Simulation Framework and Certification Guidance for Condition Monitoring and Prognostic Health Management

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ABSTRACT

The most prominent challenges to the successful qualification of Integrated System Health Monitoring (ISHM) systems are appropriate technology development processes and Verification & Validation (V&V) methods towards certification. This paper outlines a survey of recent ISHM programs in diverse industrial sectors across the globe, offers guideline towards ISHM development at each Technology Readiness Level (TRL), and sets forth a V&V process and certification roadmap. This paper provides insight into Cassidian's ISHM Simulation framework and emphasizes the relevance of this framework to an effective V&V solution of ISHM.

1. INTRODUCTION

With growing financial uncertainty, air vehicle operators (both commercial and military) are under tremendous pressure to reduce operational and support costs. It is accepted across the aerospace industry that ISHM is a potentially valuable strategy for the manufacture and management of vehicle platforms. At the same time, ISHM has not yet fully matured as a technology in several key functional areas. Research and development to address this shortfall is occurring across both the automobile and aerospace industries. Although technologies related to Built–In-Test (BIT) and diagnostics have advanced greatly and research into enhanced diagnostics are progressing very fast, prognostics technology for all types of aircraft sub-systems are in a very nascent stage.

Validation & Verification (V&V) method leading to the qualification and certification of ISHM is a key area of development. Although there has been considerable effort in this direction, ISHM system at the aircraft level is yet to be certified. Certification agencies (EASA, FAA, SAE, etc.) have yet to establish comprehensive certification regulation for Integrated System Health Monitoring system.

Kevin R. Wheeler et al. (2010) contribute to an extensive survey of recent ISHM programs and mention that vast differences in user objectives with regard to engineering development is the major barrier for successful V&V. The paper identifies in detail the objectives and associated metrics across operational, regulatory and engineering domains for diagnosis and prognosis algorithms and systems.

James E. Dzakowic et al. (2004) introduce a methodology for verifying and validating the capabilities of detection, diagnostic and prognostic algorithms through an on-line metrics based evaluation.

Martin S. Feather (2005) mentions in his publication that state-of-the-practice V&V and certification techniques will not suffice for emerging forms of ISHM systems. However, a number of maturing software engineering assurance technologies show particular promise for addressing these ISHM V&V challenges.

Dimitry Gorinevsky et al. (2010) describe the importance of a NASA-led effort in open system IVHM architecture. Detailed functional decompositions of IVHM systems with respect to criticality, on/off board operation and development cost are presented and certification standards are mapped accordingly. This paper also addresses the current NASA IVHM test bed along with development and deployment steps corresponding to increasing TRL.

The FAA's advisory circular (AC), AC 29-2C MG-15, provides guidance in achieving airworthiness approval for rotorcraft Health and Usage Monitoring System (HUMS) installations. It also outlines the process of credit validation, and Instructions for Continued Airworthiness (ICA) for the full range of HUMS applications.

Brian D Larder et al. (2007) converted the text of AC 29-2C MG-15 into a flow chart. His intention was to define the generic end-to-end certification process for HUMS CBM credit. Further, he sought to identify the relationships and interactions between different elements of the certification process that are contained in the three separate sections of the AC (installation, credit validation, and Instructions for Continued Airworthiness). This paper also mentions that HUMS have achieved very few credits, and that the material in the AC is largely untested. However HUMS in-service experience shows that the potential for future credits does exist.

ADS-79B HDBK (2011) describes the US Army's Condition Based Maintenance (CBM) system and defines the overall guidance necessary to achieve CBM goals for Army aircraft systems and Unmanned Aircraft Systems (UAS).

Praneet Menon et al. (2011) published a paper, which summarizes the work of a Vertical Lift Consortium Industry Team to provide the detailed guidance for the Verification and Validation (V&V) of CBM Maintenance Credits.

SAE ARP 5783 summarises the key metrics for evaluating diagnostic algorithms along with expression of these matrices.

As per the SAE news letter (2010), an Integrated Vehicle Health Management (IVHM) Steering Group has been formed to explore the need for standardization in order to drive IVHM technology towards the following objective.

- the development of a single definition and taxonomy of IVHM to be used by the aerospace and IVHM communities
- the identification of how and where IVHM could be implemented
- the development of a roadmap for IVHM standards,
- and the identification of future IVHM technological and regulatory needs

Deployment of ISHM in an aircraft and the resulting qualification process demands a huge investment. Verification and validation of these ISHM technologies is an important step in building confidence, both qualitatively and quantitatively. Practically, the cost of correcting an error after fielding an ISHM system is dramatically greater then during the testing phase, thus highlighting the need for appropriate verification and validation techniques. Certification considerations must be addressed during the very early stages of technology development in order to successfully meet any significant qualification goals. Appropriate guidelines and strategies should be followed in ISHM technology development to ensure successful certification within the desired time frame. Additionally, trade studies in the selection of V&V platforms reduce the eventual cost of V&V processes. This paper focuses on development of such guidelines for the V&V process while emphasizing the relevance of ISHM simulation frameworks, and a well devised certification roadmap.

2. Certification Aspects of ISHM

2.1. Evolution of ISHM

Maintenance credits are acquired when an ISHM system can replace the existing industry standard maintenance for a given component or complete aircraft system and this enhances availability, maintainability and mission capabilities of aircraft. To reach this level, evolution of ISHM development has to pass through effective process for technology maturation, development, verification, validation, qualification and finally certification.

Figure 1 illustrates the evolution phases of an ISHM system, which span maturation (concept refinement and technology development), development, production, installation, control introduction to service, benefit/credit validation, certification phases and continued airworthiness. The certification phases involve both the system developer and the regulator; they are initiated through an application made by the system developer to the appropriate regulatory authority; they are often performed in parallel to the various evolution phases.

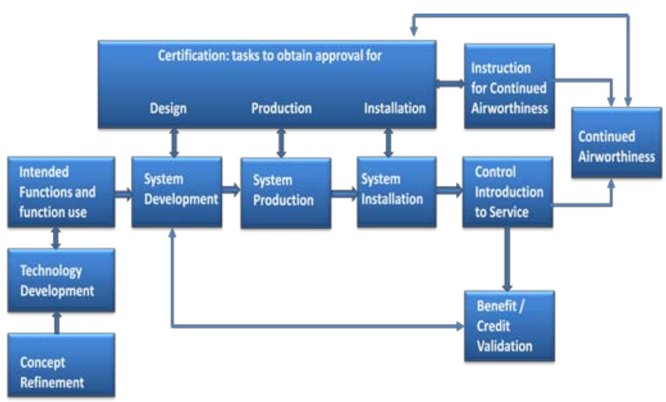

Figure 1. Evolution of Aircraft Product including ISHM

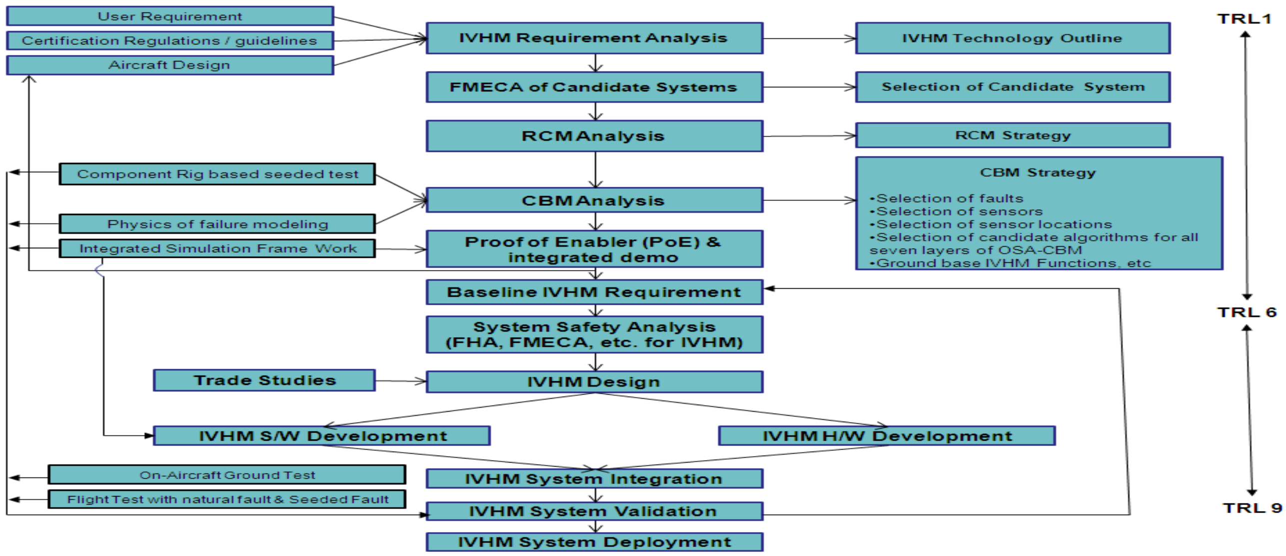

Figure 2. Guidance for Technology Maturation & Development

2.2. Technology Maturation

After the determination of the potential functionality and benefits of ISHM, maturation efforts are initiated. Usually, the maturation phase starts before the development and certification phases, and can overlap them.

The maturation efforts are often performed through Research and Development (R&D) programmes guided by technology and product roadmaps: efforts are allocated to develop sensing technologies, algorithms and software for ISHM, and to enhance the performance of ISHM in terms of increased accuracy, reduced weight, improved reliability, advanced communication and efficient data transfer. Technology gaps and risks are identified and efforts are allocated to fill the gaps and to mitigate the risks. During the maturation phase, the potential benefits and credits of ISHM are re-assessed and validation evidence is gathered. Efforts can also be allocated to develop and test ISHM prototypes, and to develop efficient production processes and reliable installation techniques. The Figure 2 defines the activities involved during technology maturation and development of ISHM system.

2.3. Development

The main development phases of a system, which can involve iterations through the following activities: determination of detailed system requirements, determination of the criticality levels and associated integrity requirements, system design, system test and evaluation, system integration, identification methodologies for credit validation, etc.

2.4. Guideline for V&V and Certification

Brian D Larder et al. depicted in form of flow diagram three important steps viz. installation, credit validation and Instructions for Continued Airworthiness (ICA) of HUMS certification as per FAA's advisory circular. In the similar line, Praneet Menon et al. (2011) provided in terms of flow diagram detailed guidance for verification and validation of CBM Maintenance Credits. This paper attempts to combine the both concepts and depict very prominently how development process, V&V, certification and qualification are linked each other in terms of interdependency and phases of verification & validation maturity towards successful maintenance credit.

2.4.1. Certification for Installation

This consists of the following steps:

- Check criticality versus integrity
- Mitigating Actions
- Airborne Equipment Installation
- Ground base Equipment Installation
- Credit plan approval

If any credit is to be gained, the general guidelines for determination of criticality levels will be either Minor, Major, or Hazardous/Severe-Major. They will be in agreement with the resulting effect of the end-to-end criticality assessment.

A mitigating action is an autonomous and continuing compensating factor which may modify the level of qualification associated with certification of an ISHM application. These actions are often performed as part of continued airworthiness considerations and are also an integral part of the certification.

The overall installation considerations for airborne equipment should include, as a minimum, supply of electrical power, environmental conditions, system non-interference, and human factors if operations are affected along with considering environmental qualification (RTCA/DO-160/ED 14) and software development standard (RTCA/DO-178/ED-12).

Since the ground based equipment may be an important part of the process for determination of intervention actions, its integrity and accuracy requirements must be the same as any other part of the ISHM process. The independent means of verification activity is required due to the use of COTS software.

If the integrity assessment (IA) has mitigation spelled out for all possible functional failures of the algorithm, then one can proceed with the next V&V steps, i.e. establishing the V&V criteria and getting the V&V plan approved by the aviation authority. V&V criteria are driven by certification basis.

The Certification Basis, summarised for ISHM in the Table 1, is the listing of all requirements from regulatory authorities or related advisory circulars which will ensure qualification of the system for airworthiness and to achieve maintenance credit in the context of ISHM.

Generally certification basis is derived from Certification Specification (CS), Technical Standard order (TSO), along with the recent compliance recommendations (AMC,..), amendments and interpretations which are to be negotiated between certification coordinator (CC) and authority.

ASPECT OF CERTIFICATION	STANDARD / GUIDANCE	COMMENTS
S/W Development (on-board)	DO-178	Software assurance level varies from A to E depending on criticality.
S/W Development (ground base)	DO-278	Software assurance level varies from AL1 to AL6 depending on criticality.
H/W Development	DO-254	Assurance level varies from A to E depending on criticality.
Safety Consideration	ARP 4754 /4761, MIL-STD-1629A	MIL-STD-1629A for FMECA
Environmental	DO-160	Standard AMC
Integrity of Data	DO-200A	Applicable for data management system.
BIT/BITE Function	MIL-STD-1591, MIL-STD-2165	MIL-STD-2165 for testability.
Integrated Diagnostics	ARINC 604, 624-1	ARINC 604: design & use of BITE, ARINC 624-1: Design guidance for OMS.
V&V guidance for ISHM	AC-29-2C MG-15, SAE ARP 5783	AC-29-2C MG-15 - FAA's advisory circular for HUMS. SAE ARP 5783 - key metrics for evaluating diagnostic algorithms.
Overall guidance for ISHM	ADS-79 B or C (US Army)	ADS-79C yet to be released for public. SAE ARP 5987 will be released soon.
Interface across layers	OSA-CBM, OSA-EAI	OSA-CBM is an implementation of the ISO-13374 functional specification.

Table 1: Certification Basis for ISHM

2.4.2. V&V for Maintenance Credit

This can be done after the installation certification has been completed, however it is highly recommended to start this well before the installation certification is complete. Since the description of application and intended credit of the CBM process has already been defined it is now necessary to prove that the underlying physics of the monitored equipment and it's failures has been understood.

The verification of the credit methodology is taken up. Upon completion of the verification steps, it is necessary to determine whether the verification criteria outlined in the plan have been met. If no, then the system element, i.e. the algorithm and corresponding configuration needs to be redesigned and re-verified. If yes, next step in the maintenance credit process is generation of production unit. It is to be noted that at this point the Air-Worthiness Report (AWR) has not yet been written for the credit methodology.

The next step in the process is validation of the credit methodology. It needs to be determined whether the validation criteria outlined in the V&V plan have been met. If no, then the system element, i.e. the algorithm and corresponding configuration needs to be redesigned, re-verified and re-validated.

If the validation was successful, then an AWR for the methodology can be written and the unit can be officially introduced into production.

Once the system has been validated, a controlled introduction to service should be conducted, since there may still be some elements that can't be fully validated in the development phase. In this phase, data is collected from use in the actual aircraft, this data is then used to calibrate sensors and to tune and train the detection and prognosis algorithms. This basically means treating the maintenance credit as a maintenance benefit, only providing advisory activities for the time being.

As soon as this phase has been completed, a full introduction to service can be performed (FAA's advisory circular AC 29-2C MG-15).

2.4.3. Instruction for Continued Airworthiness

The final part of the certification process mainly focuses on training, documentation and operations of the CBM system.

A plan is needed to ensure continued airworthiness of those parts that could change with time or usage and includes the methods used to ensure continued airworthiness.

The applicant for ISHM is required to provide ICA developed in accordance with FAR/JAR Part 29 and Appendix A. This section provides supplemental guidance with addressing aspects unique to HUMS (FAA's advisory Circular AC 29-2C MG-15).

Regulatory requirements for the "Instructions for Continued Airworthiness", which must be written in English as a manual, contains: system description, installation, operation information, servicing information, system maintenance instructions including troubleshooting, methods of removal/replacement, access diagrams, etc.

2.5. V&V Roadmap

The Figure 3 depicts the V&V road map of ISHM with increasing Technology Readiness Level. On the basis of earlier discussion, V&V process towards airworthiness certification of ISHM will be spread over the following phases:

- Concept Refinement & Technology Development
- Development
- Controlled Introduction to Service
- Instruction for Continuous Airworthiness

V&V platforms or methods, which are mentioned in the second row of the figure corresponding to each phase, are summarized here.

- Concept Refinement & Technology Development
  - RCM Tools
  - Component Simulation
  - Component RIG
  - Formal Method for Analysis
  - Integrated Simulation Framework
  - Integrated Simulation Framework driven by offline Flight Data
  - Integration Rig extended from Simulation Framework
  - Hardwire-in-Loop Simulation

- Developmentt
  - Ground System Deployment
  - Non-critical Flight System Deployment

- Controlled Introduction to Service
  - Maturation of ISHM
  - Critical Flight System Deployment

- Instruction for Continuous Airworthiness

- In Service Validation – continued airworthiness

Note: On the basis of cost and impact analysis, applicability of formal method & HILS are decided.

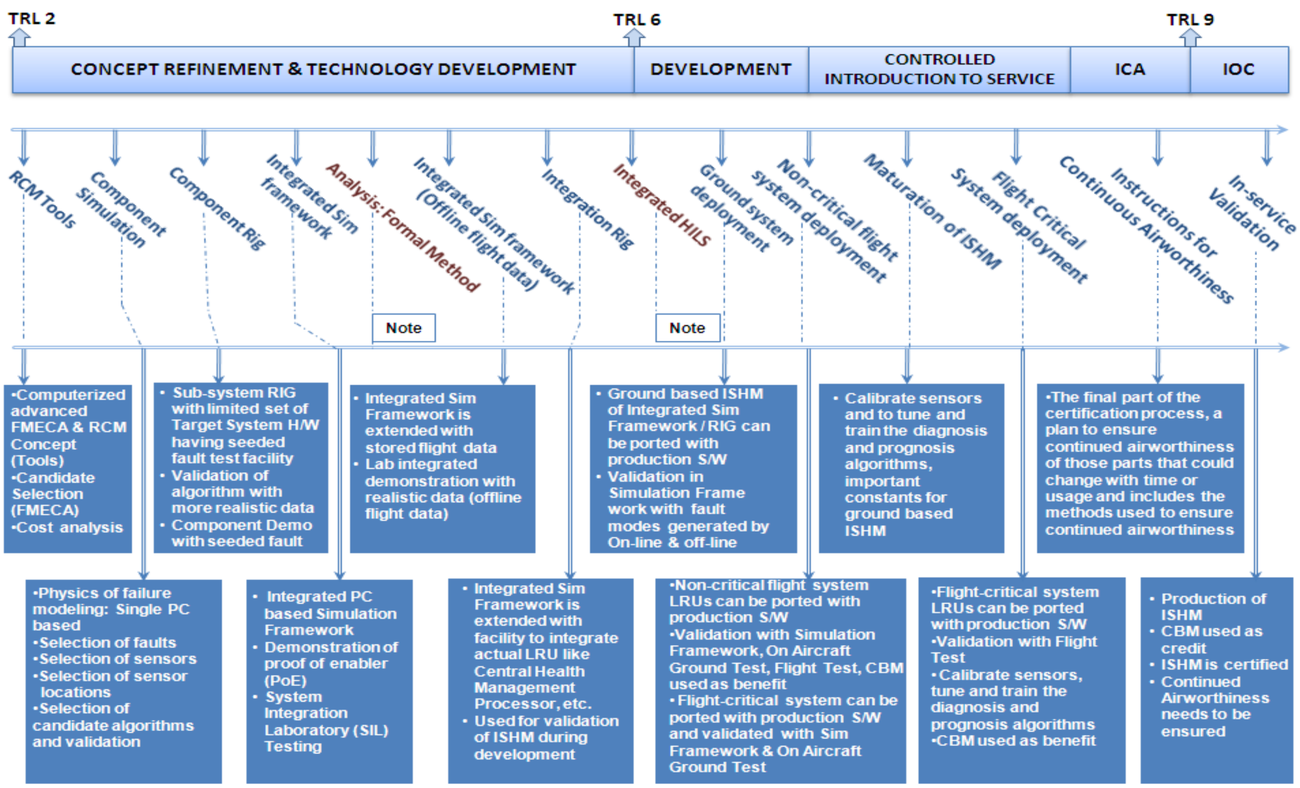

Figure 3. V&V Roadmap with increasing TRL

3. ISHM SIMULATION FRAMEWORK IN V&V PROCESS

Cassidian develops a comprehensive integrated PC based simulation framework for integrated system health monitoring and management research and development. This ISHM framework is used primarily for demonstrating Proof of Enablers (PoE) and System Integration Laboratory (SIL) testing which is goal of concept refinement and technology development. User objective and metrics related to ISHM can be refined through Exhaustive Monte Carlo simulation of off-nominal seniors. Ground based ISHM systems can be deployed in this environment. This framework with high fidelity modelling of sub-systems and sensor data provides enough confidence in installation of on-board ISHM non-critical systems before controlled introduction to service for further tuning & refinement of algorithm.

The integrated Simulation Framework is extendable enough to include offline stored flight data. In case of similar types of sub-systems already being flown in different aircraft, recorded sensor data could be made useful for more realistic validation of algorithm. Aircraft System models within the Simulation Framework are able to load, store off-line flight data and generate sensor data specific to sub-systems. In this mode, computation of physics based models is made disabled.

Integrated HILS will have simulation of Aircraft Dynamics, Aircraft Subsystem H/W and adverse environmental effects. Also, there is the capability to inject system faults. This facility can expedite the validation process of ISHM and reduce validation time period during Controlled Introduction to Service. However this capability demands a huge investment of time and capital. These investments can be greatly reduced in case of V&V of aircraft's ISHM by utilization of Simulation Framework.

Integrated Simulation Framework can be integrated to individual test bed like SHM test rig. The conclusive evidence would be structural fault detection capabilities observed during the operation of the aircraft. The occurrences of structural faults such as cracks are infrequent, and hence, years of flight tests might be required to collect validation evidence; small number of flights would be only sufficient to prove the system "fitness for flight" and would be insufficient to prove "fitness for purpose". Therefore, a validation approach would be required to extrapolate from laboratory tests to actual aircraft. Reference (HAHN Spring Limited. (2011)) has suggested that a generalisation and calibration approach would be required to extrapolate from laboratory specimens to actual aircraft; such an approach is expected to vary between the different tasks and technologies of SHM systems.

From the V&V roadmap, it is very much evident that different facilities are needed towards V&V, certification & qualification of ISHM technologies. Cassidian's ISHM simulation Framework plays multi-role being as a single platform.

3.1. ISHM Simulation Framework

The goal of ISHM system are preparation of intelligent Maintenance Plan, intelligence Mission Plan and automatic logistic function for enhancing availability, maintainability and mission capabilities. These functions are achieved through Condition Based Maintenance (CBM). The Simulation Framework, which is built around OSA-CBM and OSA-EAI architecture, simulates all ISHM functional layers through different sub-system models

Prognostic Health Management (PHM) is the core of ISHM technology. Like in any other domain, challenges in the introduction of PHM systems in the aerospace domain are twofold. On the one hand, there are individual challenges in developing sensor technology, state detection and health assessment methodologies and models for determining the future life span of a (possibly deteriorated) component. On the other hand, there are integration challenges when turning heterogeneous data from disparate and distributed sources into consolidated information and dependable decision support on aircraft and fleet level. It has therefore been recognized in the community that standardized and open data management solutions are crucial to the success of PHM. Such a standard should introduce a commonly accepted framework for data representation, data communication and data storage.

Key findings through the development of Cassidian's ISHM Simulation Framework are:

- ISHM Simulation Framework plays vitals role in V&V process for ISHM.
- State-of-the-practice in using open architecture standards like OSA-CBM, OSA-EAI are not sufficient. This may require customisation or improvement in standards. These include standardizing non-XML-based transportation formats for OSA-CBM data packets for real-time operating condition, optimization of OSA-EAI database model for analytical tasks, etc.
- This provides a comprehensive RCM based CBM ground-base framework to realise and validate the full benefit of ISHM.

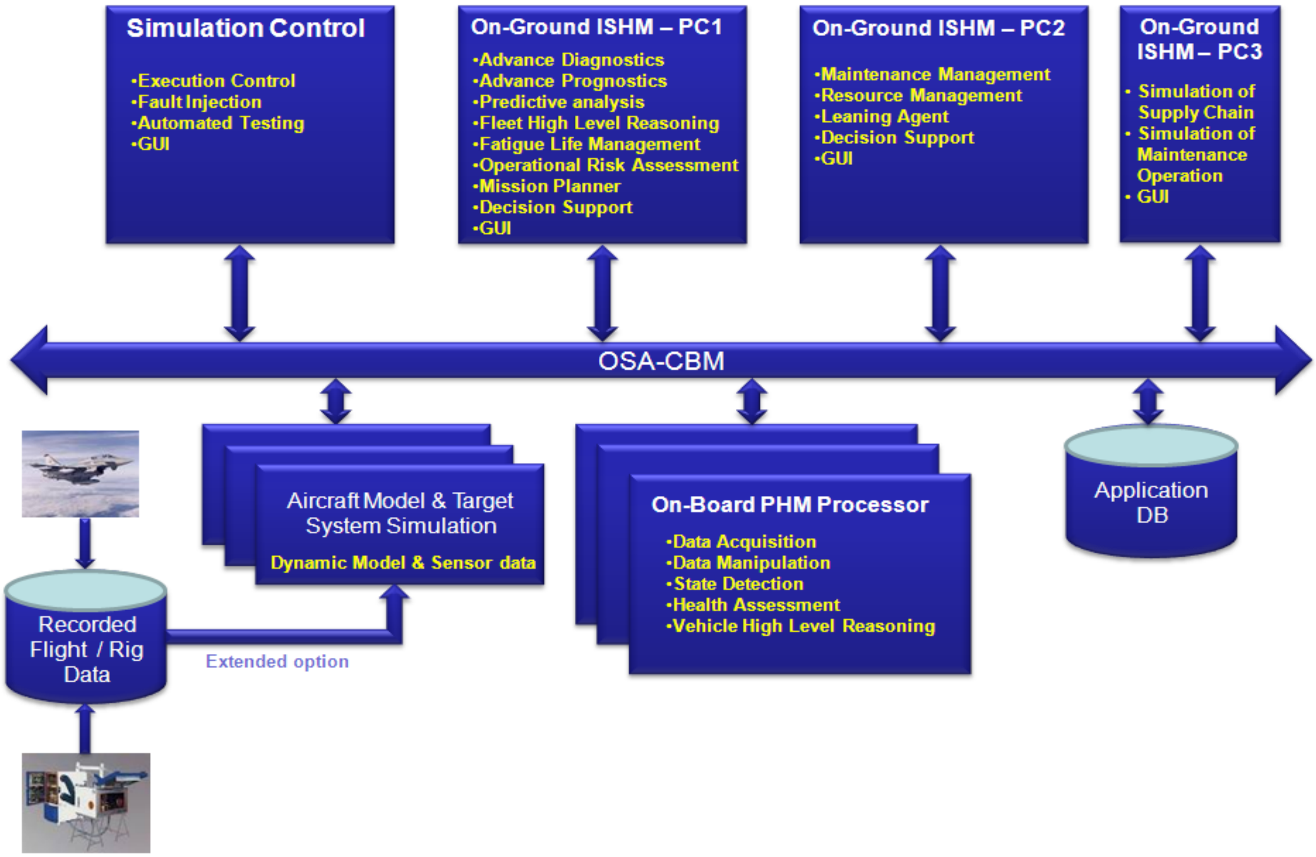

Figure 4. ISHM Simulation Framework

ISHM Simulation Framework simulates following modules:

- Aircraft System Model
- On-board ISHM System
- On-ground ISHM System
- Supply Chain (Enterprise Level)
- Simulation Management

Simulation of Aircraft system model and supply chain (Enterprise Level) create simulation environment for ISHM system models and simulation management controls the operation of complete ISHM Simulation Framework.

3.1.1. Aircraft System Model

Aircraft System Model simulates those systems and their sensors for which we intend to develop ISHM capabilities. Aircraft System Model have high fidelity modeling of Aircraft aerodynamics model, Hydraulics / Actuator System Model, Landing Gear, Fuel, ECS and Aircraft Structure, etc. Each sub-system implements physics based modeling of dynamic behavior, physics of fault, and computation of states or parameters for deriving senor data for each sub-system. Sensor data for each sub-system are generated from computed states and parameters after corrupting with all possible errors that might occur in real-life scenario, as well as with noise specific to those sensors. All faults are injected from simulation control GUI. Any system for which ISHM specific monitoring and prediction capabilities should be validated and verified, needs to be modelled with a high level of detail. This should enable the realistic simulation of failures to support the validation of diagnostic and prognostic functions. Respective controller model simulates Built-in-Test (BIT) and Reactive Health Assessment (RHA) of the sub-system.

3.1.2. On-board ISHM

On-board ISHM function includes a central ISHM data processor. Sensors push their data to the IVHM data processor via an OSA-CBM implementation. The underlying message protocol is optimized for embedded systems. The ISHM data processor calculates ISHM information according to the OSA-CBM layer specifications, up to health assessment layer.

As per OSA-CBM, there are seven functional layers. Central ISHM data processor has following functions:

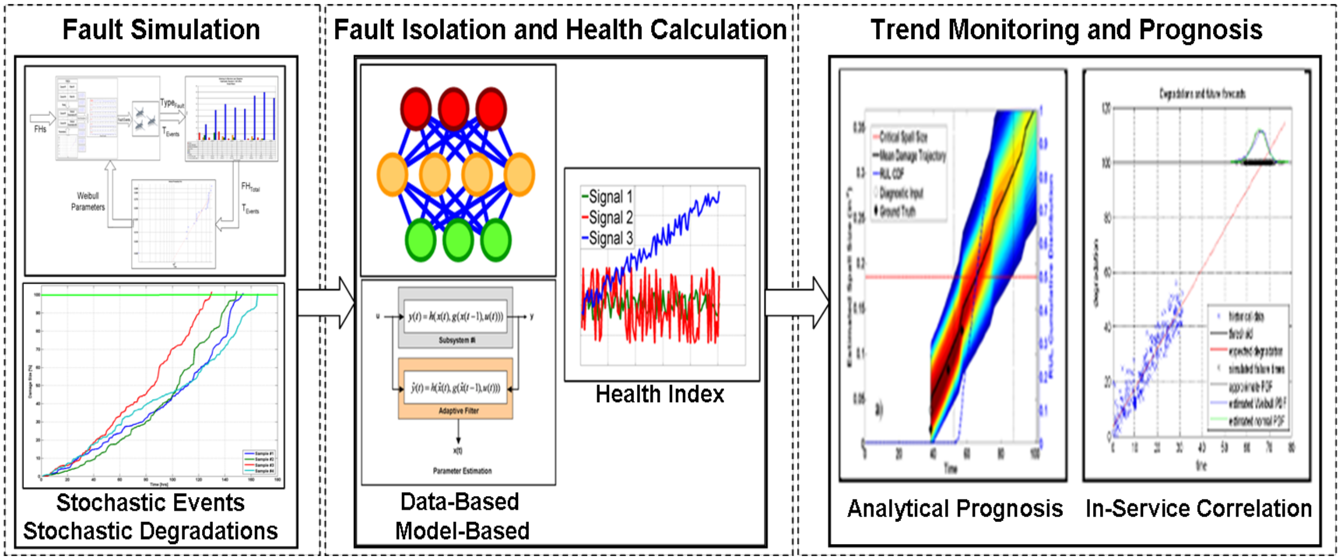

Figure 5. Fault simulation concept for Simulation Framework

- First four functions of OSA-CBM
  - Data Acquisition
  - Data Manipulation
  - State Detection
  - Health Assessment
- High Level Reasoning
- BIT Function
- Storing of on-board health data

Several seeded fault tests under fixed conditions are sufficient to enable the model-based development of diagnostic functions. The development of prognostic functions (to be part of ground based ISHM) needs also to cover the development of suitable failure mode specific degradation models. Once the degradation models have been developed, it is possible to verify the diagnostic and prognostic functions through Monte-Carlo simulations. These simulations should include stochastic fault insertion for so-called "hard faults" (stochastically occurring failures without impacts on observable system parameters before the specified failure threshold is exceeded) and the usage of degradation models for "soft faults" (stochastically occurring degradations with impacts on observable system parameters before the specified failure threshold is exceeded). This concept is illustrated in Figure 5.

3.1.3. Ground based ISHM

Major functionalities towards enhancing availability, maintainability and mission capabilities related to ISHM system are realized by ground base sub-systems. On-board ISHM function includes only data acquisition and diagnostic function of equipment health along with intermediate processing of data. Ground base ISHM system has significant amount of processing related to the following prime functions:

- On Ground Heath Management function
- Operational Risk Assessment / Fleet High Level Reasoning
- Maintenance Management
- Maintenance Planer
- Resource / Logistic Management
- Mission Planer
- Learning Agent
- Simulation of Enterprise System
- Presentation Layer

Ground-base ISHM functionalities are enhanced from the core concept provided by Fatih Camci et al. (2006).

On Ground Health Management function:

On ground health management function consists of advance diagnostic, advance diagnostic and predictive analysis. Advance diagnostic validates further on-board diagnostic result with historical data of same aircraft and fleet wide fault data base and refine diagnostic decision. Advance prognostic computes RUL & Confidence for CBM candidate. Predictive Analysis (Trend analysis) identifies impending failure using trend analysis of historically collected data, but does not predict when failure will occur.

Maintenance Management:
Maintenance Management functions finds one of the following maintenance solutions for a sub-system depending upon RCM process:

- Run-to-Fail
- Reactive
- Preventive (calendar based)
- Predictive
- CBM

Maintenance Management executes the following functions:

- Identification of Maintenance task corresponding to sub-system / functional failure
- Rank of optimal maintenance task is computed as a function of maintenance effectiveness for the failure mode, maintenance downtime and cost.
- Execute Maintenance (work order generation, Track Maintenance action, Receive feedback and close work order) as per approved maintenance plan

Maintenance Planer:
Opportunistic Maintenance agent finds opportunistic maintenance time and task using rank of maintenance task, Mission capability of sub-system / function for future mission, RUL for future mission. Maintenance planner schedules the intelligent maintenance plan, validates with Resource Management Feedback and publishes maintenance plan after getting approval from decision support system.

Resource / Logistic Management:
This function tracks the availability along with configuration parameters of LRUs, tools, parts, consumables and personnel, etc. (configurable items). On the receipt of maintenance plan, Resource / Logistic management function sends feedback on validity of maintenance plan to Maintenance Planner on the basis of resource availability. This function finally generates a plan for resource / inventory and generates order for parts or LRUs to OEMs or suppliers as per present and projected status of inventory.

Mission Planer:
Mission Plans & Flying Programmes are entered using digital map and editing GUI. Mission planner instructs user to reschedule the Mission Plan if performance of aircraft exceeds as per mission plan entered and edited. Flying programs are asked to reschedule if approved maintenance plan superimposes with mission plan. Applicability of mission segments of a particular aircraft is checked further with respect to operational capabilities of the aircraft for the segment, computed by Operational Risk Assessment (ORA). If capability of flight segment or complete mission is less than critical threshold, Mission Planner instructs user to reschedule or cancel the mission for particular Aircraft.

Learning Agent:
As experience is accumulated, some of the parameters within the model can be learned automatically by analyzing the feedback from the maintainer, OEM industry, Mission Commander, Resource Manager. The parameters to be learned are opportunistic maintenance threshold, required maintenance threshold, resource lead time, maintenance effectiveness and different co-efficient related to diagnostics & prognostics, etc

Simulation of Enterprise System:
This module simulates supply of specific LRUs or parts from OEM, Service/Industry Support organization, Wholesale Stock point accounting appropriate accumulated delay attributed due to order process by resource management function, manufacturing (if applicable), shipping process, etc related to Supply Chain Management.

Presentation Layer:
Decision support personal interacts through Presentation Layer which consists of following GUIs distributed across different terminals.

- Health Management & Monitoring
- Interactive GUI for Maintenance Management
- Resource Management & Monitoring
- Maintenance Planner
- Mission Planner

High Level Reasoning / Operational Risk Assessment:
High Level Reasoning (HLR) is the capability that can estimate an airplane's (or vehicle's) functional availability. The purpose of HLR concept is used to estimate the functional availability of a vehicle based on the health assessment results from lower level systems and subsystems. Both concepts are part of the HLR development and integration into the simulation framework. RUL & confidence is recomputed for each component failure for all future missions and used by HLR. ORA finally determines and quantifies remaining functional / operational availability at the subsystem, vehicle levels and mission levels.

4. CONCLUSIONS

From above discussion, it is evident that nature of challenges in V&V and certification of ISHM is different compared to standard stand alone system. One of the major challenges in certification of ISHM system is due to non-availability of comprehensive regulatory standards for ISHM. V&V also poses challenges mainly due to the fact that ISHM has to handle a large number of off-nominal scenarios, has to ensure performance, safety, and reliability across the entire performance envelope and has to reliably avoid 'false alarm'. Moreover, V&V has to deal with multidisciplinary aspects of ISHM. Most prominent aspect is direct evidence gathering for faults effects related to V&V of diagnostics and much more difficult for prognostics. To handle these issues, the key aspects of ISHM V&V mentioned above are summarized here:

- V&V maturity starts from concept refinement and technology development phase.
- If specific sub-system / function of ISHM, is classified as Hazardous/Severe Major, then direct evidence must be gathered. (FAA's advisory circular AC 29-2C MG-15).
- If specific sub-system / function of ISHM, is classified as Major or Lower, then indirect evidence is sufficient. (FAA's advisory circular AC 29-2C MG-15).
- During 'Controlled Introduction to Service', CBM maintenance credit is considered as maintenance benefit. i.e. CBM output is compared with maintenance instructions suggested by conventional RCM process.
- After maturation of algorithm and certification, CBM obtains maintenance credit.
- Appropriate sequence of V&V process of ISHM function layers are to be considered.
- It must be noted that the V&V of ISHM functionalities in Simulation Framework do not completely address defects created by designer. It is evident from Figure 3 (V&V Roadmap with increasing TRL) that subsequent V&V phases (i.e. V&V in integration RIG, Integrated HILS, V&V during controlled introduction to the service and ICA) are suggested in order to achieve maintenance credit.
- Since ISHM simulation framework plays vital role in V&V process, simulation framework has to be qualified (Robert G. Sargent. 1998).

The survey of works towards ISHM certification, suggested customization and experience in using simulation framework for V&V provide impression that certification of ISHM is not impossible although it is not easy job. This study may give enough confidence to ISHM community towards achieving maintenance credit through implementation of this technology.

NOMENCLATURE

AC	Advisory Circular
AMC	Acceptable Means of Compliance
ARP	Aerospace Recommended Practice
AWR	Airworthiness Report
BIT	Build-In Test
CBM	Condition Based Maintenance
CC	Certification Coordinator
CS	Certification Specification
EAI	Enterprise Application Integration
FHA	Functional Hazard Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
GUI	Graphical User Interface
HILS	Hardware in Loop Simulation
HLR	High Level Reasoning
HUMS	Heath Usage Monitoring System
IA	Integrity Assessment
ICA	Instruction for Continued Airworthiness
ISHM	Integrated System Health Monitoring
IVHM	Integrated Vehicle Heath Monitoring
LRU	Line Replaceable Unit
OEM	Original Equipment Manufacturer
ORA	Operational Risk Assessment
OSA	Open System Architecture
PHM	Prognostic Health Management
RCM	Reliability Centered Maintenance
RUL	Remaining Useful Life
SHM	Structural Health Monitoring
TRL	Technology Readiness Level
TSO	Technical Standard order

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BIOGRAPHIES

Matthias Buderath - Aeronautical Engineer with more than 25 years of experience in structural design, system engineering and product- and service support. Main expertise and competence is related to system integrity management, service solution architecture and integrated system health monitoring and management, **Today he is *head of technology development in* CASSIDIAN**. He is member of international Working Groups covering Through Life Cycle Management, Integrated System Health Management and Structural Health Management. He has published more the 50 papers in the field of Structural Health Management, Integrated Health Monitoring and Management, Structural Integrity Programme Management and Maintenance and Fleet Information Management Systems.

Partha Pratim Adhikari - has more than thirteen years of experience in the field of Avionics and Aerospace Systems. Partha worked with RCI, DRDO; Aeronautical Development Agency (Ministry of Defence) and CAE Simulation Technology before joining Cassidian, CAIE, Banglore where he currently leads the Integrated System Health Monitoring (ISHM) program from Bangalore center. Partha has Bachelor's degrees in Physics (H) and B. Tech in Opto-electronics from Calcutta University and a Master's degree in Computer Science from Bengal Engineering and Science University. In his tenure across various aerospace organizations, Partha made significant contributions in the fields of Navigation systems, Avionics and Simulation technologies. Partha published several papers in the fields of estimation, signal processing and simulation of flight systems in national as well as international conferences and journals. **Partha, in his current role as Tech Lead, Avionics at Cassidian, CAIE, Banglore** is working on devising ISHM technologies for aviation systems with focus on complete vehicle health, robust implementation and certification of the developed technologies.