Application and Design of PHM in Aircraft's Integrated Modular Mission System

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***Abstract*—a hierarchical PHM (Prognostic and Health Management) architecture divided into subsystem-level and system-level is proposed with its functions and interfaces at various levels to satisfy PHM requirements of the integrated modular mission system. At the subsystem level, integrated condition monitoring method is developed to monitor the operational conditions of various modules, data buses and functional applications according to their characteristics and requirements. At the system level, a MBR (Model-based Reasoning) engine and its diagnostic knowledge model are developed for the integrated PHM data processing, and a graphical PHM display-control interface and a PHM database are designed to display and store PHM data centrally. The overall design method is applied on a project of the scout's integrated modular mission system and a PHM subsystem is developed, which can provide integrated health condition monitoring and accurate fault diagnosis for the mission system, as well as the real-time and comprehensive health information for pilot and maintenance personnel.**

Keywords- integrated modular mission system; prognostic and health management; system-level PHM; subsystem-level PHM; condition monitoring; model-based reasoning

I. INTRODUCTION

With the rapid development of electronic information technology and for the requirements of modern warfare, a large-scale complex mission system capable of performing multiple combat missions and with multiple functions has emerged [1, 2]. This kind of system generally adopts a highly integrated and modular open system architecture and two grade maintenance policy. PHM technology has become a key technical means to improve system's safety, mission reliability and maintainability [3, 4].

Firstly, fault reconstruction ability, which is based on comprehensive, real-time fault detection and accurate fault isolation capabilities, becomes a key technical means to improve mission reliability and safety of integrated mission system because of common modular hardware design and dynamic reconfigurable features of functional software. Secondly, from the perspective of maintenance support, mission system is consist of many components with complex signal cross-linking among them. Therefore, the system failure performance has the characteristic of complexity, hierarchy, correlation and uncertainty. It is a big challenge to locate the cause of a functional fault into a single LRM (Line Replaceable Modular) based on the line test equipment and maintenance personal experience without the assistance of the PHM subsystem.

At present, PHM technology has been successfully applied to advanced military aircraft and civil airliners in America and Europe, and has achieved good economic and military benefits [5, 6]. However, the application of PHM in domestic projects is not approving because of the reasons below [7-9]:

1) At present, online fault monitoring of domestic aero electronic system is mainly realized by BIT (Built-in Test), which is limited by the size, weight and reliability of the embedded test circuit. Therefore, the fault detection and isolation rate is hard to meet the user's expectations. And the integrated monitoring technology is needed to improve fault detection and isolation abilities for the electronic system.

2) System-level fault diagnostic capability is insufficient. The fault diagnositc technology for the complex integrated mission system is still needs to be demonstrated. The uncertainty of test evidence and fault propagation as well as the problem of multiple faults in complex electronic system have to be considerd in system-level fault diagnostic algorithm design [10-13].

3) The PHM display interface is not designed to be graphical interface and can only show text messages, which is unconvenient for pilots and maintenance personnel, especially in the large-scale mission system. Because it consists of large number of LRMs (more than 400), and the distribution is concentrated (centralized distribution in a few integrated racks), so that it is difficult for maintenance personnel to accurately associate the fault codes with the physical locations.

4) condition monitoring system itself is poorly maintainable. For example, the configuration parameters of condition monitoring system, such as fault detection thresholds, often need to be adjusted due to false alarms and missed detections at the beginning of the use phase. However, the existing design does not provide the viewing, analysis and setting functions for fault detection thresholds, which affects the maintainability of the condition monitoring system.

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After analyzing the difficulties in PHM design and application, the design of PHM for integrated modular mission system is proposed, consisting of the overall PHM architecture, integrated condition monitoring and system-level PHM software, as well as display-control interface and database design.

II. Overall Design

A. PHM Architecture

Mission system PHM uses combined technologies to realize advanced data collection, information fusion and data mining for fault detection, prediction, diagnosis and health assessment, as well as failure prevention and maintenance decision-making based on the knowledge of the failure modes and mechanisms of electronic products, which supports intelligent sensor management and autonomic logistics support. Mission system is divided into two levels: sub-system level and system level, which consists of five parts logically, as Fig. 1 shows.

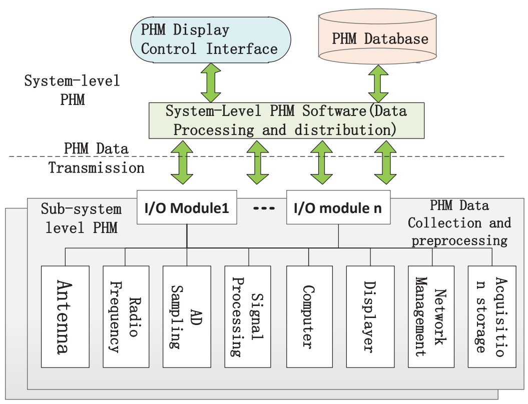

Figure 1 Mission system PHM architecture

1) PHM data collection and preprocessing. BITE(Built-in Test Equipment) of each modular, data bus network management unit and management software of each function independently monitor the operational status of modular, data bus network and function, and perform the prelimiliarly diagnosis. All the condition monitoring data is collected and encapsulated by the regional (divided by frequency band) management unit in the integrated rack, and then reported to the system PHM software.

2) PHM data transmission. Mission system health data transmission means include CAN data bus, RS485 data bus, 100M network 、Gigabit network and 10G network, etc. Among them, the CAN data bus is used for health data transmission of modules in the rack; RS485 data bus and 100M network are used for health data transmission of independent equipment, antenna and its interface unit; Gigabit network is used for health data transmission of display-control computer in the rack; 10G network is used for large-scale health data transmission among each regional management unit, system PHM software, PHM display-control software and storage server.

3) PHM data processing and distribution. It is completed by the system PHM software, which includes collecting the health management data of modules, functions and data bus networks from each regional management unit; conducting integreted fault diagnosis and functional assessment; forming fault log records; distributing and reporting health information as needed.

4) PHM display and control. PHM display and control interface is designed to show the health management infomantion of the mission system's function, modular and data bus network, and control their self-test process. The PHM information is displayed differently for different users, such as aircrewman and maintenance personnel according to their different PHM informantion requirements,.

5) PHM data storage. Special PHM database is designed in mission system to store the health data at all levels.

B. System Diagnostic Status Diagram

The mission system includes four states: power-on Initialization (power-on BIT), continuous self-test (normal or degraded operation), maintenance mode (Maintenance BIT) and system failed (running in safety mode). System state transition is shown in figure 2.

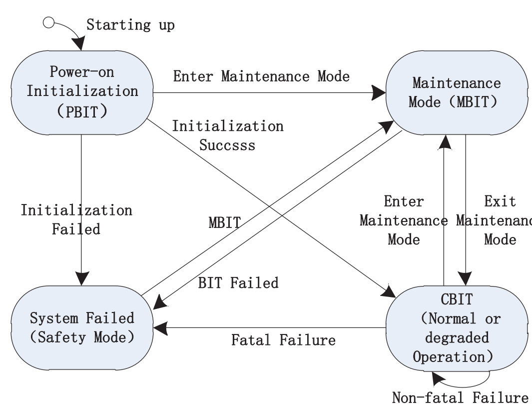

Figure 2 System state transition diagram

The system power-on self-test is executed during system startup in order to confirm that the system is remaining intact state. The power-on self-test is limited by the system startup time, and it includes module power-on self-test, data bus node in-position detection and thread level test for function.

The system continuous self-test is executed periodically during system operational process. It cannot interrupt the function operation of the system, and it generally only detects the status of the aero data bus network node, critical hardware resources and software running status.

The system maintenance self-test is executed in maintenance mode. At this time, the system health management software has full resource control authority and can perform complete fault detection and isolation. The mission system can initiate maintenance self-test, set self-test parameters and fault detecting thresholds for single or multiple functions and modules in maintenance mode.

C. *Interface Message*

As shown in Fig. 3, the mission system PHM interface messages could be divided into four types according to different objects: the health message of modules, the health messages of data bus networks, the health messages of functional threads and system-level health messages. The module health management messages define the health management interface messages between the regional management unit and its subordinate modules. The data bus network health management messages define interface messages between the system PHM software and each network management unit. The functional thread health management messages define interface messages between the system PHM software and the functional thread management software. The system-level health management messages define interface messages among PHM display and control interface, system PHM software and system framework software.

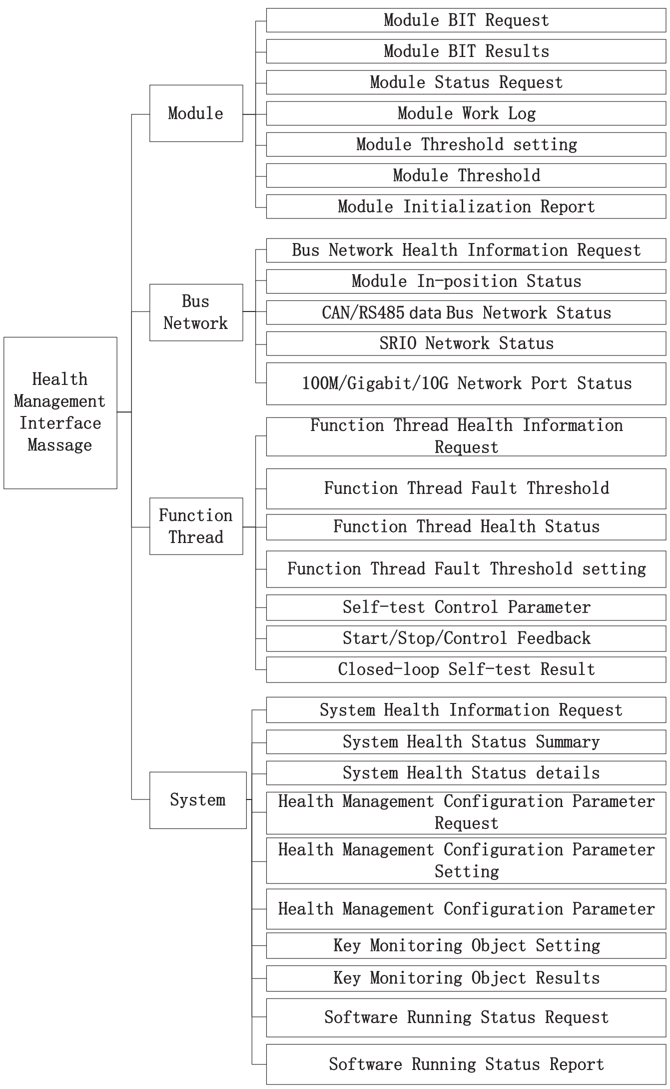

Figure 3 Mission system PHM interface message

III. INTEGRATED CONDITION MONITORING DESIGN

The subsystem-level PHM is combined with the subsystem design and provides an integrated condition monitoring of mission system's hardware modules, application software and various aero data buses, which is the basis of system-level PHM.

A. *Module Condition Monitoring*

The module condition monitoring includes the operating status of the main functional circuit, the module input and output signals, the temperature, voltage and current of the module. The test point of BIT is set on the position where the electronic component have higher failure rate according to the FMEA results.

The module level condition monitoring is performed as shown in Fig. 4, which includes BIT data acquisition, BIT information processing, log storage and external interface. The BIT information processing perform the preliminary fault judgment based on the fault threshold, and the fault filtering technology such as fault delay and multiple decisions is used to eliminate false alarms caused by instantaneous external reasons. Module-level condition monitoring can be achieved by using a special health management chip, or re-using the management processor in the module. In order to achieve boundary scan function, it is recommended to use a special health management chip to implement BIT function of the module.

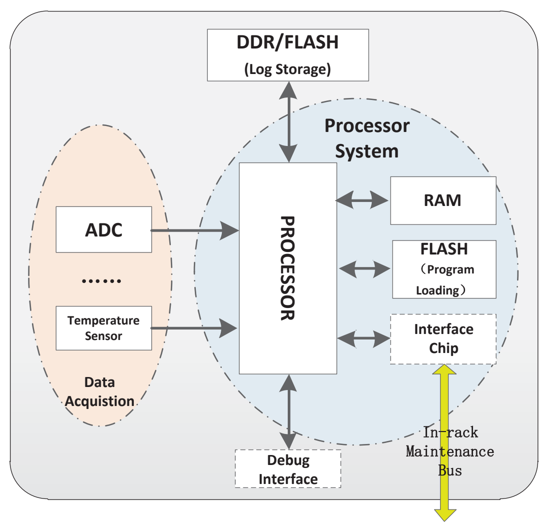

Figure 4 Module-level condition monitoring

B. *Data Bus Condition Monitoring*

The aero data bus could be divided into two levels: in the rack or outside the rack, as shown in Table I. The data buses in the rack connect among the internal circuits on the backboard, which include Rapid I/O, CAN, RS485, etc. The data buses outside the rack connect devices among the racks.

TABLE I. AERO DATA BUS CLASSIFICATION

Rate / Interconnect level	Low-speed	Medium-speed	High-speed		
	1Mbps	2400~3.125Mbps	1.25G/2.5G/3.125G	2G/4G/8Gbps	10Gbps+
Outside the rack	1553B/CAN	RS422/485	RapidIO	FC	10G network
In the rack	CAN				

The data and control command flow is running on the data bus during system operation, and it is quite complicated. As a result, monitoring methods for different kinds of aero data bus networks are demanded. To monitor and collect the operational status of each node, light-weighted monitoring methods for Rapid I/O, CAN and RS485 are proposed, in order to detect the communication failures and locate the fault cause to a single hardware component or software.

C. Software Fault Monitoring and Reporting

The software faults and errors of signal processing software and information processing software above the driver layer are monitored in this case, which include the fatal faults (stack overflows, dead loops) and non-fatal faults (data conversion errors, invalid inputs, invalid outputs, file access errors, insufficient storage space and message routing errors).

The software fault monitoring and reporting structure is shown in Fig. 5. It generally adopts a star structure including three parts: monitoring task module installed in the node required monitoring, fault processing software module in system control node and black box.

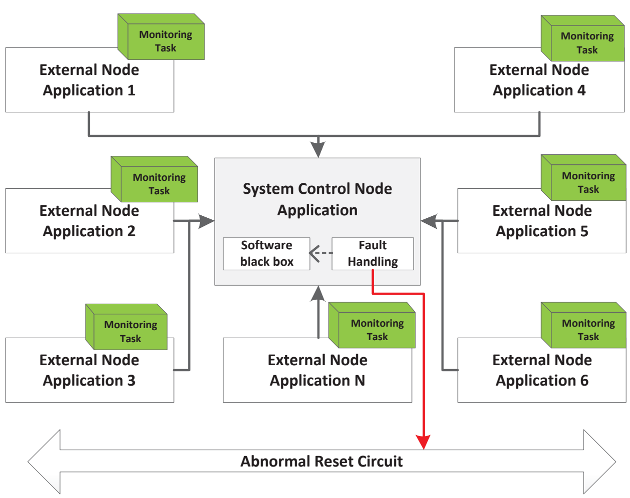

Figure 5 Software fault monitoring and report structure

The monitoring task module is responsible for monitoring the running status of the application software in real time. And when the software fault is detected, the fault information is packaged in a fixed format and sent to the fault processing unit of the system control node. The fault processing software module is responsible for receiving and summarizing the software fault information reported by each node monitoring mission module, and deciding the processing priority according to the fault severity, as well as executing the recovery strategy. When an unrecoverable fatal fault happened, the fault processing software module notifies the reset circuit to perform a hardware reset of the corresponding node. The black box is responsible for recording and storing software fault reports, and providing a read interface for troubleshooting afterwards.

IV. SYSTEM-LEVEL PHM DESIGN

A. Technical Characteristics

System-level PHM includes system-level PHM software, PHM display-control interface and PHM database, which has the following characteristics:

1) A diagnostic reasoning engine with fault correlation ablility is designed by using MBR method after resolving the problems of test evidence uncertainty, fault propagation uncertainty and multi-faults. These problems must be resolved before the diagnositc algorithm being applied to complex mission syetems;

2) Diagnostic knowledge model independent of diagnostic reasoning engine is developed, which is convenient for algorithm updating and appling to different systems because of its independence;

3) Graphical PHM display-control interface is designed to replace the traditional textual display mode of fault list. The PHM information is displayed on more intuitive form and convenient for maintenance personnel to accurately locate the fault module among mass components of the integrated rack.

4) PHM database is built to fully record various PHM data which play a key role in intermittent fault analysis and complex fault diagnosis off-board.

B. System-level PHM Software

System-level PHM software performs system-level fault detection, enhanced diagnosis, functional health assessment and fault prediction. Its composition is shown in Fig. 6.

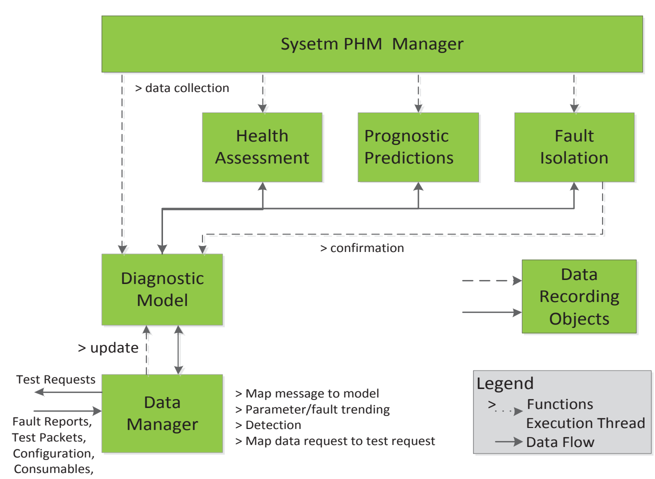

Figure 6 System PHM software composition

The data manager responds to the input messages and parses them, and then maps those messages to the input of the diagnostic model. It manages the PHM test request to the subsystem and establishes a mapping of the data request of the diagnostic model to the test request sending to the subsystem. In addition, it performs fault detection while the fault detect threshold is updated with the system mode dynamically, degradation trends tracking and predictive feature extraction.

The diagnostic model serves as a knowledge base for system-level diagnosis, containing prior knowledge data related to fault diagnosis, such as fault attributes, test attributes and D matrix, etc. Different types of tests are considered in test attribute definitions, such as absolute test, non-absolute test and uncertainty test to describe the uncertainty of fault propagation.

The PHM manager keeps a time-consistent set of PHM data inputs, and initiates fault isolation, health assessment and prognostic predictions process.

The fault isolation manager uses the key diagnostic algorithm to achieve a higher level of PHM capability. The diagnostic process involves data manager, diagnostic model and diagnostic reasoning engine. MBR algorithm is adopted to perform fault isolation, confirmation and correlation analysis (eliminating related faults and identifying false alarms). The uncertainty of test evidence, the uncertainty of fault propagation and the problem of multiple faults should be considered in diagnostic reasoning engine design. The outputs of the fault isolation process include fault cause or fuzzy group, as well as a description of the fault, such as fault type, existential status and confirmation status, etc. In order to reduce the size of the fuzzy group, additional data may be needed, and additional test request will be send to the subsystem.

Data driven method is used in fault prediction, mainly for components with obvious degraded features and fault patterns, such as analog/RF circuit degradation (due to aging, environmental factors or manufacturing processes), communication errors (non-random or excessive communication data loss due to degradation), DC voltage drift, etc. However, most of the remaining life estimate will be done off-board, and the main functions onboard are data collection and feature extraction, as well as fault prediction for safety critical components and rapidly degraded fault modes.

Functional health assessment combines the current or future health status (normal, failure or degradation) of all LRC with the system mode and configuration, assessing the remaining capability of system at the current or in the future.

The data record object is responsible for organizing PHM data in a specific format for persistent storage or off-board analysis.

C. *PHM Display and Control Interface*

The PHM display-control interface allows users directly to view the health status of each hardware component, software and data bus network on a digital model or picture by combining health information with product digital models or pictures. The graphical interface facilitates maintenance personal controlling the function and module self-test process and viewing their results. The repair time of the system is greatly reduced.

The PHM display-control interface includes the main interface of system health status monitoring, data bus network status monitoring interface, health trend tracking interface, aircraft health monitoring interface (showing the status of engine, power distribution box, cooling equipment related to mission system), fault log display interface, fault threshold setting interface, module health information display interface (BIT, fault log, maintenance record, software configuration, etc.) and maintenance self-test control interface.

Fig. 7 shows the main interface of the mission system health monitoring.

Figure 7 Main interface of the mission system health monitoring

D. *PHM Database*

PHM database resides in the storage server of mission system to provide storage for PHM raw data and diagnostic results for off-board analysis. It includes system-level PHM data, function thread PHM data, module PHM data, software fault report, data bus network PHM data and diagnostic results.

V. CONCLUSION

A PHM subsystem has developed in a scout mission system project, which has verified the proposed PHM design. It is indicated that the hierarchical PHM architecture, integrated condition monitoring method and MBR diagnostic algorithm could satisfy the PHM requirements of the integrated modular mission system. Compared with the traditional text style display interface, the graphical PHM display interface is more convenient for the maintenance personnel to locate the failed module accurately from the mass modules of the integrated rack, which can reduce the repair time. The PHM database records various PHM data, which could be useful for intermittent fault analysis and complex fault diagnosis. It is suggested that the fault prediction algorithm should be studied and the MBR algorithm should be verified through the applications on more projects to achieve better performance.

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