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## **REVIEW AND PROSPECTS OF INTELLIGENT DIAGNOSIS TECHNIQUE FOR SPACECRAFTS<sup>1</sup>**

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**Abstract** In this paper the failure records of spacecrafts over the world are reviewed to confirm the urgency of the diagnosis of faults. The special features of the diagnostic technology for a spacecraft are discussed, and accordingly the problems of diagnostic technology for a spacecraft system are reviewed and prospected such as: the strategy and architecture of the intelligent diagnostic system, the hierarchical structure of the knowledge model, the distributed diagnostic technology and so on. Finally, the prospects of the intelligent diagnostic technique for a spacecraft are reviewed..

### **1. The Spacecraft safety assurance**

#### **1.1 Diagnosis -- an Urgent Mission for a Spacecraft**

The health management is an extremely important mission for a spacecraft. To achieve reliability and safety of a spacecraft, although every effort has been paid in the phase of design and manufacturing, miserable failures are still unavoidable. A minor malfunction of an element of the system may cause a large failure and even a vital accident of the whole system. That is why attentions are paid to study how to predicate the faults and how to find the sources of faults to avoid development of failures. In this way diagnosis plays a very important role in health management of the spacecraft.

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## 1.2 Some Failure Records

In Tab. 1 and Tab. 2 an incomplete statistics is given to show the failure rates of spacecrafts over the world. We see that in the early years the failure rates of some launching vehicles and satellites were very high. Recently safety is highly raised by use of highly qualified design and manufacturing, but also the extensive adopt of advanced diagnostic technique gives important contribution.

Tab. 1 The Failure Rates of Some Launch Vehicles

Launch Vehicles		Period	No. of Launches	No. of Failures	Failure Ratio
	<i>Vanguard</i>	1957.12--1959.6	11	8	72.7 %
	<i>Juno-1 and 2</i>	1958.1--1961.12	16	8	50 %
	<i>Thor Series</i>	1958--1983	388	51	13.1 %
US	<i>Delta</i>	1960--1993.6	220	12	5.4 %
	<i>Atlas Series</i>	1960--1990	185	30	16.2 %
	<i>Titan Series</i>	1964--1986	122	13	10.6 %
	<i>Saturn Series</i>	1961--1973	32	555 Faults	
	<i>Moon</i>	1958.5--1960.4	12	9	75 %
USSR	<i>East SL--3</i>	1960.1--1988.12	148	3	2 %
(Former)	<i>Union SL--4</i>	1963.11-1962.12	991	12	1.2 %
	<i>Proton Series</i>	1965--1988	169	12	7.1 %
	<i>Zenith</i>	--1993	26	6	23 %
ESA	<i>Ariane</i>	1979.12--1994.1	63	6	9.5 %
Japan	<i>NI</i>	1975.9--1982	7	1	14.3 %
China	<i>Long March</i>	1964.6--1992.3	31	3	9.6 %
India	<i>SLV--3</i>	1979.8--1993.9	4	2	50 %

Tab. 2 Failures and Faults of 350 Satellites in 1958--1978

	Failures and Faults	Number	Rate
1	Failures	43	12.3 %
2	Faults	267	76.3 %
3	Without Report	40	11.4%

## 1.3 Historical Aspects

Since the eighties a lot of diagnostic expert systems were developed for various satellites, space vehicles, space shuttles, etc., the typical ones were the Failure Diagnosis Prototype *DR*<sup>[1]</sup> and the Failure Recovery Planning Prototype *Rx*<sup>[2]</sup> for the former Space Station Project *Freedom*, which is the basis of the present *International Space Station*<sup>[3]</sup>.

The United States Congress in Public Law 98--371, dated July 18, 1984, states that NASA will identify 'specific space station systems which advance automation and robotics technologies, not in use in existing spacecraft, and that the development of such systems shall be estimated to cost no less than 10% of the total space station costs'. Recognizing the need of NASA's mission requirements, the Office of Aeronautics and Space Technology granted approval in Nov. 1985 for the systems Autonomy Demonstration Program, and a series of 'four milestone Demonstrations' were envisioned<sup>[4][5]</sup> showing the course of development of diagnostic technology for spacecrafts in nineties.

## **2. Special features of diagnosis for spacecrafts**

Comparing with technique of fault diagnosis for a ground equipment, the technique of diagnosis for a spacecraft is a more complicated and difficult task with special features such as:

- (1) The high safety assurance requirements demand high accuracy of diagnostic results and hence high reliability of diagnostic system itself;
- (2) The spacecraft is a complex large-scale system, it consists of a series of subsystems which are coupled closely with respective functions and mutual relations. Consequently a distributed and hierarchical architecture is reasonable for the diagnostic system;
- (3) Along with the progress of flight mission of the spacecraft and the variation of space environment, the configuration and structure of the spacecraft are regulated continuously, and the fuel and resources are consumed regularly, thus the system has to be considered as a time-varying system;
- (4) The constraints of space and weight in a spacecraft lead to a demand of compactness of diagnostic system with limited functions;
- (5) The constraints of sensors setup and accordingly the constraints of limited information available increase the difficulty of diagnostic technique;
- (6) The human experiences for failure diagnosis of spacecrafts are still very limited compared with diagnosis for ground equipments, that needs further research on theory and practice of diagnostic technology.

## **3. The Architecture of an Intelligent Diagnostic System for a spacecraft**

### **3.1 The Onboard and Ground Diagnostic Systems**

Because of the constraints of space and weight of a spacecraft, the diagnostic systems have to be partially set on ground, and the signals from the sensors on board are first transmitted to the Data Center, then transmitted to the

Diagnostic Center. For various spacecrafts the arrangements of the onboard and ground diagnostic systems are different, for a large space station the onboard diagnostic system possesses the ability of autonomous diagnosis, but for a small satellite the diagnosis is performed mainly on the ground.

### **3.2 The Hierarchical Structures of a Diagnostic System**

The spacecraft system is composed of a series of subsystems which are in turn composed of components, these components are still composed of parts and elements that present a character of hierarchy and inheritance of structure.

The model of hierarchy and inheritance is not only for physical structure but also for the status ( by sensors ), the functions and the failures events. Every one of these four aspects has its hierarchy and inheritance structure, but they have mutual corresponding relationship each to other. This character determines the hierarchy and inheritance structure of the diagnostic system, and also the hierarchy and inheritance structure of the diagnostic technology such as the knowledge-base structure and the reasoning strategy, and so on.

### **3.3 The Distributed Architecture of the Diagnostic System**

The spacecraft system is a complex large-scale system, its diagnosis is a very complicated procedure. Since the spacecraft is composed of subsystems, it is reasonable for the diagnostic system to distribute diagnostic missions to expert subsystems for various subsystems of the spacecraft, and what the global diagnostic system has to do is to carry out the diagnostic mission management including the task decomposition, task distribution and task coordination for subsystems whose status and behavior relate and affect each other. After the submissions of subsystems are solved, the solutions of submissions are synthesized by global system to give final diagnostic conclusion of the spacecraft system. In Fig. 1 an example of distributed architecture of intelligent diagnostic system is shown to illustrate the diagnostic procedure and the relationship of the global system and the diagnostic expert subsystems.

## **4. The Technique of Intelligent Diagnosis for a Spacecraft**

### **4.1 The Knowledge Representation**

The method of knowledge representation is the core of the diagnostic technique. There are a lot of methods of knowledge representation and consequently there are a lot of corresponding diagnostic techniques. The

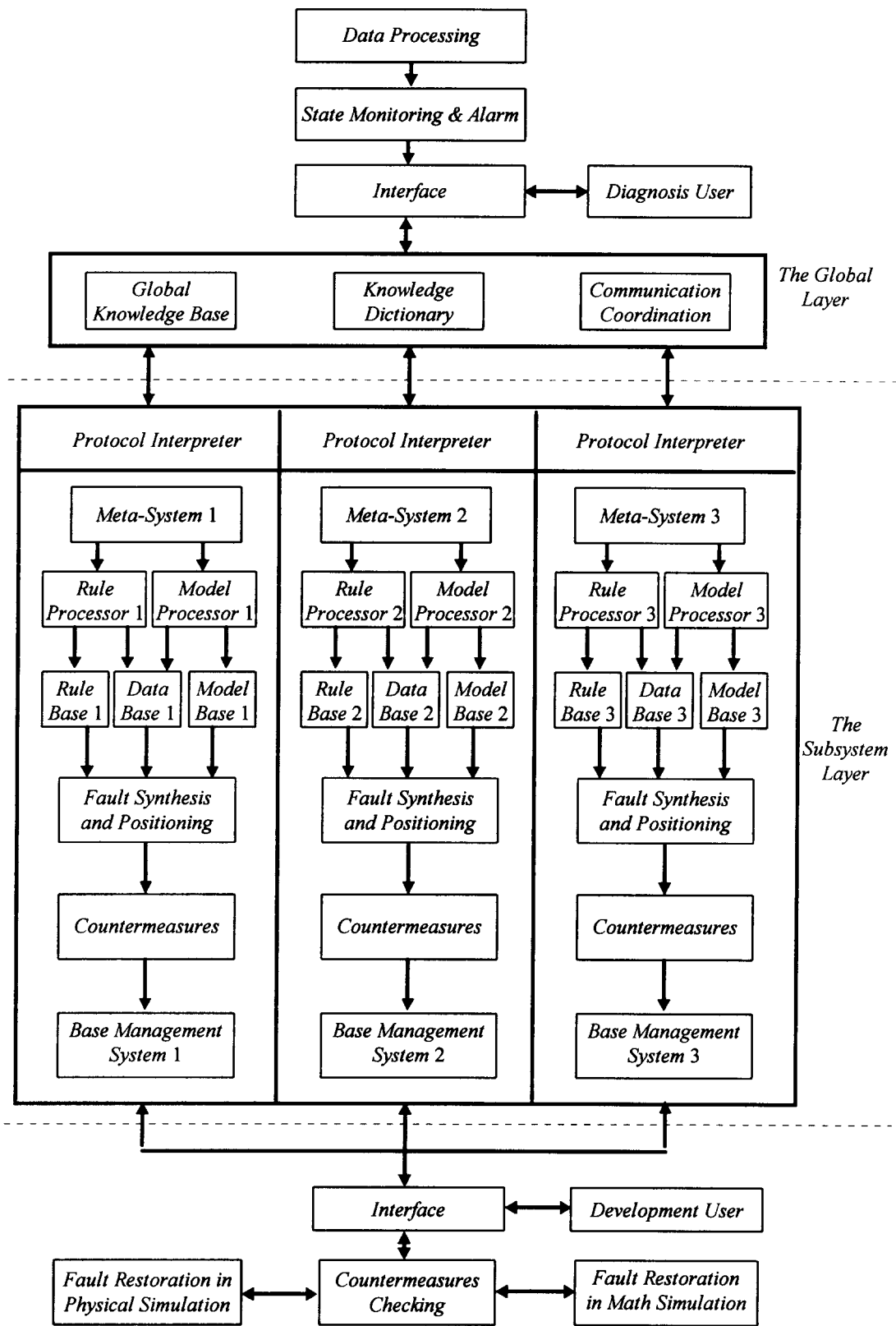


Fig. 1 The Architecture and Structure of a Distributed Knowledge-Based Global Diagnostic System for a Spacecraft

diagnostic techniques that can be used to the intelligent diagnosis for a spacecraft are the diagnostic technique based on rule reasoning, on case studies, on semantic networks, on frame-matching, on predicate reasoning, on qualitative models, on quantitative models and on artificial neural network, etc.

Roughly speaking, the above mentioned diagnostic techniques fall into one of the two categories: rule-based techniques or model-based techniques. Diagnostic systems with rule-based knowledge representation encode expert's knowledge about the diagnosis problem as declarative rules. These systems have been quite successful, but it is difficult to maintain consistency when updating or adding to the rule-base of such systems. The problem will even more serious for spacecrafts because the human experience and diagnostic rules are seriously insufficient. Diagnostic systems with model-based knowledge representation usually simulate the system being diagnosed and find faults by comparing the simulation results with actual data. The simulations are usually quite time-consuming and the diagnosis problem could become quite complex when multiple failures exist. As for spacecrafts, since it covers wide areas, the above mentioned various techniques should be incorporated.

#### **4.2 The Parity Space Approaches to Fault Diagnosis<sup>[7]</sup>**

The focus of attention in diagnosis in recent years has been on robustness methods for fault detection and isolation, following a growing awareness of the need for more reliable systems. Robust methods are able to detect incipient (soft or small) faults in system components, before they are manifested as problems requiring either human operator or automatic system intervention (accommodation or control reconfiguration). The parity space approach is a powerful method to meet this demand. It is a kind of model-based diagnostic technique. The parity space is a space in which all elements are residuals or parity vectors having the similar meanings with the 'parity checks' in computer software reliability. The model-based parity space fault detection and fault isolation process consists of two stages including 'Residual Generation' and 'Decision Making'. The algorithm for use in the real-time applications based only on input-output processing of all measurable signals. It has the advantages of isolability of specific faults and robustness with respect to uncertainties. This technique has the potential in spacecraft diagnosis applications.

#### **4.3 The Knowledge Acquisition Problem**

The knowledge acquisition is a bottle-neck problem in artificial

intelligence. The wide variety of information for a complex spacecraft system further causes the knowledge acquisition problem even more difficult. An approach has been suggested by correlating the diagnosis knowledge acquisition with the work 'Failure Modes and Effect Analysis' ( FMEA ).<sup>[9]</sup> The architecture of the diagnostic system based on Fault Tree Modes are built upon a hierarchically decomposed functional model that determines 'failure' through abnormal component behavior. The system is based on the failure cause identification and has been enhanced in this implementation by replacing the knowledge base of 'if-then' rules with the 'object-oriented' fault tree representation. This allows the system to perform its task much faster and facilitates dynamic updating of the knowledge base. The diagnostic system based on fault tree models makes the knowledge acquisition problem more easier. The diagnostic technique is not domain specific, it has a general meaning.

## **5. The Prospects of intelligent Failure Diagnosis for a Spacecraft**

The failure diagnosis is an urgent mission for a spacecraft, but it is a very complicated and difficult work. It is still under development and there is a long way to be perfected. Below is the tendency of its further development:

(1) The autonomy of on-board diagnosis will become an important tendency of development for spacecrafts, so that the automation and robustness of diagnosis will attract the attention of research .

(2) The multiple faults will exist in a system simultaneously, and these faults may be coupled that increases the difficulty of diagnosis. The technique of diagnosis of multiple faults is a further research topic .

(3) In the design phase of a spacecraft any expected fault that may occur probably is considered and possible reconfiguration is performed as far as possible, but unexpected faults are still unavoidable. It is said that when the spacecraft is in flight, usually the expected faults do not occur, but the occurred faults are not expected. The unexpected faults of course can not be diagnosed by rules. It has to turn to model-based diagnosis. The diagnosis of unexpected faults is a very difficult technique and is a further research topic .

(4) The most of the existing diagnostic systems are only limited to the diagnosis of individual subsystems or only for partial functions. Attention has to be paid to the development for whole spacecraft system.

(5) The reliability of diagnostic system itself is very important. The reliability of hardware and software should be improved meticulously, and the

diagnosis of sensors and actuators themselves are tasks of first priority.

(6) The core of research is to raise and rich the theory and practise of the diagnostic technique such as the diagnostic modeling, the methods of knowledge representation and reasoning, the diagnosis of inexact facts and rules with uncertainty, the reliability, robustness and the ability of fault tolerance of the hardware and software themselves, and so on.

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