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PHM Design Based on Cooperative Design

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For complex systems, such as the aircraft, the implementation of prognostics and health management (PHM) techniques can effectively improves the system performance and achieves the required reliability, safety and supportability. Traditionally, the design of the PHM system and the aircraft is often implemented separately and sequentially, which is not optimal in the view of the whole aircraft system.
This paper focuses on the cooperative design of the PHM system. According to the design requirements of the aircraft, the design of the PHM system is integrated into the traditional aircraft design process based on the process decomposition techniques. By introducing the architecture of the cooperative PHM design, the aircraft and its PHM system can be designed simultaneously, which would significantly improve the design of the PHM system and in turn improve the design of the aircraft. The implementation of the cooperative design in the aircraft design could also reduce the development cycle-time and hence reduce the total cost.

1. Introduction

Modern aircrafts consist of numbers of subsystems and involve a lot of techniques. The prognostics and health management (PHM) technology could provide comprehensive monitoring over critical systems and the whole aircraft and implement self-repair, task degradation and provide maintenance information in advance, which is proved to be the key technique in reducing the total life cycle cost of the aircraft (Hess and Fila, 2002).
However, the integrated application of the PHM system is far from perfect (Zeng et al., 2005). The design of PHM often divorces from the design of the aircraft. Generally, the PHM system is designed and deployed after the design of the aircraft, which implies the PHM has to be designed afterwards to adapt to the aircraft, even when the aircraft is designed without considering the PHM system. Then the allocation of sensors and the collection of data often suffer from many restrictions, and the optimal design of the whole system is hardly possible. How to design an aircraft and its PHM system synchronously is discussing.
The idea of cooperative design is introduced into the design of the PHM system in this paper, which can integrate the design of the aircraft and its PHM system in a harmonic way. Then the design of the aircraft could be optimized and the total life cycle cost could be reduced.
The remainder of this paper is organized as follows. In section 2, general description of the cooperative PHM design for the aircraft is introduced. In section 3, a typical PHM architecture is discussed in four aspects: system definition, data perception, information fusion and decision-making. In section 4, the cooperative design of the PHM system in the aircraft design is discussed, where the PHM design is incorporated into the planning phase, the preliminary design phase, the detailed design phase and the final design phase of the aircraft. Conclusions are given in the end.

2. Cooperative design in PHM system

The aircraft design involves multiple disciplines, which requires engineers from different domains to cooperate in a same program. Hence, departments in different regions have to communicate properly with each other. In another hand, before designing the PHM system, it is essential to understand the structure of the critical subsystems to identify which parameters to be monitored and where to locate the sensors.

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Therefore, the PHM design for the aircraft requires cooperation across time, space and disciplines, which can achieve an optimal design for both the aircraft and its PHM system in an efficient way.
Compute supported cooperative design is an efficient design technique, in which designers from different regions can share and exchange the information about the product via the network and cooperatively accomplish the design of the product (Gao and He, 2004). It carries forward the idea of concurrent engineering, which is a new design technique that requires the designers considering not only the technical issues involved in the design of the product, but also the user's requirements, the manufacture process, the assembly and the maintenance. The core concept of the cooperative design is the optimization of the system and the integration of the process, anticipating all the problems that might arise in the development and coming up with the corresponding solutions at the very beginning of the design process (Rui, 2003). During the development of the product, applying cooperative design method could handle different stages in the life cycle of the product in a harmonic way. Therefore, cooperation between different departments, sharing of resources and collaborative decision-making could be achieved and the disadvantages in the traditional development are thus eliminated.
One of the key points of the computer supported cooperative design is data and information sharing. In the design process, data and information in the planning, preliminary design, detailed design and final design phase, are shared and exchanged by data management system. By data sharing, the aircraft designers and the PHM designers could understand each other's requirements and adjust the differences of opinion. In the cooperative design involving different places, the data management can be implemented with the product data management (PDM) technique. Based on the constraints and some influential factors of the logical information of the product, PDM could support the product form process on the basis of concurrent engineering. Within PDM the focus is on tracking and sharing all data related to a product. It plays its role at the early stage of the cooperative design for a product, such as in the preliminary product design stage, in the conceptual design, detailed design and process design stage, and in the staffing and collaboration arrangements during these stages (wang et al., 2003). The role of PDM in the cooperative PHM design is illustrated in Figure 1. In different stages of the design, the aircraft designers and the PHM system designers can exchange their information by PDM, change the design with the feedback and thus reduce the development cycle-time.

3. The architecture for PHM system

PHM system involves data acquisition, data transmission, data preprocessing and data fusion, etc. Figure 2 shows the architecture of the PHM system. The system definition sets the overall description of the system and the mission requirements at the early development stage. Data perception is performed by the device for PHM and information fusion is done with the system PHM. The decision-making part is performed by the plane PHM and the off-board integrated diagnostic system. On the basis of the input-output relationship in different activities and the inner connection, the relevance in the system definition, data perception, information fusion and decision-making should be analyzed thoroughly to clarify the requirements in different PHM design phases.
(1) System definition. First, the performance and functions of the objects monitored by the PHM system should be described in detail, including qualitative and quantitative descriptions. A system model should be established to analyze the system effectively. Then, the failure models and failure mechanisms for the components, equipments, subsystems and systems in the aircraft should be analyzed. At last, the characteristic parameters defining faults could be extracted as the monitored parameters.

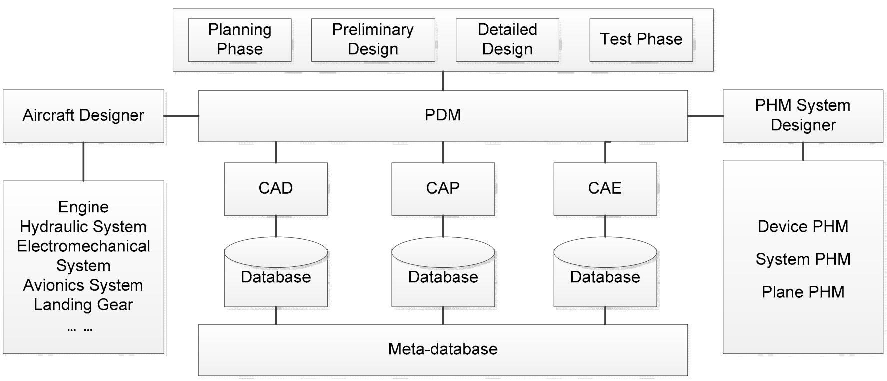

Figure 1: The data management in the cooperative design

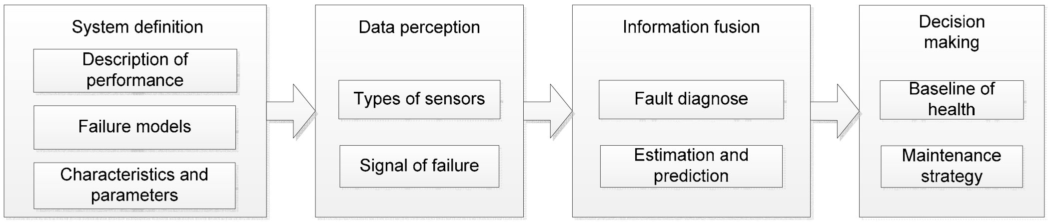

Figure 2: The architecture for the PHM system

(2) Data perception. The output of system definition is the input of perception. According to the feature and the type of the monitored parameters, the sensors can be selected. The physical characteristics, the performance and the installation condition of the sensors should also be considered. The information acquired by the sensors provides an input for the PHM system. By analyzing the time domain and frequency domain signals of the monitored parameters, the data is transformed into the required format for the subsequent status monitoring, fault prediction and health management (Sun et al., 2007).
(3) Information fusion. According to the feature of the data, the output of perception, fault prediction algorithms can be applied to achieve the precise results in a collaborative or competitive way. The current system status can be obtained by comparing the extracted data with the predetermined criteria. The failure of the system or the remaining useful life can be predicted by the fault diagnosis and prognosis algorithms, based on the historical data or the known product data and the parametric models.
(4) Decision making. To implement the health management for complex systems, the parametric indicators that directly reflect the system status or the information that imply the system health level should be identified. The system status can be obtained with the results of the fault diagnosis and prognosis acted as the input. Then the manager platform can provide advices on whether or when to implement maintenance, what activities should be implemented and so on.

4. Cooperative PHM design process

The PHM system should be designed to accommodate the aircraft and its design should be decomposed into the design of components, equipments and subsystems. In the aircraft development, the design of the aircraft and its PHM system should be carried out simultaneously, i.e. designed cooperatively. The design of the aircraft would affect the design of the PHM system and vice versa. By cooperatively implementing the PHM design and the aircraft design, the unfavourable effects on the aircraft support may be found and the design could be modified at an early stage. Then the aircraft design is optimized and the total cost would be reduced. The cooperative design of the PHM system in the aircraft is illustrated in Figure 3.
When the design is accomplished, an overall assessment of the aircraft and the PHM system should be carried out to check whether the design meets the requirements. If any aspect of the aircraft or the PHM system cannot meet the requirements, the design has to be modified or revised. The design of the aircraft is an iterative process. This process would continue until the performance of both aircraft and its PHM system meet requirements.
In the following, the cooperative PHM design in the planning phase, the preliminary design phase, the detailed design phase and the final design of the aircraft design is discussed.

4.1 The cooperative PHM design in the planning phase

In the planning phase of the aircraft development, system definition is of vital importance. The feasibility of the project should be discussed, including working out the tactics requirements and the technical requirements, considering the main function design of the system, estimating the development cost and providing a system development requirement. The maintenance and support of the aircraft has to be considered in this phase. According to the aircraft development requirement, a draft of the integrated support plan has to be provided, which involves the required manpower, resources, information and the management of these resources (Gu, 2001). With the support plan, the requirements for the PHM system could be considered and a preliminary PHM design should be proposed. Combining the historical data and the current system requirement, the technical requirements for the PHM system could be raised, such as the fault detection rate (FDR), fault isolation rate (FIR), false alarm rate (FAR), cannot duplicated (CND) ratio, monitoring period, lifetime tracking on the critical components and the accuracy of the remaining useful life estimation (Xu et al., 2010). This task is mainly accomplished by the general designing department and the requirements are allocated to the specialized designing departments once the plan is drafted. The specialized designing departments then begin the work according to the requirements.

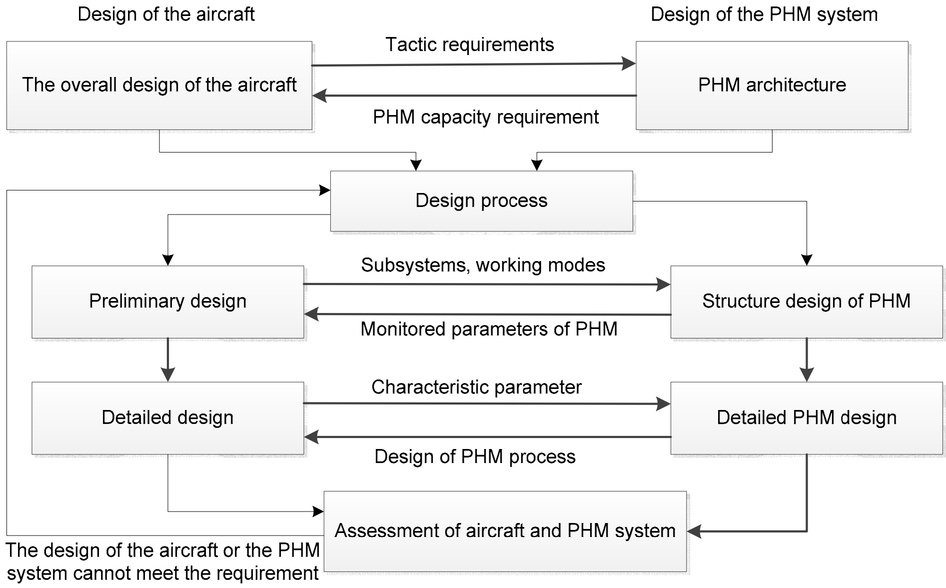

Figure 3 : The structure of the cooperative PHM design in the aircraft development

4.2 The cooperative PHM design in the preliminary design phase

In the preliminary design phase, the overall technical plan of the aircraft, such as the layout of the aircraft, is proposed according to the system requirements. By analysing the requirements of the main subsystems and the interaction between different working modes, these main subsystems are preliminarily designed. During this phase, the work elements of different levels for the PHM should be decomposed according to the functions and the working modes of the subsystems of the aircraft, and thus integrates the PHM design into the aircraft design.

- First, for the device PHM, the structure of the aircraft should be clear, and the risk assessment and trade-off analysis on the subsystems of the aircraft should be done. For the critical subsystems, the Failure Mode Effects and Criticality Analysis (FMECA) should be applied to identify the possible failure mechanism and the corresponding characteristic parameters.
- Second, establish the correlation matrix between the characteristic parameters and different components, as shown in Table 1. Each entry of '0' and '1' in the matrix implies a certain parameter and a certain component are correlated and uncorrelated, respectively. By doing so, the duplicated parameters or the missing parameters can be found out.
- Then figure out the weak parts in the system, identify the failure cause and the characteristic parameters that could reflect the failure state and establish the rules to recognize faults and degraded working states. The working modes of the subsystems in the aircraft would influence the design of the PHM system on identifying faults and degraded working states.
- When the main airborne equipment is selected and the FMECA is completed, the relation between the measurable parameters and the lifetime of the equipment can be obtained with the failure models. Then the importance of different measurable parameters should be analysed. Generally, one parameter may contain information about several components and the measuring points are limited. Therefore, it is of vital importance to find out these parameters that can reflect as much information of the components as possible and set them as the critical monitoring parameters for each subsystem. After then, the data collection design can be carried out. Typically, the monitored parameters include performance parameters, physical parameters, electrical parameters, environmental conditions, operational conditions and so on (Shunfeng et al., 2010).
- For the system PHM, one key consideration is to process the signals acquired by the lower level systems, and preliminarily establish the framework of the PHM inference engine (involving diagnostic, prediction and exception handling) based on the available failure models and historical data.
- For the plane PHM and the off-board integrated system, their main task is maintenance decision and lifetime prediction. Hence, the algorithms in different subsystems should be integrated and proper algorithms should be selected to build the plan PHM and the off-board decision-making system.

Table 1: The correlation matrix between the characteristic parameters and the parts

	Parameter 1	Parameter 2	Parameter 3	……
Component 1	1	0	1	
Component 2	0	1	1	
Component 3	1	0	0	
……				

4.3 The cooperative PHM design in the detailed design phase

In the detailed design phase, the details of the aircraft are designed according to the preliminary design. The characteristic parameters of each component, such as the size, material, and manufacturing are settled. Then the production drawings are provided to the manufacturing department, and the manufacturing department has to work out an overall process plan for the aircraft and implement process examination of the drawings. At the same time, the detailed PHM system design has to be implemented simultaneously.

- Data acquisition in the preliminary design is an input for the detailed PHM design. According to the detailed design of the aircraft, the sensor allocation design and the monitoring plan for temperature, pressure and deformation, can be carried out. At the same time, the impact of the sensor allocation on the aircraft design should be considered, such as sufficient space for the sensor and the compatibility between the PHM data transmission and the aircraft control system.
- With the preprocessed data from sensors and the historical data, the system status monitoring and fault prediction design, which is the core of the PHM system, can be put forward. Usually, one or several different monitoring and prediction methods can be applied according to the real condition, such as threshold value comparing or other reasoning methods.
- The maintenance strategy is based on the data from status monitoring, fault prediction and health assessment and provides advices on maintenance activities. This part mainly involves the decision making on the ground, which requires detailed design of the hardware and the software for the off-board system, such as the configuration of the computer and the selection of the correlation algorithm.
- One key point in the data transmission is the interface. Interfaces include the interface between different modules in the PHM system, the interface between the PHM system and the aircraft and the man-machine interface.
- Validation should be implemented after the design of the PHM system. If the overall performance of the PHM system and the aircraft cannot meet the demands, the design of both systems should be revised.

4.4 The cooperative PHM design in the final design phase

After the assembling of the whole aircraft, ground tests such as static mechanical test, resonance test and electromagnetic compatibility test have to be implemented before test flight. According to the aircraft development requirements, the test flight should be carried out thoroughly to verify its performance. Whenever the failure occurs, it has to be investigated and understood, and modifications have to be done when necessary.

In the final phase, both the design of the aircraft and its PHM system are validated. The validation system for the PHM system can be divided into the hardware part and the software part. These two parts cooperatively implement the validation for the fault prediction algorithms and the performance assessment. The process of the aircraft design and cooperative PHM design in the four phases are shown in Figure 4.

5. Conclusion

In this paper, the idea of the cooperative design is introduced into the PHM design of the aircraft. First, the data management technique for the cooperative design is introduced and the architecture of the PHM system is analyzed. Then, the PHM design is decomposed into different phases according to the development stages of the aircraft. Thus the PHM design can be accomplished cooperatively with the aircraft design. During the cooperative PHM design, any improper design of PHM system or the aircraft can be modified in time, and optimal system performance could be achieved in terms of both PHM system and the aircraft, which could reduce the life cycle and cost at the same time. This paper focuses on the cooperative PHM design during the development process, while the cooperative PHM design in management and test should also be considered. Our future study is to carry out the cooperative PHM design in management and test to establish a complete framework of the cooperative PHM design.

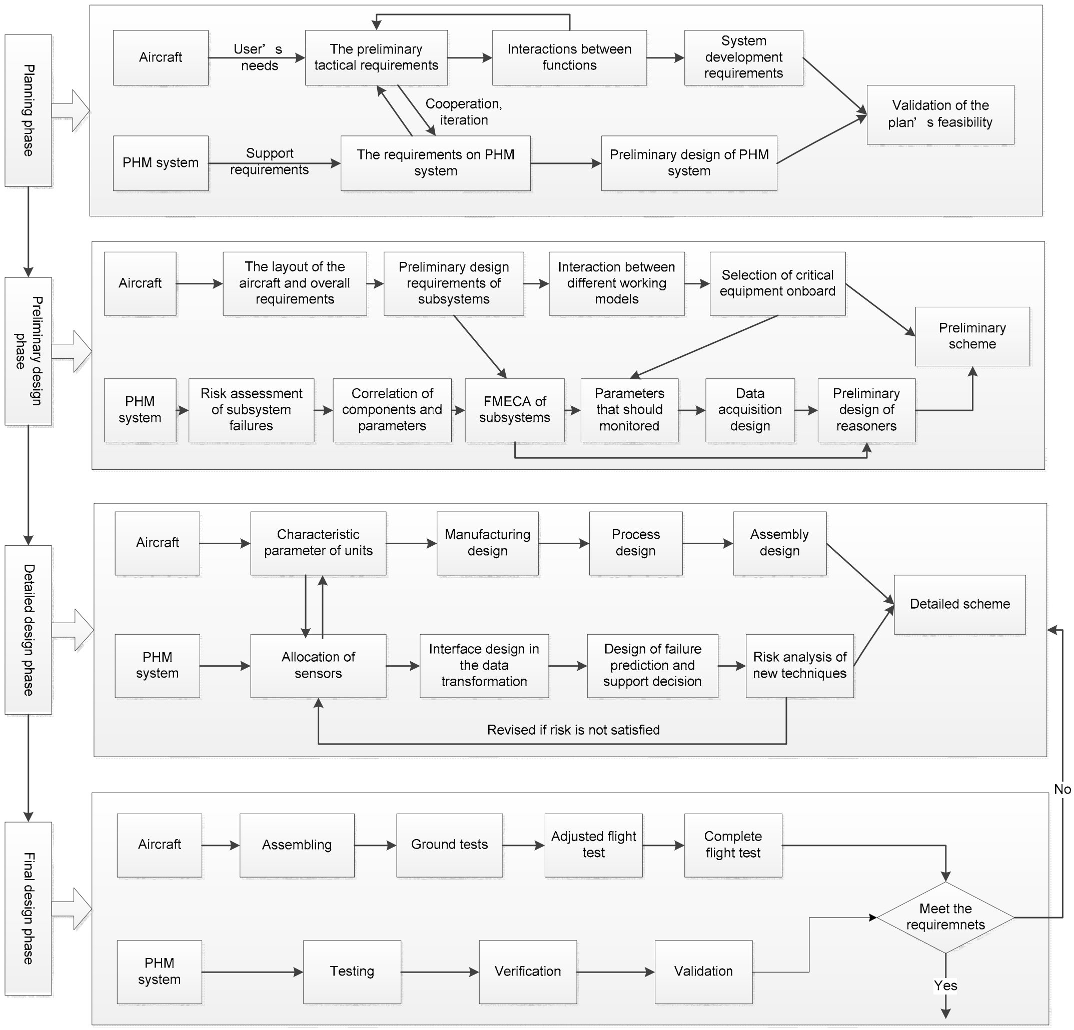

Figure 4：The process in four design phases

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