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A Functional Architecture of Prognostics and Health Management using a Systems Engineering Approach

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ABSTRACT

Prognostic and Health Management (PHM) describes a set of capabilities that enable effective and efficient approaches towards data analysis for fault diagnostics and failure prognostics. This can support decision making related to health management, sustainment and operation of critical systems, such as aviation systems. As a result of the rapidly growing interest in PHM, a substantial amount of research proposes and discusses PHM frameworks and system architectures. Previous research efforts conceptual formulation of design methodology to proposes a set of PHM system architectures based on different frameworks, and the derivation of architectures from system requirements. However, further interpretations of PHM system architecture derived from requirements in functional view are lacking. Research on a generic PHM architecture allowing communication and integration with the various contributing systems are lacking. To address these gaps, this research outlines an architecture design methodology incorporating a functional view from a systems engineering perspective. In addition, it proposes a functional architecture for PHM system as the application of the methodology, which has compatibility and interoperability to integrate with the various systems, due to its compliance with the standard of Open System Architecture for Condition-Based Maintenance (OSA-CBM).

1. INTRODUCTION

Aircraft maintenance plays an important role to sustain airline operations in terms of safety and cost. Prognostic and health management (PHM) and related technologies enable airline maintenance services on systems and processes based on the system condition by diagnostic analyses and the expected future performance through prediction of the remaining useful life (RUL). Several authors (Vogl & Donmez, 2014; Saxena et al., 2010) explain that a PHM system aims to reduce burdensome maintenance tasks while increasing the availability, safety, and cost-effectiveness for aviation systems by optimizing maintenance operations via diagnostic and prognostic functions.

Cocheteux et al. (2009) express that the design of PHM system and its components require the use of systems engineering principles to ensure the effective and efficient design of complex systems. Hence, some literature outline the design methodologies based on system engineering, covering general system design principles and the concept of development life cycle, as shown in Aizpurua, Ignacio, and Catterson, 2016 and Aizpurua, Ignacio, and Catterson, 2015. A significant amount of research mainly discuss the related PHM techniques, e.g. diagnostic/prognostic techniques or maturation (Elattar et al., 2016; Baghchehsara et al., 2016), whereas several papers address the transversal methodological items, such as requirements, architecture, or validation and verification (Saxena et al.,2012; Felke et al., 2010). More specifically, the system architecture is defined as the fundamental concepts or properties of a system in its environment, as embodied in its elements, relationships and in the principles of its design and evolution. A substantial research has been performed with respect to PHM frameworks and architectures, as summarized in (Vogl, Weiss, & Helu, 2016). Wang, Youn, & Hu (2012) proposed an aviation PHM system framework based on a big data center and demonstrated the engineering proposal in detail including key technologies, scientific problems and application systems. A research of a three-abstraction-layer hierarchical architecture to identify distributes data sources and cloud-based PHM service center as a visual model-based framework has been presented in the literature (Mao et.al, 2017). Dumargue, Thomas & Pougeon (2016) discussed an overview of most system engineering aspects in the design of a PHM system, addressing the system architecture and presenting the model-based system engineering to apply the context of PHM system.

The report of condition monitoring and diagnostics of machines (ISO-13374-1, 2003) defines that the Open System Architecture for Condition-Based Maintenance (OSA-CBM) specification is a standard architecture for moving information in a condition-based maintenance system proposed. Choudhary and Perinpanayagam, (2016)

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have proposed an architecture suitable for CBM integration that is able to support interoperability between multiple vendors of CBM components and insertion of new CBM capabilities, which is one application of OSA-CBM framework.

In summary, the state of the art features a number of proposed specific PHM system architectures based on different frameworks, and the derivation of PHM system architectures from system requirements (related to functions, behaviors, structures) using a systems engineering perspective. However, further interpretations of PHM system architecture derived from requirements in different views (functional, logical and physical) are lacking. Most of the proposed systems are discussed and designed independently, whereas, in reality, they need to be integrated to offer monitoring functions and services. Thus, the research into PHM architectures allowing integration and communication with the various contributing systems is lacking.

The paper presents an architecture design methodology incorporating the views of functional architecture, logical architecture, and physical architecture. Meanwhile, it also proposes a functional architecture for PHM system, incorporating function decomposition, functional elements identification, and interfaces (internal and external) representation. It will be validated through the method of functional analysis and modeling. Further, this functional architecture enhances the compatibility and interoperability with various systems as a result of its compliance with OSA-CBM functional blocks.

The remained of this paper is organized as follows: In Section 2, the architecture design methodology is introduced. Section 3 proposes a functional architecture for a generic PHM system. Following, section 4 presents a case study for validation and verification, by application of functional analysis, SysML modeling, and discussion of compatibility and applicability. Conclusions and future research are addressed in section 5.

2. ARCHITECTURE DESIGN METHODOLOGY

2.1. Architecture Definition Process

The purpose of the architecture definition process is to generate a system architecture that frames stakeholder concerns and meets system requirements and to express that in a set of consistent views, as shown in INCOSE's Systems Engineering Handbook (2010). The design of system architecture is conducted from the functional view, logical view and physical views, describing of system functions, system behaviors, and physical items respectively, as shown in Figure 1.

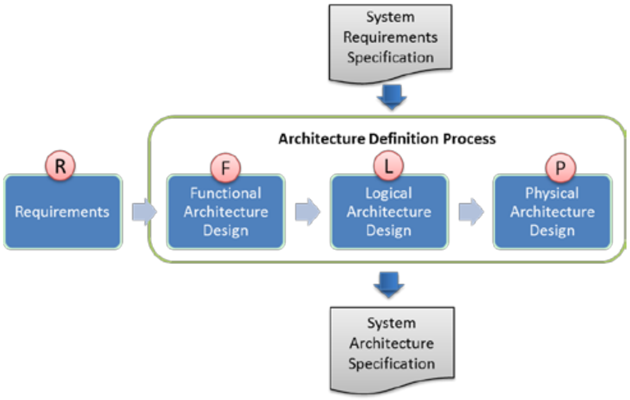

Figure 1. Architecture Definition Process.

The standard report of Processes for Engineering a System (ANSI/EIA-632, 1998) defines that a functional architecture is a set of functions and their sub-functions that enables to identify functional interfaces and interactions between system elements, and ensure that the system functions and the related requirements are analyzed, decomposed, functionally detailed across the entire system, feasible and effective. The logical architecture focuses on the description of system behaviors, the execution sequencing, conditions for control or data-flow, states and operation mode, as well as performance level necessary to satisfy the system requirement, as shown in INCOSE's Systems Engineering Handbook (2010). Differently, the physical architecture is a traditional term to define the physical elements and physical interface, including software and hardware component to implement the functions and services, as defined in NASA system engineering handbook (2007). In this paper, it combines the fundamental concepts in system engineering and the specific solution of system engineering in industrial application to propose an architecture definition process based on "RFLP" (requirement, functional, logical, and physical), where system requirement specification is the input.

2.2. Functional Architecture Definition Process

The system architecture design is an iterative and incremental development combining functional architecture, logical architecture and physical architecture design derived from system requirements. This paper mainly focuses on the functional architecture design as the first study, and the future research will discuss the process of logical and physical architecture definition. The functional architecture definition process defines the details of activities for contributing to conducting the system functional architecture, as shown in Figure 2.

- Identify and decompose system functions

Firstly, this process starts with defining system top-level functions and functions hierarchy based on the understanding of PHM system and the conceptual design.

The functional analysis method is able to examine the system's functions and sub-functions that accomplish the system mission.

- Identify functional elements and interfaces

The functional architecture is described by the functional elements and the interfaces among these elements. This task requires analyzing the functions hierarchy, input-output flows and operational scenarios for each defined function. All functional elements of the system should be identified and delineated.

- Describe Functional Architecture

Subsequently, it is the task to describe the system architecture with a hierarchical arrangement of functions and interfaces that represent the complete system from a performance and functional perspective. The description with diagrams or tools can enhance the visibility and transparency to comprehend the functional system.

- Validate and Verify

Verification is the activity to ensure the quality and completeness of system function/requirements and the consistency of the set of system requirements, while validation is used to demonstrate that this architecture is compliant with stakeholder requirements.

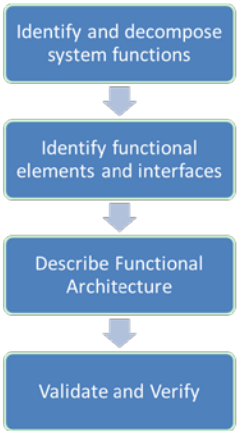

Figure 2. Functional architecture definition process

2.3. Validation and Verification

Concerning verification and validation, the case study in this paper will focus on checking and examining the system's correction (e.g. boundary, elements, interfaces), and establish traceability between architectural elements and functions, due to the limitation of research scope (functional architecture) and implementation restrictions. In the other words, It plans to use the method of analysis (functional analysis, compatibility analysis and applicability analysis), as well as the modeling method (block definition diagram and internal block diagram) to validate and verify some factors of the proposed architecture, as listed in Table 1.

Items	V&V consideration
Decompose system functions	Based on literature review, identify the top-level functions of PHM system, as defined in Section 3.1
Identify functional elements	Verify the system boundary, functional elements via the method of modeling, as identified in Figure 5 and Figure 6
Identify functional interfaces	N-2 diagram is used to identify and analyze the interaction between each function, as identified in Figure 4. Verify the interfaces between functional elements within PHM system via the method of modeling, as defined in Figure 6.
Compatibility Analysis	Demonstrate the compatibility of this architecture by the compliance matrix with the blocks in OSA-CBM framework, as illustrated in Table 2
Universal Applicability Analysis	Analyze the applicability and executable of this architecture by its compliance matrix with the functionality facets defined in IEEE Reliability Society 2007 Annual Technology Report, as presented in Table 3

Table 1. Matrix for V&V analysis

3. FUNCTIONAL ARCHITECTURE OF PHM SYSTEM

PHM system indicates the specific processes involved with predicting future behavior and RUL of the monitored system, in sense of current operating state and the scheduling of required maintenance actions to maintain systems health in the literature (Niu, Gang, 2017). Si et al. (2011) presented that the prognostics were essentially a condition-based prediction of RUL with the aim to make better maintenance decisions.

3.1. PHM System Functions

Preliminary functions definition allows the PHM system to be decomposed into the relevant top-level functions and low-level functions required to meet system missions and goals. Several literature (Hoffman, 2007; Gorinevsky et al., 2010, Patrick et al., 2009) have discussed the functions in PHM system. To summary, PHM system may involve the main capabilities of diagnostics, prognostics and health management, and also need some other accessibility functions to support the system operation, such as data processing and data acquisition. Thus, the functions of PHM system are defined as follows:

a) F1-Data acquisition (DA)

The PHM system should have the capability of collecting a significant amount of information and record data from various aviation participants, such as aircrafts, airports, spare parts warehouse, repair factor, maintenance training, overhaul base, accident rescue, etc., to build a database, as presented in the paper (Yang, Wang, & Zhang, 2016). For example, the in-flight information of aircraft includes the various fault reports, maintenance information, history data, real time parameters, pilot reports, engine data, and sensor data of components (e.g. temperature, pressure etc.).

b) F2-Data Processing (DP)

The collected data are from a variety of aviation systems (e.g. engine, avionics, landing gears etc.) with the different formats (e.g. ARINC 664, analog, ARICN 653 etc.). As a result, PHM system should provide the data manipulation and integration functions to process the raw data along with the capability to transmit the data within the PHM system (Zhang, et al., 2015).

c) F3-Diagnostic Assessment (DCA)

The diagnostic assessment function provides the services to analyze data and generate a descriptor for a measurement location, component, or system as normal or abnormal, including the degree of abnormality in the associated operational context, which is state detection, as found in the report (ISO-13374-1, 2003). Furthermore, it can perform agent-specific assessments of the current health state of a component or system with the associated diagnoses of discovered abnormal states in the associated operational context (ISO-13374-1, 2003).

d) F4- Prognostic Assessment (PA)

The main capability of PHM is prognostic, as the process of predicting the future reliability of the system by assessing the degradation of operation capability with the current operating conditions and the history of normal and abnormal data. As previously stated, prognostics are essentially a condition-based estimation of RUL in order to make smart informed maintenance decisions.

e) F5-Health Management (HM)

Health Management (HM) function has the capability of analyzing the health information (e.g. safety, environment and related assessment reports) and maintenance information (e.g. maintenance schedule and resource), to generate optimizing maintenance advisories as the respond of forecasting assessment requests.

3.2. Functional Architecture Description

The system architecture identifies the boundaries of the target system and interfaces with other systems, as well as the elements within the system itself, providing the functional services and performance within the defined operational conditions as described in system engineering handbook (NASA 2007). This paper proposes a functional architecture of PHM system as indicated in Figure 3. This architecture figures out the system boundary and interfaces with the external systems, as well as the sub-elements within the boundary. In addition, it also formulates the external and internal interfaces to identify the interaction with external systems and among the internal elements.

3.2.1. External system and interface

One of the external systems is the in-flight health management system providing the flight-data, operation data, and various fault reports from aircraft. Another is the data sharing network, e.g. Avionics Full-Duplex Switched Ethernet (AFDX), which has the capability to transmit the flight data to a ground database (Scharbarg, Ridouard & Fraboul, 2009). The in-flight health management system consists of indicating/recording system, onboard maintenance system (OMS), power plant health management system and data management system, as shown in Figure 3.

In particular, the indicating/recording system is able to collect the information in display system and flight recording system, including aircraft condition parameters, engine parameters, power supply information, flight data recording, records of data-link and image records etc. The OMS system has the capability of automatic failure detection, faults isolation and report for the system/component, which is mainly composed of the central maintenance system, aircraft condition system and data loading and configuration system (Tai & Alkalai, 1998). Moreover, it provides the health monitoring information, various faults reports, and configuration information to other ground-based health management system, e.g. PHM system. Similarly, the power plant health management system is responsible for monitoring the condition of engines and analyze the performance, providing the history and condition data of engines. Finally, all of the collected monitoring information will be shared with other facilities through the aviation data-network system.

3.2.2. Internal element and interface

As shown in Figure 3, there are some partitioning modules integrated together to perform the configured functions within the PHM system boundary. The specific internal elements and interfaces are characterized in details as follows:

a) Database

The database is an auxiliary module to store the data acquired from aircraft and related maintenance information collected from maintenance resource. Specifically, this database may encompass the technique data (e.g. aircraft design data, safety report, manuals etc.), operation data (e.g. airline operation, monitoring data and sensors data etc.), maintenance data (maintenance schedule/plans and maintenance history records etc.) and resources data (spare parts resource, inventory information and manpower resource), in the research (Yang, Wang, & Zhang, 2016).

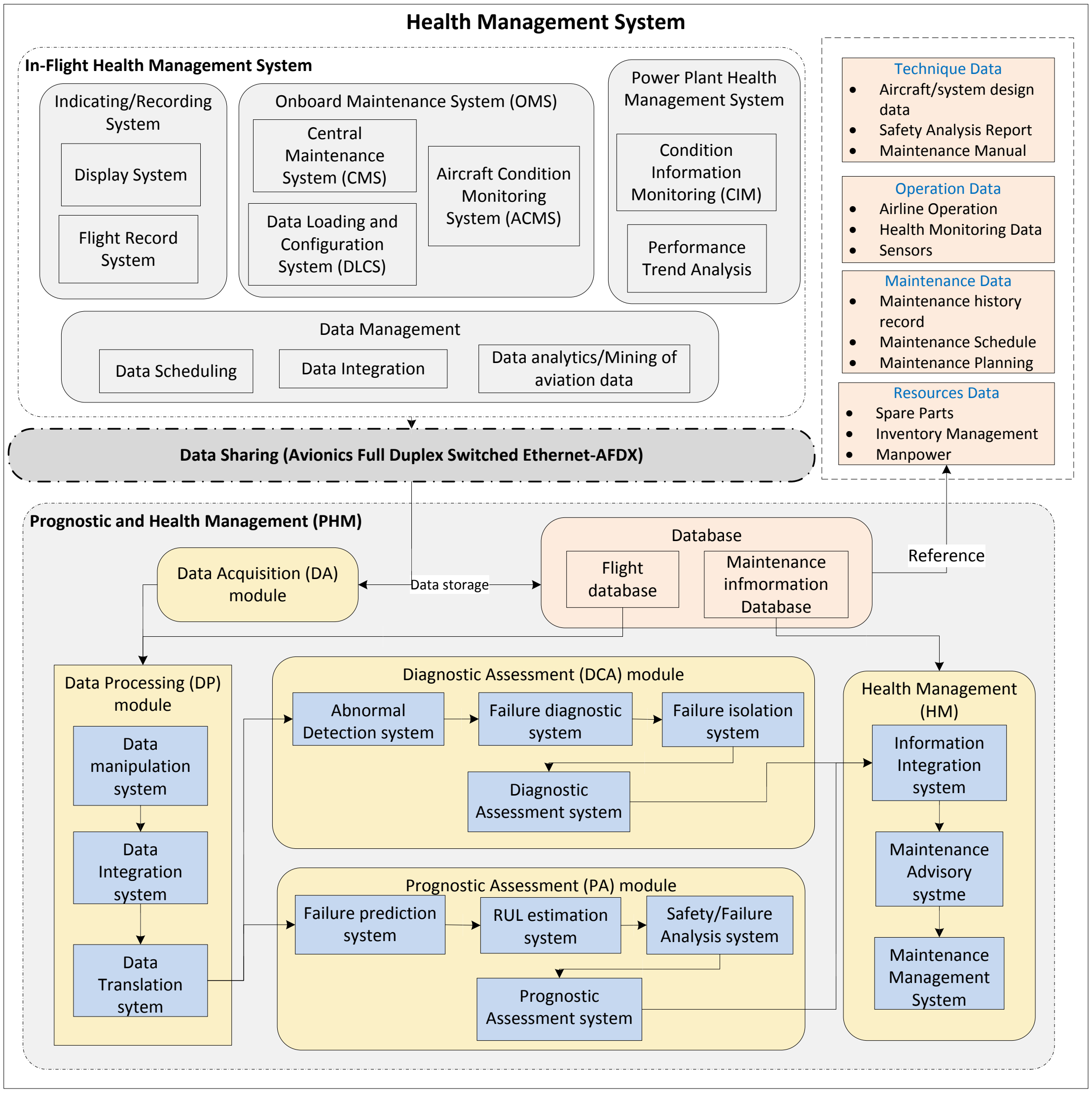

Figure 3. Functional architecture of PHM system

b) Data Acquisition Module

The data acquisition is a functional module with the capabilities of loading the flight data and storing these data to the ground databased, with the interfaces to the databased, data processing module and the external interface to data sharing network (Zhang, et al., 2015). Concerning the flight data, PHM system gathers the massive diverse monitoring data from different subscribers of the in-flight health management systems, providing the history data of monitored system to implement the algorithms of diagnostic and prognostic.

c) Data Processing Module

The data processing module is responsible for manipulating and integrating the flight data, and then transmitting them to diagnostic or prognostic functional modules. As a result, it has the interfaces with DA module, DCA module, PA module and the database facility. This module is configured with specific procedures to calculate descriptors (features) from sampled sensor data, other descriptors, or the output of computations. In the report (ISO-13374-1,2003), examples of the descriptor outputs of the data processing module may include extracted feature, calculated non-interpretative values, the virtual sensors (e.g. pressure and temperature), filtering information, normalization data, time series sampling information and so on.

d) Diagnostic Assessment Module

The diagnostic assessment module is allocated to implement the diagnostic function to detect, diagnose and isolate with the failures, as well as report the assessment result to health management module for maintenance decision making. The diagnostics process can be summarized as the process of identifying and determining the relationship between cause and effect in that its function is to isolate faults and identify failure root causes, as found in the literature (Lee, et al., 2014). Furthermore, it is able to automatic isolate the failures when it detects any failures, and then reports the health status to health management module. Accordingly, this module has the interfaces with bot data processing module and health management module.

e) Prognostic Assessment Module

In Figure 3, the prognostic assessment module is to predict the future state of the monitored system, taking into account projected future operational usage and estimate the RUL (Hoffman, 2007; Mao et al., 2017). The ultimate embodiment is to assess the future state of health and future failure modes by combining the relevant data and apply a prognostic algorithm or model based on supplied projected operational utilization (ISO-13374-1, 2003). Assessment of future health or RUL may also have an associated prognosis of the projected fault condition, which is used to take the maintenance decision in HM functional module (Mao et al., 2017). Consequently, the prognostic assessment module implements its configured functions by combining the relevant DP and HM modules via interfaces.

f) Health Management Module

Lee, J, et.al (2014) defined that health management was the process of taking timely, appropriate maintenance actions and making accurate logistics decisions based on outputs from diagnostics and prognostics, available resources and operational demand. As a crucial function, this module can integrate the health information from other functional modules, including assessment reports and maintenance information, and make the maintenance advisory for the monitored systems. Therefore, this module interfaces with the DCA, PA functional modules and the database facility, as presented in Figure 3.

4. CASE STUDY

To enable validation and verification, a case study is conducted in this section according to the plan in Table 1. Firstly, the functional analysis (N-2 diagram) studies the interactions between the defined functions, which is used to verify the correctness and completeness of the interfaces among the functional elements. Furthermore, the modeling of functional architecture is established to check the functional elements based on functions hierarchy and exam the internal connections between functional elements, and the details of how elements wired with each other through Block definition diagram (BDD) and Internal Block Definition (IBD). Finally, the analysis method presents the compatibility and universal applicability of this proposed architecture.

4.1. Functional analysis (N-2 diagram)

The N-2 diagram is a visual matrix representing functional or physical interfaces between system elements, to systematically identify, define, design, and analyze functional interfaces (Jackson, S., 2016). The related functional elements are placed on the diagonal axis and the interface inputs and outputs in the remainder of the diagram squares, and a blank square indicates that there is no interface between the respective functions.

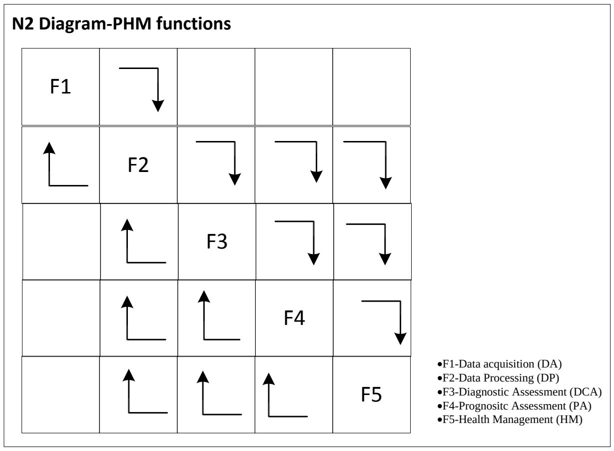

Figure 4. N-2 diagram of PHM system

The N-2 diagram, in Figure 4, is the functional analysis result of PHM system. This diagram demonstrates that the DA model links to DP module in order to provide the operation data and monitoring data, while the DP model has the bi-interfaces with DCA, PA and HM model with the aim to transmit the data to implement the assessment algorithms. Moreover, the DCA and PA modules will submit the health assessment reports to HM model through the configured interfaces to generate maintenance advisories for the monitored system.

4.2. Structure Diagrams Modeling

Mao et al., (2017) described that modeling was a helpful visualization method to understand the PHM system, and was able to present the operation conditions, relevance and completeness. The block definition diagram and internal definition diagram are utilized with the aims to verify the static structure and interactions of the functional PHM architecture (Mao et al., 2017).

4.2.1. Block Definition Diagrams (BDD)

The early literature (Jackson, 2016; John & Richard, 2016) mention that block definition diagram (BDD) is a black-box structure of the system, which focus on the connections between components and external interfaces as the first step of embodiment design modeling. The connector between blocks presents a whole part or composition relationship, where one model element with black diamond arrowhead is the subject component and the other end with arrowhead is a part of the whole component, as discussed in the literature (Mao et al., 2017).

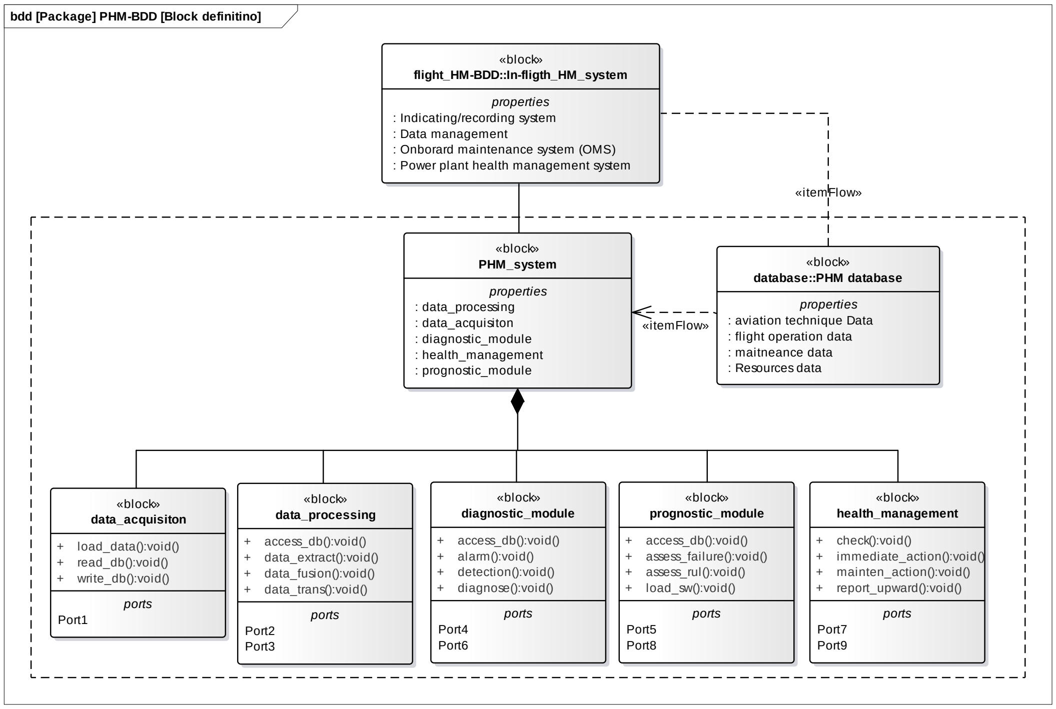

Figure 5. Block definition diagram of PHM system

Figure 5 is the modeling of PHM system static structure, in which PHM system is composed of five partitioning blocks and has a connection to the ground database via item flows. Additionally, the PHM system block also has the interaction with some external system, e.g. in-flight health management system. This diagram has the functionality to configure the specific attributes, operations and ports information for each block, as shown in Figure 5. Based on the block features, it is able to design and develop each module independently and then integrate them as a system subsequently, with the assumption that each block is a partitioning module in the proposed architecture.

4.2.2. Internal Block Diagrams (IBD)

The research (John & Richard, 2016) expressed that Internal Block Definition (IBD) diagram was used to define the internal connections between parts, and the details of how parts wired with each other. It means that the IBD diagram gives greater detail regarding the specific nature of the relationships between blocks, e.g., showing the details of flows or information transfer among blocks (Huang, Ramamurthy & McGinnis, 2007).

Figure 6 is the embodiment model of PHM system with the interaction information. In this diagram, each block is a fundamental module with the linkage to the block illustrated in the BDD diagram with the attributes operations information, as shown in Figure 5. As the heart of PHM system, this diagram has the capability of analyzing a large amount of data from distributed instances of the resource, assessing the current health status of systems and individual monitored units and providing advisory solutions to improve the health status (Mao et al., 2017). Moreover, the identified ports of each block are used to realize the specific connection interface among blocks, regarding as the interaction of control flow or data flow to implement the configured functions and operation services. For example, as shown in Figure 5, both diagnostic module and prognostic modules are able to share health assessment information with health management module via the ports as publisher respectively, although the diagnostic and prognostic modules are partitioning with each other. This modeling study provides an effective mechanism for the designer to analyze the behaviors and logical consequence of PHM operating process (John & Richard, 2016).

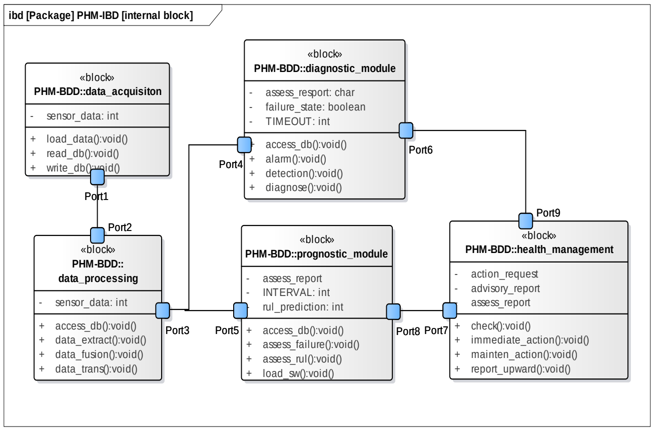

Figure 6. Internal block diagram of PHM system

4.3. System Analysis

4.3.1. Compatibility Analysis

OSA-CBM (ISO-13374-1, 2003) specification is a standard architecture and establishes the general guidelines for data processing, communication, and presentation of machine condition monitoring and diagnostic information. The data-processing blocks of OSA-CBM framework are addressed in Figure 7. In this framework, the basic data is converted into digital form in Data Acquisition (DA) and is processed in various ways as it is transformed into actionable information, resulting in Advisory Generation (AG), after each block in the system has been properly configured. As the processing progresses from data acquisition to advisory generation, data from preceding blocks need to be transferred to subsequent blocks and additional information acquired from or sent to external systems.

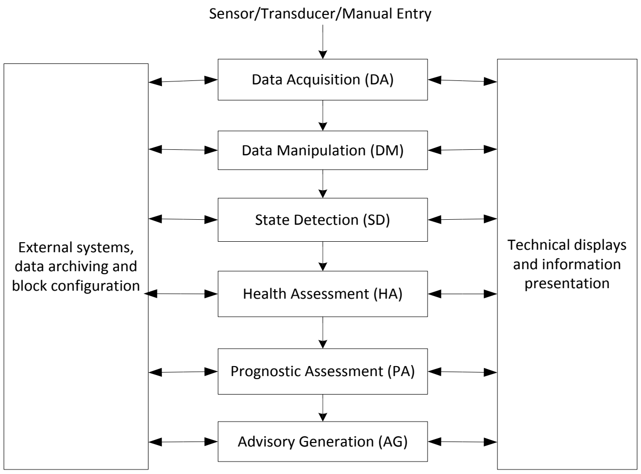

Figure 7. Data-processing blocks of OSA-CBM

OSA-CBM Functional Blocks	PHM functions				
	F1	F2	F3	F4	F5
Data Acquisition (DA)	X				
Data Manipulation (DM)		X			
State Detection (SD)			X		
Health Assessment (HA)			X		
Prognostic Assessment (PA)				X	
Advisory Generation (AG)					X

Note: F1-Data acquisition; F2-Data Processing; F3-Diagnostic Assessment; F4-Prongostic Assessment; F5-Health Management

Table 2. Compliance Matrix with OSA-CBM

Table 2 demonstrates that the proposed architecture in this paper is compliant with the blocks and framework of OSA-CBM outlined in Figure 7. Regarding the evaluation, it ensures the credibility and compatibility of this architecture; what is more, its feasibility integration and interoperability are enhanced. Consequently, it improves the communication performance among various diagnostic and prognostic modules, but more importantly, it supports the integration with a variety of other manufacturing planning and information systems that together enable an organization to operate efficiently and competitively. A more in-depth look reveals a way to reduce costs, improve interoperability, increase competition, incorporate design changes, and further cooperation in the realm of CBM, as has been described (Choudhary & Perinpanayagam, 2016).

4.3.2. Universal Applicability Analysis

This article (Hoffman, 2007) delineates the related techniques and the functionality facets of PHM system, generally, which are seemed as the generic configured functions of the prognostic systems. The functions decomposition in this paper is compliant with these facets as presented in Table 3. Furthermore, associated pitfall and facets of designing PHM system are addressed, this research progress in overcoming them, and suggests a generic functional architecture. Thus, this architecture enhances the acceptable, universal applicability and reliability from the system engineering perspective.

Facets of PHM	F1	F2	F3	F4	F5
Fault Detection			X		
Fault Isolation			X		
Advanced Diagnostics			X		
Prognostics/Condition-Based Maintenance				X	
Useful Life Remaining Predictions				X	
Component Life Tracking				X	
Performance Degradation Trending				X	
Selective Fault Reporting			X	X	
Aids in Decision Making and Resource Management					X
Fault Accommodation					X
Information Reasoners					X

Note: F1-Data acquisition; F2-Data Processing; F3-Diagnostic Assessment; F4-Prongostic Assessment; F5-Health Management.

Table 3. Compliance Matrix with functionality facets.

5. CONCLUSION AND FUTURE WORK

An architecture design methodology has been proposed, incorporating the views of functional architecture, logical architecture, and physical architecture derived from system requirements (RFLP). The current study focuses on the design methodology of a functional architecture process, taking into account functions decomposition, functional elements identification and internal/external interfaces representation. A generic functional architecture of PHM system is proposed in this paper, which is validated through the method of functional analysis, modeling and analysis by case studies. Compatibility and interoperability with various (socio-) technical systems and evidence of compliance with the OSA-CBM standard have been provided, as well as evidence to show the universal applicability of this functional architecture.

The current research has focused on the functional view and functional architecture of a generic PHM system, but has not addressed the logical and physical architecture aspects of the PHM design methodology. In future research, the following elements will be addressed:

- Analyze the behaviors of PHM system with logical views.
- Validate the relationship among the proposed functions by functional flow block diagram
- Analyze the PHM system dynamic states transitions and activity changes
- Behavioral modeling of the PHM architecture using SysML, including activity diagram, state diagram, and consequence diagram.
- Analyze the robust partition of the PHM system architecture.

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