only one candidate and the number of the ambiguity groups close to the number of the faults. According to this idea, equation (5) defines the system level diagnosability evaluation based on ambiguity features.

$$S = \frac{\sum_{i=1}^{n}(C_i - \frac{1}{m})}{n(1-\frac{1}{m})} \tag{2}$$

n is the size of fault space, m is the number of ambiguity groups, C_i is component level evaluation, defined in (1). If each indication has only one fault as a candidate, which means $C_i = 1$ and $n = m$, then $S = 1$. System gets its best diagnosability. If $m = 1$, system has the worst diagnosability.

Time, cost and failure rate information can be added to the evaluation metrics as weights of component evaluations. For example, consider failure rate p_i for component i, then system level evaluation becomes

$$S = \frac{\sum_{i=1}^{n} p_i(C_i - \frac{1}{m})}{(\sum_{i=1}^{n} p_i)(1-\frac{1}{m})} \tag{3}$$

2) For fully defined systems

When failure modes are considered, component level evaluation metric can be defined as

$$C_i = \frac{n_i}{\sum_{k=1}^{m_i} d_k^i} \tag{4}$$

n_i is the number of faults of component i and m_i is the number of ambiguity groups. d_k^i is the size of ambiguity group k related to component i. If component i can be uniquely isolated, then corresponding ambiguity group have only one fault candidate or all the fault candidates belong to the same component, and evaluation metric C_i gets its maximum value $C_i = 1$.

System level metric is

$$S = \frac{\sum_{j=1}^{M}(\frac{1}{s_j} - \frac{1}{M})}{N(1-\frac{1}{M})} \tag{5}$$

N is the size of fault space, M is the number of ambiguity groups, s_j is the size of ambiguity group j. When each indication combination has only one fault as a candidate, which means $s_j = 1$ and $N = M$, then $S = 1$, system gets its best diagnosability. If $M = 1$, then all the faults are in one ambiguity group, the system has the worst diagnosability.

In summary, with all above four elements and diagnosability procedure, diagnosability evaluation can be easily and systemically carried out in different stages of product life cycle.

4. Conclusions

A unified diagnosability evaluation framework is presented in the paper. In this framework, diagnosability analysis can be simply regarded as a fault-indication relationship analysis and four elements, faults space, indication space, fault-indication relation and metrics, are used to describe the diagnosability evaluation problem. Specifically, with the evolvement of system design, the changes of information sources for faults space and indication space are discussed. At last, ambiguity features based evaluation metrics are developed to assess the component and system level diagnosability.

This framework can give designers a better understanding of the whole diagnosability analysis process and is a useful guideline for performing diagnosability analysis.

Acknowledgments

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