



AEROSPACE RECOMMENDED PRACTICE

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IVHM Concepts, Technology and Implementation Overview

RATIONALE

This SAE Aerospace Recommended Practice (ARP) provides an overview of the concepts, technologies, and implementation practices associated with designing and implementing an Integrated Vehicle Health Management (IVHM) capability on an aerospace platform. This document is intended to provide guidance and recommended best practices for engineers and stakeholders to initiate the design and implementation requirements for an IVHM solution. This document is also relevant to other industrial sectors and vehicles outside of aerospace.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) examines a comprehensive construct of an Integrated Vehicle Health Management (IVHM) capability. This document provides a top-level view of the concepts, technology, and implementation practices associated with IVHM. This keystone document of the SAE HM-1 Committee is not intended as a legal document and does not provide detailed implementation steps, but does address general implementation concerns and potential benefits. Figure 1 provides a document flow map of the documents currently in work or planned by the Committee. The documents shown below will provide the recommended practices for IVHM implementation. This document map reflects the current SAE IVHM document configuration as of the date of publication. Future documents that are released will be included in the flow map in future updates of this document.

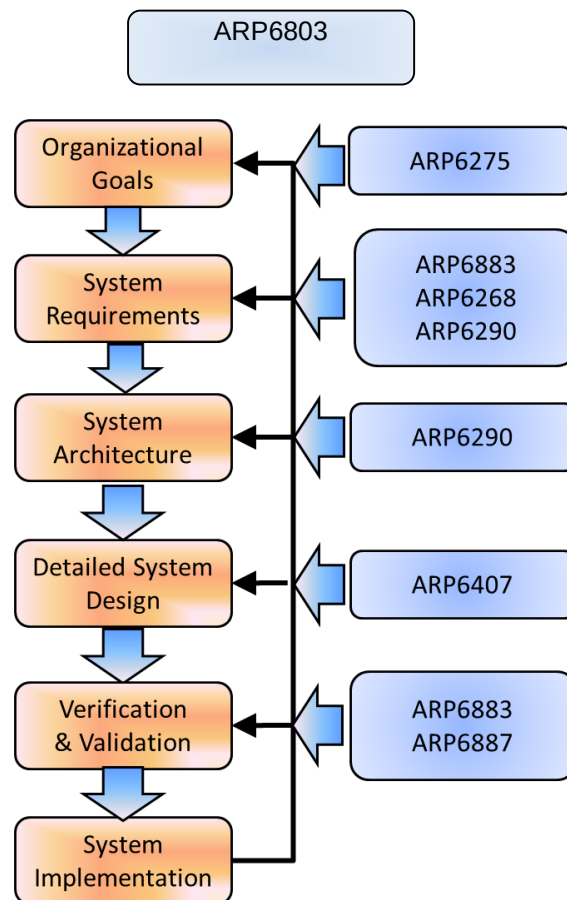


Figure 1 - HM-1 document flow map

An indication of the scope of IVHM is diagrammed in Figure 2. When an organization decides to implement an IVHM capability as part of their product sustainment strategy, the decision must consider the business objectives and user perspectives driving the decision, the system architecture and design to support the impetus, the Technology Readiness Level (TRL) or maturity of the technologies involved, the unique aspects of the operational environment and infrastructure, and the tools required to support the IVHM life cycle. This document discusses significant aspects and considerations of the interrelated IVHM elements listed in this diagram.

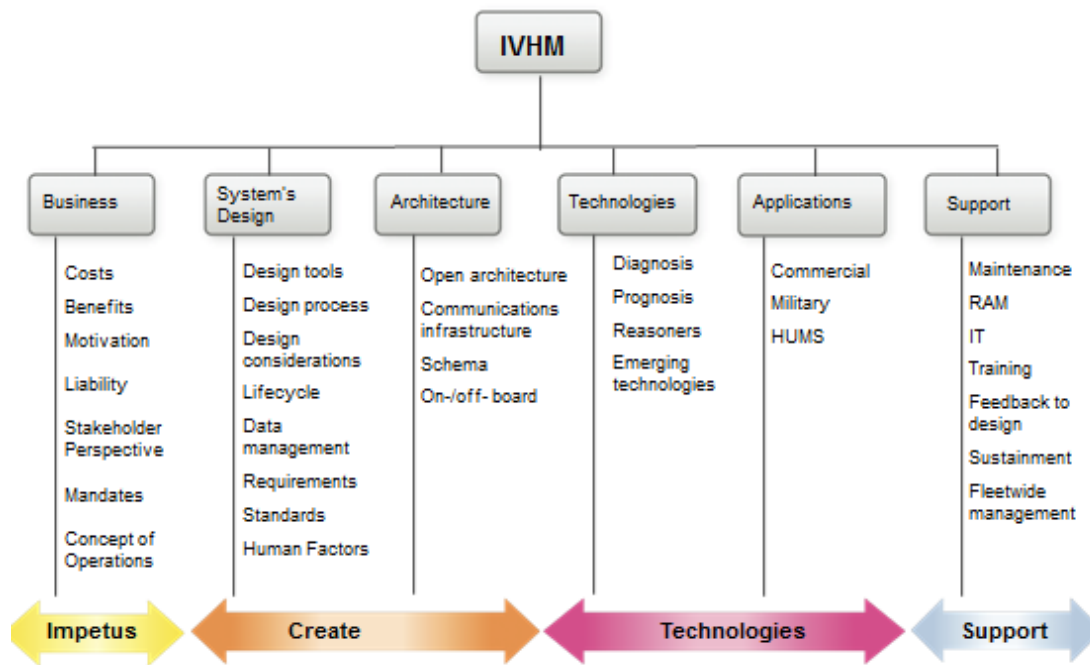


Figure 2 - IVHM taxonomy

1.1 Purpose

Aerospace asset owners, operators, and maintainers are under increasing pressure to reduce maintenance and operations costs, to maximize system and component useful life, to reduce maintenance down time, and to increase availability, while not compromising safety. At the same time, maintenance personnel need to know what component or system requires maintenance and what maintenance actions must be taken. Operations personnel need to know when an aircraft can be operated reliably and when it can no longer be operated without incurring an unacceptable risk of failure. Additionally, fleet management personnel need to know when an aircraft should be scheduled for maintenance, what components are required in advance of a scheduled maintenance event to reduce logistics-related maintenance delays, and what impact these maintenance events will have on the availability of resources with respect to the overall fleet. All this needs to be achieved with, at a minimum, no adverse impact on existing safety levels. As a result, the objective for implementing an IVHM capability is to provide unambiguous actionable information on the health of aircraft systems and components that can be used to reduce operating and maintenance costs while taking into consideration the life cycle cost and satisfaction of safety requirements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1587	Aircraft Gas Turbine Engine Health Management System Guide
ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
AIR5113	Legal Issues Associated with the Use of Probabilistic Design Methods
ARP5580	Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications
ARP5783	Health and Usage Monitoring Metrics, Monitoring the Monitor
ARP6275	Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System
JA1011	Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes
JA6097	Using a System Reliability Model to Optimize Maintenance Costs – A Best Practices Guide
GEIA-HB-649	Implementation Guide for Configuration Management

2.1.2 SAE ANSI Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ANSI/EIA-649	National Consensus Standard for Configuration Management
ANSI/EIA-836	Configuration Management - Data Exchange and Interoperability

2.1.3 SAE ISBN Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ISBN 978-0-7680-6432-2	Integrated Vehicle Health Management - Perspectives on an Emerging Field, Jennions, I.K., editor, 2011
ISBN 978-0-7680-7645-5	Integrated Vehicle Health Management - Business Case Theory and Practice, Jennions, I.K., editor, 2012
ISBN 978-0-7680-7952-4	Integrated Vehicle Health Management – The Technology, Jennions, I.K., editor, 2013
ISBN 978-0-7680-8067-4	Integrated Vehicle Health Management – Essential Reading, Jennions, I.K., editor, 201
ISBN 978-0-7680-8088-9	Integrated Vehicle Health Management – Implementations and Lessons Learned, Jennions, I.K., editor, 2014

2.1.4 SAE Conferences Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Shao, G., Goldstein, D., Kim, K., Nwadiogbu, E., Proenza, R., Tran, M., Williams, D. "Creating a System Architecture for a Vehicle Condition-based Maintenance System", Aerospace Electronics and Avionics Conference, Phoenix, AZ 2012.

2.1.5 AHS Publications

Available from the American Helicopter Society, 217 N Washington St, Alexandria, VA 22314, Tel. (703) 684-6777, www.vtol.org.

Dora, Ray, Wright, Johnny, Hess, Robert, and Boydstun, Byron. "Utility of the IMD HUMS in an Operational Setting on the UH-60L Blackhawk", American Helicopter Society, Baltimore, Maryland. 2004.

Hasty, Joshua C., Speaks, Kenneth W., and Kennedy, Joshua S. "Comparison of HUMS Benefits – A Readiness Approach", American Helicopter Society, Grapevine, Texas. 2009.

2.1.6 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE 610.12 Standard Glossary of Software Engineering Terminology

IEEE 1012-2004 Standard for Software Verification and Validation, June 2005

IEEE 1232-2010 Artificial Intelligence Exchange and Service Tie to All Test Environments

Wilmering, Timothy J. "A Practical Examination of Model Reuse" IEEE Autotestcon, Salt Lake City, Utah. 2008

Ofsthun, Stan, and Abdelwahed, Sherif, "Practical Applications of Timed Failure Propagation Graphs For Vehicle Diagnosis," IEEE Autotestcon, Baltimore, Maryland. 2007

Sheppard, John, "Accounting For False Indication In A Bayesian Diagnostics Framework," IEEE Autotestcon, Anaheim, California. 2003.

Lee, Gao, Schneeman, "Sensor Network and Information Interoperability – Integrating IEEE 1451 with MIMOSA and OSA-CBM," IEEE Instrumentation and Measurement Technology Conference, Huntsville, Alabama. 2002

2.1.7 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160F RTCA Document, "Environmental conditions and test procedures for airborne equipment," DO-160F (EUROCAE ED-14F), Dec 2007

DO-178C RTCA Document, "Software considerations in airborne systems and equipment certification," Dec 13, 2011

DO-254 Design Assurance Guidance for Airborne Electronic Hardware, July 5, 2005

DO-278 RTCA Document, "Guidelines for communication, navigation, surveillance and air traffic management (CNS/ATM) system software integrity assurance," DO-278 (EUROCAE ED-109), Mar 2002

2.1.8 U.S. Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

- AD-2009-0328 FAA Airworthiness Directive: General Electric Company (GE) CF34-1A, CF34-3A, and CF34-3B Series Turbofan Engines. Docket No. FAA-2009-0328; Directorate Identifier 2008-NE-44-AD; Amendment 39-16103; AD 2009-24-11. Download from:
http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAD.nsf/0/2fd050be5fe7a5198625767e00540421!OpenDocument&ExpandSection=-5
- AC 25.1309 Federal Aviation Administration (FAA) Advisory Circular, "System design and analysis," AC 25.1309-1A, June 1988.
- AD-A066-579 United States Department of Defense (DoD) Report, "Reliability-Centered Maintenance", Nowlan F. Stanley, and Howard F. Heap, 1978.
- CAST-15 FAA Certification Authorities Software Team (CAST), Merging High-Level and Low-Level Requirements, Position Paper, CAST-15, February 2003.
- MIL-HDBK-502A Product Support Analysis

2.1.9 Applicable References

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- Rausland, M., and A. Høyland (2004). *System Reliability Theory – Models, Statistical Methods, and Applications*, "2nd Edition", John Wiley & Sons, ISBN 978-0-4714-7133-2.
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- Vachtsevanos, G., Lewis, F. L., Roemer, M., Hess, A., Wu, B. (2006). *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*, John Wiley & Sons, ISBN: 0-471-72999-1.
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2.2 Acronyms and Abbreviations

A4A: Airlines for America

AC: Advisory Circular

ACM: Air Cycle Machine

AD: Airworthiness Directive

AHS: American Helicopter Society

AI: Artificial Intelligence

ALIS: Autonomic Logistics Information System

ALE: Application Level Events

AMOC: Alternative Means of Compliance

ANSI: American National Standards Institute

APU: Auxiliary Power Unit

ATA: Air Transport Association

ATC: Air Traffic Control

B2B: Business to Business

BIT: Built In Test

BITE: Built In Test Equipment

BoM: Bill of Materials

CAD/CAM: Computer Aided Design/Computer Aided Manufacturing

CBM: Condition Based Maintenance

Cert: Certification

CIR: Common Interoperability Register

CONOPS: Concept of Operations

COTS: Commercial Off The Shelf

CPS: Cyber-Physical Systems

DA: Data Access

DFR: Design for Reliability

DoD: Department of Defense

DoDAF: Department of Defense Architecture Framework

DR: Dispatch Reliability

EASA: European Aviation Safety Agency

ECTM: Engine Condition Trend Monitoring

EHM: Engine Health Monitoring (or Management)

EICAS: Engine Indication and Crew Alerting System

EPC: Electronic Product Code

ERP: Enterprise Resource Planning

ETOPS: Extended Twin Operations

EVM: Engine Vibration Monitoring

FAA: Federal Aviation Administration

FDM: Flight Data Monitoring

FDR: Flight Data Recording

FHA: Functional Hazard Analysis

FFT: Fast Fourier Transform

FMEA: Failure Modes and Effects Analysis

FMECA: Failure Modes, Effects, and Criticality Analysis

FOQA: Flight Operations Quality Assurance

FRACAS: Failure Reporting, Analysis and Corrective Action System

GA: Genetic Algorithm

GEIA: Government Electronics and Information Technology Association

GVA: Generic Vehicle Architecture

HM: Health Management

HUMS: Health and Usage Monitoring Systems

HVDC: High Voltage Direct Current

H/W: Hardware

IATA: International Air Transport Association

IBM: International Business Machines

ICAO: International Civil Aviation Organization

IEEE: Institute of Electrical and Electronics Engineers

IETM: Interactive Electronic Technical Manuals

IMD: Integrated Mechanical Diagnostics

IPHM: Integrated Portfolio Health Management

ISO: International Standards Organization

IT: Information Technology

IVHM: Integrated Vehicle Health Management

KPI: Key Performance Indicator

LSA: Logistics Support Analysis

LRU: Line Replaceable Unit

MAA: Military Aviation Authority

MoE: Measures of Effectiveness

MoP: Measures of Performance

MRO: Maintenance Repair and Overhaul

MES: Manufacturing Execution System

MIMOSA: Maintenance Information Open System Alliance

ML: Machine Learning

MoD: Ministry of Defense

MSG 3: Maintenance Steering Group 3

NASA: National Aeronautics and Space Administration

NDI: Non-Destructive Inspection

NEA: Nitrogen Enriched Air

NFF: No Fault Found

NN: Neural Net

O&M: Operations and Maintenance

OCM: On-condition Maintenance

ODM: Oil Debris Monitoring

OEM: Original Equipment Manufacturer

Ops: Operations

OSA-CBM: Open System Architecture for Condition Based Maintenance

OSA-EAI: Open System Architecture for Enterprise Application Integration

P-F interval: Potential to Functional failure time or interval, or prognostic horizon

PDA: Personal Digital Assistant

PLM: Product Lifecycle Management

PLSC: Product Life Support Cycle

PM: Preventative Maintenance

RM&S: Reliability, Maintainability, and Safety

RCM: Reliability Centered Maintenance

RFID: Radio Frequency Identification

RTCA: Radio Technical Commission for Aeronautics

RT&B: Rotor Track and Balance

RUL: Remaining Useful Life

SB: Service Bulletin

SSA: System Safety Analysis

SATAA: Sense, Acquire, Transfer, Analyze, Act

SE: Systems Engineering

SHEL: Safety Health Environment and Legislation

SHM: Structural Health Monitoring

S/N: Signal-to-Noise

SOA: Service Oriented Architecture

STC: Supplemental Type Certificate

STEP: Standard for the Exchange of Product data

TBO: Time Between Overhaul

TC: Type Certificate

TCP-IP: Transmission Control Protocol – Internet Protocol

TRL: Technology Readiness Level

URL: Uniform Resource Locator

V&V: Verification and Validation

3. IVHM CONCEPTS

This section describes the history and evolution of IVHM and the conceptual process of an IVHM capability.

3.1 History and Evolution of IVHM

The evolution of IVHM can be traced through the historical development of maintenance itself. As the complexity of vehicles grew over time, the approaches to maintenance evolved. The initial phase was characterized by simple machinery built using locally available materials which could be fashioned by craftsmen with little external support. Maintenance consisted of servicing routines which were predominantly lubrication and environmental protection as well as inspections. Most assets were repaired when broken. It was very apparent to the asset owners and maintainers when machinery failed.

The second phase gradually developed throughout the industrial revolution when the complexity of machinery increased. A major factor for change was systems that contained stored energy (such as steam boilers) which eventually required safety devices to avoid catastrophic failure consequences. These devices could start to degrade and not be noticed by the asset owners and maintainers, which influenced the introduction of functional tests (such as relief valve testing). The aerospace sector was at the forefront of technology with complexity of machinery in the early 1900s. The concept of preventative maintenance was later developed to attempt to improve the reliability.

As commercial airlines started to introduce jet aircraft into their fleets in the 1950s, the airlines found that the old approaches to maintenance, combined with the increased complexity of these new aircraft, were increasing maintenance costs and down time to unsustainable levels. By the late 1950s, a general consensus had formed across the airline industry that a basic assumption about preventive maintenance, namely that increasing preventive maintenance would improve reliability, was actually incorrect. In 1960, a task force composed of representatives from the Federal Aviation Administration (FAA) and the airlines was formed to assess the capabilities of preventive maintenance. Based on their work, the entire approach to aircraft maintenance would eventually change from a protocol based on preventive maintenance and fixed interval inspections and component replacement to one that performed maintenance only when it was needed, called On-Condition Maintenance (OCM).

Over the next few years, approaches to maintenance continued to evolve. In 1968, the Air Transport Association (ATA) published “MSG-1 - Maintenance Evaluation and Program Development”, based on a basic decision tree approach developed by United Airlines in 1965 for evaluating maintenance strategies for aircraft systems and the best course of action to address component failures. MSG-1 formalized the process as an industry-wide accepted best practice, and the Boeing 747 became the first platform to use the process that would become known as “Reliability-Centered Maintenance” (RCM).

In the late 1970s, the US Air Force contracted with United Airlines to document the RCM process. The report produced from this effort, AD-A066-579 “Reliability Centered Maintenance” (Nolan & Heap 1978), included an empirical study of failure patterns that contradicted many long-held assumptions of how failures occurred. One of the most surprising findings of that study was that functional failures for complex systems were typically random in nature. This revelation showed that traditional approaches to maintenance, using fixed interval inspections and component replacement, was of little or no consequence; it could only be applied to age related (wear out) failures. The RCM report also acknowledged that OCM, along with redesign and/or redundancies (for critical systems), were the only practical and effective approaches to deal with most failures.

IVHM was subsequently conceived by the National Aeronautics and Space Administration (NASA) as a means of integrating a disparate approach to Vehicle Health Management, with certain stakeholders applying predictive maintenance to their part of the space vehicle (engine, airframe, etc.) This vehicle centric view was fine when there was one or a very limited set of vehicles in a fleet. This is not the case in most other applications. “*Integrated Vehicle Health Management – Perspectives on an Emerging Field*” provides a thorough background of the evolution of IVHM, which aimed to provide a holistic platform centric view of the vehicle. This platform centric perspective placed great emphasis on Systems Engineering processes.

Today, IVHM is evolving from a platform centric perspective to a portfolio centric perspective, where different types of fleets contribute to an enterprise’s ability to deliver value. For example, most large utility companies have a mix of ‘fleets’ (gas, coal, renewable, nuclear power stations), which can be utilized according to business criteria (such as fuel prices). Maintenance policies and procedures need to be sufficiently flexible to keep up with this diverse portfolio.

The future of IVHM will lead to greater automation, which implies diluting to some degree the human expertise currently involved in maintaining vehicles, and, in some cases, manufacturing vehicles that can self-maintain and become damage tolerant. As unmanned platforms become more prevalent, IVHM will be a valuable tool to capture expert diagnostic and prognostic knowledge through the use of artificial intelligence, machine learning, and statistical techniques. Eventually, predictive maintenance will become ever more automated and commoditized as an integral expected part of any vehicle’s design.

3.2 An Overview of IVHM Capability

The SAE IVHM Steering Group defines IVHM as: “The unified capability of a system of systems to assess current or future state of member system health and integrate that picture of system health within a framework of available resources and operational demand.” As such, the data flow through an IVHM capability is typically described as a five-stage process, comprising the stages of: Sense, Acquire, Transfer, Analyze and Act (SATAA).

Figure 3 shows a typical aerospace IVHM capability for a commercial aircraft. The *sense* and *acquire* stages of an IVHM capability reside predominantly onboard. The *transfer* stage spans both onboard and on-ground systems, and the *analyze* and *act* stages are predominantly on-ground.

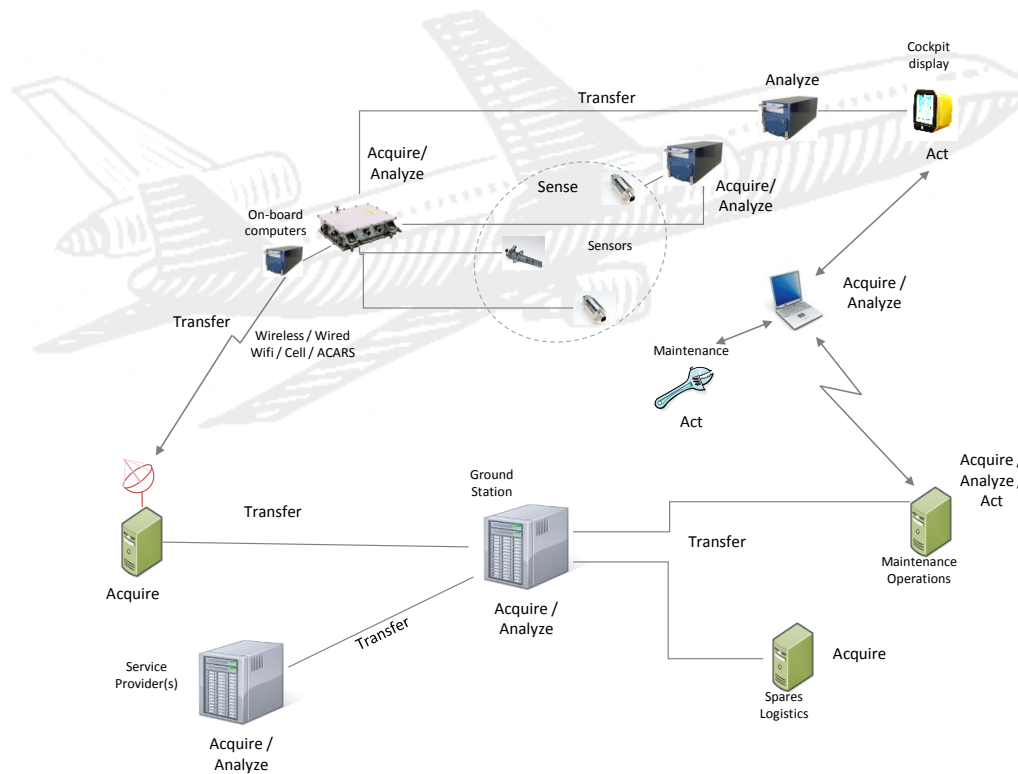


Figure 3 - IVHM capability infrastructure

The Sense stage involves the determination of the value of one or more physical parameters at given sampling rates, which are used to determine the condition of the vehicle components being monitored. The Sense stage may include physical parameters, such as pressure, temperature, speed, force, and vibration, etc., but may also include the time of utilization or cycle count. The Sense function includes any low level signal conditioning and amplification as well as the conversion of the sensor signal to a digital representation of the measurand. The sensors may be permanently installed or may be temporarily fitted for diagnostic purposes. In addition, sensed data may be crew observed data or manually sensed data. In order for manually sensed data to be used by the IVHM capability, the data must be converted to a digital representation accessible by the IVHM capability. Further, data security and data integrity are high priorities in this stage.

The Acquisition stage involves the collection of digitized data at the appropriate time or state. Many aircraft utilize a central data acquisition system to collect and record the sensor data for processing by a central function onboard the aircraft. The captured data might be snapshot data at specific conditions, events triggered by parameter exceedances, or continuous data. Some data processing and analysis, for plausibility checks or compression, may also be applied. For most recent airplane fleets, the OEM typically provides the data acquisition systems as part of the aircraft avionics suite, such as a central maintenance computer or a dedicated monitoring or data recording system. If manually sensed data is needed, the acquisition element must be considered in order to ensure the data is available to the IVHM capability.

The Transfer stage involves moving data between process stages. Typically, this process will consist of a transfer of digital data between computational resources. There may be multiple transfers in an IVHM function. The transfer of data is a very significant part of the IVHM capability, as the options will influence the choice of architecture and how effective the system can be in detecting faults that may lead to failures or detecting rapid degradation. If sufficient data can be transferred to the ground, fleet wide analysis of the data can be performed using more flexible and robust architectures. If a sufficient amount of data cannot be transferred, such as high bandwidth vibration signals, then onboard analysis may be required. Additionally, if the data is transferred infrequently, the allowable time interval between detection of the condition by the IVHM capability and failure, referred to as the Potential to Failure (P-F) interval or the prognostic horizon, will need to be longer. Data transfer is typically unidirectional. In some cases the reverse direction may be used to request additional data or to update software on the vehicle (commonly used with space probes). Data security is a high priority in this stage.

The Analyze stage involves the manipulation of the acquired data to either enhance its use and/or to create directly actionable information. Analysis of IVHM data covers the various functions that may be monitored and may be performed onboard or off-board. Traditionally the analysis was confined to integrity and performance data, but has been expanded into structures, fluids, and vibration disciplines. In some vehicle applications, preliminary analysis may be carried out onboard using reasoners for specific systems. Whether onboard or off-board, the analysis will likely include feature extraction, data sampling, data compression or other techniques to reduce the volume of data that needs to be transferred from the vehicle and/or stored in the ground-based system. To handle the amount of data involved, the analysis is often automated with thresholds being refined as aircraft enter service. Signals or readings outside the expected range are then passed to engineers for in-depth analysis and future rule refinement.

The Act stage provides information to asset owners and maintainers to make maintenance, logistics, and operational decisions regarding their vehicle assets. Depending on the type of information and the action required, the stakeholders interfacing with the IVHM capability typically include the flight crew, the line and depot maintenance personnel, and the maintenance engineering analysts. Since crew action is rarely required, IVHM information is not normally shown to the crew. The key element in this process is to ensure that specific trouble-shooting, maintenance, and logistics support advice is given to the asset owners and maintainers in time to avoid potential events or reduce their impact.

Some IVHM capabilities reside entirely onboard the asset and provide all of the above mentioned stages while the asset is flying. These onboard capabilities are obligated to immediately advise the crew of changing conditions that require their attention. Other IVHM capabilities reside entirely on the ground, such as some oil debris/condition monitoring systems that determine lubrication system and oil health by analyzing a used sample of oil. While there are hybrid IVHM solutions that perform a mixture of onboard and off-board analysis, the more traditional design is one where sensors acquire data during flight and the data is either transferred immediately or stored and transferred to a ground station after landing.

For more information about IVHM architecture (see 5.5).

4. IVHM BUSINESS CASE

As with any initiative, a motivation must exist for developing and implementing an IVHM capability. Thus, the business aspects of justifying, implementing, and maintaining an IVHM capability for any commercial or military platform need to be considered. When developing the business case analysis, the stakeholders/users, the impacted systems and subsystems, and the cost and benefits must be identified. The value proposition must be clearly derived, understood, and quantified.

4.1 Motivation for IVHM

The motivation for implementing an IVHM capability is generally to enhance safety, to increase availability (reduce passenger inconvenience for commercial applications), to increase mission effectiveness (for military applications), and to reduce the cost of operation and maintenance. Commercial aerospace asset owners and maintainers must meet the safety requirements mandated by the regulatory agencies; to do otherwise could result in severe fines, or the airline being shut down or going out of business of their own accord. Hence, the current motivation for an IVHM capability is not focused on meeting the safety requirements, but instead on enhancing the safety of the operations. The method by which an IVHM capability can enhance safety is by sensing impending faults that may impact aircraft dispatch reliability and passenger convenience before they occur.

Typically, the health of a component deteriorates with use of the component. As the component starts to degrade, (e.g., the seal in an actuator starts to wear), its health reduces and there comes a point, defined as the point of incipient failure, when this degradation can be seen by an IVHM capability (Figure 4.) This point represents the start of the Potential to Failure (P-F) interval (also referred to as the prognostic horizon). The P-F interval can be described as the interval between the incipient failure when the component continues to operate but in a continually degrading state until the eventual functional failure of the component. For effective IVHM to be possible, the P-F interval must be long enough for remedial maintenance actions to be taken, or an adaptive control mechanism must be present to enable contingency reallocation of control to other components or subsystems. An enhancement to safety is achieved by avoiding or adapting to these failures.

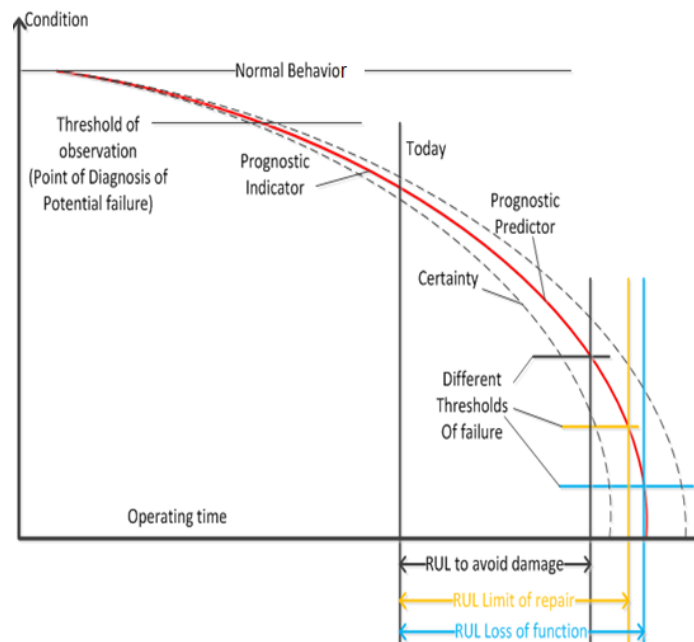


Figure 4 - Potential to Failure (P-F) interval showing different thresholds of failure and corresponding remaining useful life predictions

A primary motivation for IVHM is to turn unscheduled maintenance (the sudden surprise failure) into scheduled maintenance based on an IVHM annunciation. For example, the failure of a battery to start a car on the first cold day of the year is indicative that the battery must have already been in a degraded state for some time but the temperature conditions did not sufficiently rob the battery of its ability to perform its function, so the degraded state was not visible to the human operators and maintainers. However, continuous or regular monitoring of the cranking amps or the state of charge of the battery, could have revealed a degraded operating state and provided the warning necessary to change the battery *before* it degraded further or other conditions (such as the oncoming winter) exacerbated the issue.

Some failures have “no impact” on the overall operation of the system. Even though functional failures are monitored, a physical failure could occur without a functional failure. For example, a seal may be wearing and may eventually break, but if the seal wear does not affect the measurable functional performance of the actuator, then the seal does not yet require attention. Applying IVHM to these types of failures should be evaluated thoroughly for the practical benefit to monitor for these failures before implementing the capability. Practical benefits may include an economic benefit leading to longer life of the component or increased time between maintenance actions, an operational benefit by avoiding a service disruption, or a safety benefit by identifying the progression of a failure that could become significant.

Along with these different impact levels, P-F intervals ranging from instant to many missions can be overlaid. When very short P-F intervals are coupled with high impact/consequences of failure, the control system, not the IVHM capability, should have the authority to shut down or isolate the system safely. This action would need to happen without human intervention since the P-F interval is so short. Further, the shutting down or isolation of the system must not affect the ability to control the overall system (e.g., the airplane). In the more normal situation where a sufficiently long P-F time scale exists, onboard systems, alarms and warnings, can alert the responsible person to take informed action. Further, if the data is transferred infrequently to the ground, the P-F interval will need to be longer to ensure adequate response time after the receipt of data. Based on the above descriptions, IVHM is almost always a passive system as the P-F interval is usually considerably greater than a single mission. The IVHM information can be received at a central ground-based control room, where the data is acted upon by initiating appropriate maintenance actions.

An additional layer of benefit to consider is increased yield from maintenance resources: For example, the increased understanding of failure rates and equipment behavior would help to optimize inventory (invariably a reduction). Capital not invested in spares inventory can be invested in an earning segment of the business.

Finally, the OEM has a motivation for collecting the data available from an IVHM capability. The analysis of failure patterns and the differences in failures between the operators around the world can provide many benefits which may assist the OEM in the redesign of the components and systems. Future designs may be able to reduce or even eliminate these failures or provide an early indication to operators of future likely trends and behaviors. Section 5.2.1 addresses the subject in more detail.

4.2 Stakeholder Perspectives

The role of the stakeholders, how they relate to each other and to the assets involved, is important to understanding the stakeholders' perceived value of the IVHM capability. The other important aspect about stakeholders is their attitudes to what constitutes 'functional failure', and how variance in this regard among the stakeholders may be resolved.

This latter concern is highlighted in the P-F Diagram shown in Figure 4, which is often used to explain fundamental principles of condition based maintenance. The level of functional failure may not be established or agreed. For example, the differing attitudes of the maintenance or reliability manager may differ from that of the operations manager.

As a normal part of a Systems Engineering (SE) approach, one of the early stages in an ideal SE project lifecycle, even before functional requirements are elicited, is to conduct stakeholder analysis to identify who has interests, power, or influence over the deliverables and the conduct of the project and subsequent use.

Stakeholders are typically identified by considering the following:

- Who has responsibility for operating or sustaining the IVHM capability?
- Who benefits from implementing the IVHM capability?
- Who has responsibility for the procurement of parts for implementing and sustaining the IVHM capability?
- Who has responsibility for regulating the IVHM capability?
- Who opposes the implementation of the IVHM capability?
- Who (other subsystem) interacts with the IVHM capability?

Tactics for dealing with stakeholders may be based on an analysis of the people and the sources or the basis for their power or influence. The attributes of power may be derived from the following (French & Raven 1959):

- Positional power – by virtue of rank, seniority in an organization or social structure
- Referent Power – by who you know
- Expert Power – by what you know, and its accepted recognition
- Reward Power – by the ability to grant reward (which may be much wider than merely financial)
- Coercive power – by the ability to withhold reward
- Informational power – by the ability to share or withhold relevant information

For any given situation, the stakeholder analysis will identify these important attributes and will create a position from which to start to derive the value proposition and the functional requirements for the implementation of an IVHM capability. Figure 5 shows a typical set of stakeholders and the value propositions associated with each.