Abstract
Integrated system health monitoring and management (ISHM) is a field of research and development where lot of different industries and academia are highly focused on. Since the ISHM technology itself is still evolving, the standards available for certification and successful qualification of the systems are yet to be fully matured. And these different qualification methods and processes have to be included in the early stages of the development of the respective systems. This paper highlights the survey of different certification methodologies, provides an insight into Airbus Defence & Space’s Certification Roadmap, the role of ISHM Simulation Framework in certification and also the lessons learnt. The paper will also provide an outlook how Structural Health Monitoring (SHM) technologies can be addressed in the ISHM simulation environment to define the monitoring concept to contribute to the requirement of probability of detection.

Keywords: ISHM, SHM, Simulation, Certification, CBM, Prognostics, Enhanced Diagnostics

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 manufacturing 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 still 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.) are yet to establish comprehensive certification regulation for Integrated System Health Monitoring system.

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 than that of in 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. Main Objective of Simulation Framework
Airbus DS has developed a comprehensive integrated ISHM simulation framework which contributes in the following areas:
- Integrated demonstration of Proof of Enablers (PoE)
- Training & maturity of PHM functions
- Maturation of ISHM requirements (KPIs)
- V&V of ISHM functions

This ISHM framework is used primarily for demonstrating Proof of Enablers (PoE) and System Integration Laboratory (SIL) testing, including S/W and H/W in loop, which is the goal of concept refinement and technology development. For end-to-end demonstration of ISHM, simulation framework hosts simulation of aircraft system with fault injection provision, on-board health assessment function, off-board analytics related to prognostics, operational risk assessment, database management, fleet planning, maintenance/logistics planning, etc. in enterprise level. For SHM, Airbus Defence & Space is addressing the virtualization of structural components to be monitored by SHM and facing the challenge to model the sensing system and the insertion of failure modes.

During early stage of ISHM development for new aircraft platforms, sufficient amount of in-service or test flight data (both nominal behaviour & fault behaviour, run-to-fail data) is not available. Physics based simulation of aircraft system and fault progression model plays an important role for modelling enhanced diagnostics & prognostics modules/functions. Simulation models and PHM functions undergo continuous evolution of maturity with data (rig data, test flight, in-service flight data) available through progress of development lifecycle. Simulation framework has the mechanism to accommodate additional correction factor related to modelling imperfection.

User objective and metrics related to ISHM can be refined through exhaustive Monte-Carlo simulation of off-nominal scenarios, which is not a viable solution with real flight tests. Simulation framework supports functional analysis related to selection of candidate sub-systems, faults, sensors and performance matrices of enhanced diagnostics and prognostics. This will enrich performance requirements of key algorithms mainly related to enhanced diagnostics, prognostics, etc.

With the increase in maturity of the Simulation framework, it plays different roles of V&V platforms viz. Engineering simulator, System-subsystem Test setup, Integration Test Setup, etc. 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. 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.

3. ISHM Certification Guideline
3.1 Certification Basis

Certification agencies (EASA, FAA, SAE, etc.) are yet to establish comprehensive certification regulation for Integrated System Health Monitoring system. This section summarizes existing efforts for certification basis which will act as an overall guideline for ISHM development.

Kevin R. Wheeler et al. [15] contribute to an extensive survey of recent ISHM programs and mentions 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. [13] introduces a methodology for verifying and validating the capabilities of detection, diagnostic and prognostic algorithms through an on-line metrics based evaluation.

Martin S. Feather [16] 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. [8] describes the importance of a NASA-led effort in open system IVHM architecture. Detailed functional decompositions of IHM 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. [7] 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-79E HDBK [3] 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. [19] 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.

Existing ARPs (viz. ARP 5783, ARP 4761, etc.) published by SAE already supports some aspect of guidance in different stages of ISHM development.

SAE formed an Integrated Vehicle Health Management (IVHM) Steering Group to explore the needs for standardization to support IVHM technology towards the following objectives.

- 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.

The following figure summarizes existing ARPs and standards in the different stages of ISHM process flow.

![Figure 3-1: ISHM Process Flow mapping with ARPs and standards](image-url)
3.2 Guideline for Life Cycles

ISHM development process steps are mapped onto the ARP 4754A aircraft/system development life cycle as baseline. The ISHM development process steps can be mapped to the V-model of the ARP 4754A process with the exception of “Concept & Technology Development” and “Controlled Introduction to Service”, “Instructions for Continued Airworthiness (ICA)”, and “In-Service Validation” processes steps, which are outside of the V-model. It is assumed that after the transfer from R&T the ISHM development will be part of an aircraft system development. This concludes that the ISHM development is part of an overall aircraft and system development process. The detailed guidelines for all processes will be available in the respective standards as mentioned in Figure 3-1.

![Figure 3-2: Mapping of ISHM development process steps on to ARP4754 Aircraft development process](image)

3.3 ISHM Simulation Framework

The goal of ISHM system are preparation of intelligent Maintenance Plan, intelligence Mission Plan and automatic logistics 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 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.

This simulation framework supports key features, viz. demonstration of end-to-end value chain of ISHM, real-time simulation for the on-board computation, almost real-time for off-board, having features of simulating lifetime (with time acceleration mode), provision for refinement of physical models with data from test rigs, test flights with seeded faults and in-service data.

**Figure 3-3: ISHM Simulation Framework**

ISHM Simulation Framework simulates following modules:

- Aircraft System Model
- On-board ISHM
- On-ground ISHM
- 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.
3.3.1 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 modelling of Aircraft aerodynamics model, Hydraulics / Actuator System Model, Landing Gear, Fuel, ECS and Aircraft Structure, etc. Each sub-system implements physics based modelling of dynamic behaviour, physics of fault, and computation of states or parameters for deriving sensor 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.

3.3.2 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:

- 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 3-4.
3.3.3 On-ground ISHM

Major functionalities towards enhancing availability, maintainability and mission capabilities related to ISHM system are realized by ground based sub-systems. On-board ISHM function includes only data acquisition and diagnostic function of equipment health along with intermediate processing of data. Ground based ISHM system has significant amount of processing related to the following prime functions (Fatih Camci et al. [10]):

- On Ground Health 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

**On Ground Health Management function:**
On ground health management function consists of advanced diagnostic and predictive analysis. Advanced diagnostic validates further on-board diagnostic result with historical data of same aircraft and fleet wide fault data base and refine diagnostic decision. Advanced 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:

- Corrective
- Preventive
- 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 missions. Maintenance planner schedules the intelligent maintenance plan, validates with feedback from Resource Management 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 Planner:**
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.

**3.3.4 Key Tools related to ISHM Design**

**3.3.4.1 Functional Failure Analysis Tool**
The first step in ISHM capability design is to clearly define how the vehicle and its subsystems function and how they can potentially fail. A clear understanding and representation of the functions to be accomplished provides the framework for capturing how a system can fail, the manifestations of the failure, its consequences, and its impact on the vehicle as a whole. FFA tool plays an important role in the development of ISHM System, CBM candidate selection, refining system performance matrices, trade-off study in the design of ISHM architecture.
3.3.4.2 Maintenance Strategy Tool

Maintenance Strategy [1] aims to map all fault modes at individual and LRU levels to different maintenance categories. RCM analysis is the foundation to establish a framework for candidate selection. The decision logic is based on existing guidelines: SAE JA1011, SAE JA1012, NAVAIR 00-25-403 and ATA MSG-3 with suitable modification. After fault consequence check, maintenance options for each fault type of a LRU are short listed based on technical feasibility only. Cost effectiveness and risk are computed for each selected option of the fault type. Best maintenance option or combinations of options are selected for LRU by solving optimization problem which maximizes availability, ROI of selected option and minimizes risk at the LRU level.
4. Role of ISHM Framework in Certification

The Figure 4-1 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

From the V&V roadmap [6], it is very much evident that different facilities are needed towards V&V, certification & qualification of ISHM technologies. ISHM simulation Framework plays multi-role being as a single platform.

5. Lessons Learnt

Key findings through the development of Airbus DS ISHM program and Simulation Framework as validation platform are summarized here.
• Enhanced Diagnostics (to compute health index of degrading sub-system component), enhanced fault isolation (to isolate incipient faults), heath aggregation in higher levels (sub-system, system, operation) and prognostics (to compute remaining useful life) are key enablers for PHM functions.

• During early stage of ISHM life cycle, in the absence of in-service/test flight data, physics based model plays an important role. Physics based model undergoes continuous maturity with the help of in-service data.

• Once put into service, the PHM functions have to be continuously validated to detect potential drifts between initial design / implementation and real life behaviour [14].

• Initial PHM design/model (technical choices: algorithms, learning database, etc.) is subjected to potential changes in operational (change in the operational cycles, loading of the system) and environmental (heat, humidity for instance) conditions [14].

• The potential evolution of the maintenance operations may have an impact on the validity of PHM functions [14].

• The integration of structural health monitoring is still at a low TRL compared to system because of the complexity of modeling the characteristics of the SHM sensing system, the damage characteristic of composite material and required processing, diagnostic and prognostic capabilities.

Few of the important insights related to Simulation and ISHM certification are given in the Figure 5-1.

<table>
<thead>
<tr>
<th>Issues with Simulation Framework</th>
<th>Approach</th>
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<tbody>
<tr>
<td>1. Better the fidelity of modelling, more effective Simulation Framework</td>
<td>• Trade-off needed between high fidelity model development versus cost</td>
</tr>
<tr>
<td>2. Huge investment for high fidelity model development</td>
<td>• Mature technology with realistic flight data during control introduction to service (during maintenance benefit phase)</td>
</tr>
<tr>
<td>3. Difficult to model uncertain environment and complex sub-system</td>
<td>• Hybrid approach using both model based and data driven techniques</td>
</tr>
<tr>
<td>4. Vendors are not ready to provide critical data. How to model in the absence of vendor data?</td>
<td>• Provision to integrate with test RIGs and flight data</td>
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<tr>
<td>5. For new aircraft no flight data available</td>
<td>• Appropriate strategy during technology maturation</td>
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<tr>
<td>6. ISHM technologies (viz. prognostics, etc.) is evolving</td>
<td>• Knowledge on existing and related guidelines, standards and innovate</td>
</tr>
<tr>
<td>7. No certification standards from regulatory bodies</td>
<td>• Framework has to be qualified</td>
</tr>
<tr>
<td>8. Use as a V&amp;V platform</td>
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Figure 5-1: ISHM Simulation Framework challenges & solution approaches
6. Conclusion

The survey of works towards ISHM certification, suggested customization and experiences support SHM development as well. However, there exists a significant challenge in certification of SHM, particularly for composite structures. Modelling of sensors, Fault Progression model are some of the key challenging areas. In general, 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 gathering of direct evidence for faults effects related to V&V of enhanced diagnostics and 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 4-1 (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. [20]).

This study may give enough confidence to ISHM community towards achieving maintenance credit through implementation of this technology.

7. Acknowledgments

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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 Healt Usage Monitoring System
IA Integrity Assessment
ICA Instruction for Continued Airworthiness
ISHM Integrated System Health Monitoring
IVHM Integrated Vehicle Health 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

References


**BIographies**

**Matthias Buderath** - Aeronautical Engineer with more than 30 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 Airbus Defence and Space R&T Strategy and Senior Expert Integrated System / Aircraft Health Monitoring and Management. He is member of international Working Groups covering Through Life Cycle Management, Integrated System Health Management and Structural Health Management. He has published more than 80 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 18 years of experience in the field of IVHM, Simulation of Aircraft Systems and Avionics. 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 IVHM, Navigation systems, Avionics and Simulation technologies. Partha published several papers in the fields of estimation, signal processing and IVHM in national as well as international conferences and journals. Partha, in his current role at Airbus Group India, Bangalore is working on devising ISHM technologies for aviation systems with focus on complete vehicle health, robust implementation and certification of the developed technologies.

**Harsha Gururaja Rao** – Software Engineer with more than 5 years of experience in designing & developing enterprise level Software Applications. Harsha has a Bachelor of Engineering Degree in Computer Science from the Visvesaraya Technological University. Harsha, in his current role as an Engineer at Airbus India, Bangalore is working on developing Software for IVHM technologies and other enterprise applications to meet Aerospace & Defense Business Systems requirements.