STATE-OF-THE-ART IN INTEGRATED VEHICLE HEALTH MANAGEMENT

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Abstract: Integrated Vehicle Health Management (IVHM) is the collection of data relevant to the present and future performance of a vehicle system and its transformation into information that can be used to support operational decisions. This design and operation concept embraces an integration of sensors, communication technologies and artificial intelligence in order to provide vehicle-wide abilities to diagnose problems and recommend solutions. This paper aims to report the state-of-the-art of IVHM research by presenting a systematic review of the literature. Literature from different sources is collated and analysed, and the major emerging themes are presented. On this basis, the paper describes the IVHM concept and its evolution, discusses configurations and existing applications along with potential benefits and barriers to adoption, summarises design guidelines and available methods, and identifies future research challenges.

Keywords: IVHM; review; diagnostics; prognostics; condition-based

INTRODUCTION: The concept of Integrated Vehicle Health Management (IVHM) is an evolution of diagnostic and prognostic systems [1], [2]. The goal is to implement a strategy for prognostics and health management (PHM) that enables continuous monitoring and real-time assessment of vehicle functional health, predicts remaining useful life of components and systems, and uses this information to improve operational decision, including maintenance planning. Maintenance operations benefit from reduced occurrences of unexpected faults as the health management system will provide early identification of failure precursors, while condition-based maintenance (CBM) is enabled which can enhance availability, mission reliability, system life and affordability [1], [3], [4], [5]. Similarly, command and control functions can be enhanced by an improved awareness of vehicle condition and vehicle situational capabilities, so that safety, utilisation, vehicle turnaround time, and the chance of mission success can improve [2], [6], [7].

Some IVHM systems include logistics management where the availability of current vehicle health information can be used to automatically trigger logistics actions. An example of an IVHM system that comprises both the vehicle and its support infrastructure is the Joint Strike Fighter (JSF) Programme [4]. Here, the vehicle is designed with a fully functional PHM system that performs fault detection, isolation and reconfiguration (FDIR) across numerous components and subsystems and relays aircraft status data to a distributed information system. The information system processes PHM calculations with other information about the vehicle and the logistic cycle and, if maintenance is required, informs the supply chain infrastructure of the need for resources.

IVHM is a potentially valuable strategy for the manufacture and management of vehicle platforms. At present, there is pressure to reduce costs for both military and commercial vehicle operators [6], so much attention is being given to the operational and support activities that contribute a large proportion of the lifecycle costs of modern vehicles. Almost 95% of the lifecycle costs of commercial aircraft are attributable to maintenance activities [8]. Similarly, the US government has found that the cost of operating and supporting a vehicle may exceed the initial purchase price by as much as ten times [9]. In this climate, it is clear that new generations of vehicle platforms will be subject to significant engineering change during their lifecycles to ensure the most cost-effective field performance. The current justification for IVHM on both new and legacy vehicles is the provision of intelligent technology to enable more cost-effective decisions on design, usage, and support [10].

The concept of IVHM has been discussed in the literature for almost a decade [11] yet applications to date appear limited. Although many benefits are evident from the literature, obstacles arise from the need to accurately evaluate the costs and benefits of IVHM. Research to overcome these obstacles requires a thorough and precise understanding of existing knowledge, so the purpose of this paper is to describe the state-of-the-art of IVHM. The study described in this paper takes the form of a systematic literature review. Publication databases were searched using a range of key words associated with IVHM, and then each article identified was reviewed. The outcome of these reviews was the extraction of a set of key findings that together establish the state-of-the-art of IVHM.

RESEARCH APPROACH: The authors' initial approach to this study has been to consider the following questions:

- What is an IVHM system and how is it commonly defined?
- How does IVHM differ from conventional vehicle design and operation practices, and what are the consequences?
- Where are the leading examples of IVHM application?
- Where are the enablers and inhibitors of technical and economic success of IVHM and what are the challenges to address in the future of IVHM development?

The purpose of these questions was to guide the search, with the authors being mindful that existing literature may not be sufficient to allow these to lead directly to key findings.

Search strategy: The search first identified the relevant data sources, time frame and key words. Initially, a broad selection of databases was identified, covering academic journals, conference proceedings, books, technical reports and trade journals. Databases used included IEEE, Scopus, Compendex, Inspec and Aerospace and High Technology Database, along with more traditional library cataloguing systems. The time frame initially included only literature published between 2000 and 2007. However, this was later extended as a consequence of cross checking citations. Keywords used included: PHM, integrated diagnostics, embedded prognostics, remote monitoring, remote diagnosis and management, intelligent sensing, total health management, system-level assessment, informed maintenance and on-board maintenance. The word ‘vehicle’ was often combined as an additional keyword to ensure some direct association with the field of IVHM. The titles of all publications were checked to ensure relevance and abstracts were examined before selecting publications for detailed analysis. An Internet search was also conducted using a similar process and the results of these searches were combined.

Results and analysis: The search key words initially identified some 70 publications. It was established that 34 of them were suitable for review as part of this research but subsequent cross checking increased the list to 42, and the analysis of these publications forms the basis of the findings in this paper.

KEY FINDINGS: The literature review process allowed nine key findings to be established. This section presents each in turn.

Definition of IVHM: There is no generally accepted definition of IVHM [8], yet various authors have proposed their own illustration of the concept (Table I). By comparing the various interpretations, the concept of IVHM can be generalised as ‘the capture of vehicle condition, both current and predicted, and the use of this information to enhance operational decisions, support actions and subsequent business performance’. During the operation of an IVHM system, health data collected from vehicle components, structures and systems are and used to make diagnoses and prognoses of the present and future health of a vehicle. This information is then further processed to formulate appropriate operation and support actions and presented to the people who should execute the actions. An important feature of IVHM is that health information must be used as part of the maintenance planning process instead of merely being processed and archived for later use. This distinguishes health management from health monitoring [12], [13].

A second important feature of IVHM is the notion of integration. The health management system will consider the vehicle as a whole rather than being implemented separately on individual subsystems and components [14], [15]. As an integrated approach, the IVHM system will improve the isolation of the root causes of failures as well as facilitating improved decision making throughout the lifecycle. Although most authors see IVHM as a reliability and maintainability concept, and some link IVHM applications with automated logistics coordination [7], [16], [17] there are those who see the ultimate instantiation of IVHM as a competitive proposition for aftercare service providers [1], [10]. Such authors refer to the increased viability of performance-based arrangements through IVHM however this concept does not appear in any of the definitions.

Finding 1: An IVHM system is a condition monitoring system that delivers value in supporting efficient fault reaction planning. IVHM offers a capability to make intelligent, informed, appropriate decisions about operation, maintenance and logistics based on the assessment of present and future vehicle condition. The IVHM logic is premised on integrating vehicle components and subsystems to both increase the level of health state determination and improve the ability to formulate responses.

Table I - IVHM Definitions

Author (Date)	Definition of IVHM
NASA (1992)	'the capability to efficiently perform checkout, testing, and monitoring of space transportation vehicles, subsystems, and components before, during, and after operation.'…'must support fault-tolerant response including system/subsystem reconfiguration to prevent catastrophic failure; and IVHM must support the planning and scheduling of post-operational maintenance.'
Aaseng (2001)	'all the activities that are performed to understand the state of the vehicle and its components, to restore the vehicle to nominal system status when malfunctions occur, and to minimize safety risks and mission impacts that result from system failures'
Baroth et al. (2001)	an 'effort to coordinate, integrate and apply advanced software, sensors, and design technologies to increase the level of intelligence, autonomy and health state determination and response of future vehicles'
Roemer et al. (2001)	'integrates component, subsystem and system level health monitoring strategies, consisting of anomaly/diagnostic/prognostic technologies, with an integrated modelling architecture that addresses failure mode mitigation and life cycle costs'
Price et al. (2003)	'an example of an intelligence sensing system. The purpose of such system is to detect and measure certain quantities, and to use the information and knowledge obtained from the measured data, and any prior knowledge, to make intelligent, forward-looking decisions and initiate actions'
Paris et al. (2005)	'the process of assessing, preserving, and restoring system functionality across flight and ground systems'
Jakovljevic et al. (2006)	'ensures the reliable capture of the "health status" of the overall aerospace system and helps to prevent its degradation or failure by providing reliable information about problems and faults'
Karsai et al. (2006)	'its goal is to provide better ways for operating and maintaining aerospace vehicles using techniques, such as condition monitoring, anomaly detection, fault isolation, and managing the vehicle operations in the case of faults'

Evolution of the IVHM concept: The acronym IVHM is only used in the aerospace sector although several authors have suggested that IVHM functions can be found in other vehicle types including helicopters, land vehicles and maritime systems [8], [11], [15], [23]. There is also literature that describes potential applications of IVHM to non-vehicle systems, like production machines, industrial process plants or power generation plants [5], [10]. IVHM was first conceptualised by NASA in a report that described IVHM as the highest priority technology for present and future NASA space transportation systems [18], although their concept is said to date back to the early 1970s [6]. Most of the literature on IVHM has been published since the late 1990s with conferences being the most popular dissemination route for research and the 'IEEE Aerospace Conference' being prominent among these. Almost no papers have been published in academic journals but some articles have appeared as special reports, typically from government agencies and military organisations. These articles cover a range of aspects of IVHM, with approximately 35% describing potential impacts or cost-benefit analyses [11], [24], [25], [26]; 15% discussing design approaches [15], [27], [28]; and about 25% focusing on examples of IVHM systems in use or under development [8], [29], [30]. Other topics are related to technology evolution and integration. Most contributions to the literature on IVHM come from prime contractors or government agencies such as NASA, the Boeing Company or the US DoD. There have been relatively few contributions from academic institutions, and those that do exist have originated in the US research centres such as the Applied Research Laboratory at Pennsylvania State University or the Intelligent Control Systems Laboratory at Georgia Institute of Technology [10], [17].

Finding 2: IVHM originated in the aerospace sector in the 1970s and, to date, most contributions have been from industrial, military and governmental organisations involved with developing IVHM systems, typically presented at the IEEE Aerospace Conference after 2000.

Configurations of IVHM systems: An IVHM system comprises a set of sensors and associated data processing hardware and software distributed between the vehicle and its support system. Figure 1 shows an IVHM system for an aircraft in which appropriate sensors are positioned on critical components of the aircraft to monitor the relevant subsystems and state variables. Health and usage data are analysed onboard the vehicle while a reduced subset of the data (due to bandwidth limitations) are also transmitted to a ground support centre for additional analysis. Less critical data can be stored on the aircraft during the flight and accessed post-flight at the ground station. The onboard and ground-based systems monitor vehicle health continuously and predictions are made regarding the remaining life. Then, if necessary, actions are suggested to mitigate any faults or plan the repair or replacement of failing components.

This example illustrates a typical IVHM system configuration however there is a range of different IVHM configurations described in the literature. At the one end of this range all health management functions are incorporated onboard the vehicle, while at the other the data processing is carried out with entirely remotely. Onboard processing increases vehicle autonomy and therefore reduces operation costs and improves response to unexpected events [6], [14]. On the other hand, diverting the analysis of health data to a remote support centre enhances fault forwarding and troubleshooting while reducing the amount of equipment and processing power that is needed onboard the vehicle [8], [28], [30]. The preferred IVHM solution depends on the complexity of the vehicle, mission challenges and operational environment, and is therefore sector specific. For example, the space industry aims for the highest level of vehicle autonomy [5], [14], [31]; whereas the automotive industry is trying to minimise the number of sensors needed for health management and to implement remote diagnosis and maintenance systems [30].

Finding 3: An IVHM system will integrate onboard and remote hardware and software resources to collect, monitor and analyse vehicle health data. IVHM systems can be seen in a range of configurations, depending on the amount of analysis that is performed onboard the vehicle or alternatively diverted to the remote support.

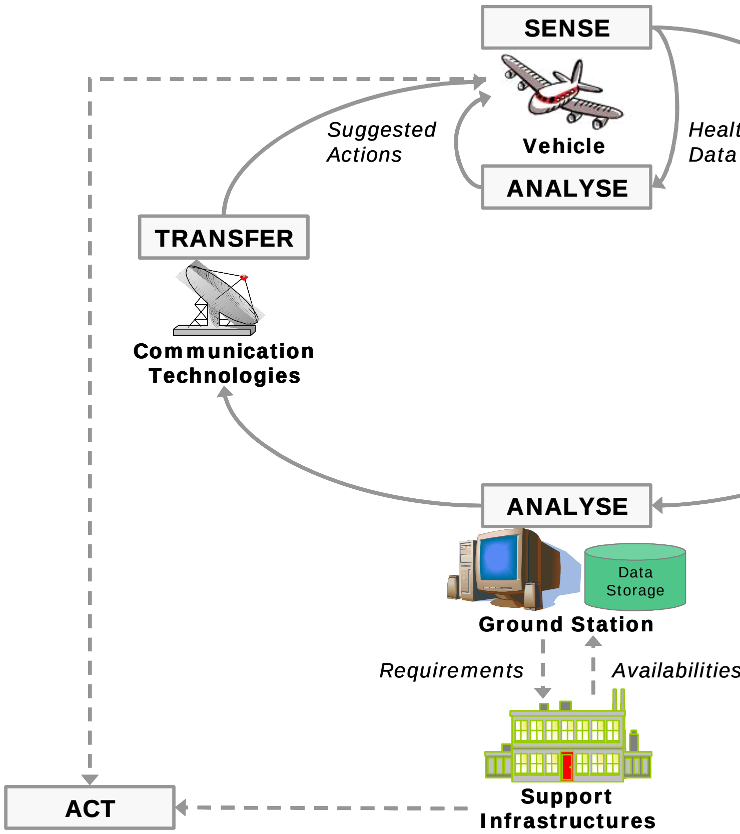

Figure 1 – Example of IVHM system configuration

Examples of IVHM applications: Examples of IVHM applications are quite rare in the literature and most of the systems described are under development. Baroth et al. [12] give an overview of the leading applications across the automotive, space, military and commercial aviation sectors while Janasak and Behshears [2] discuss health management systems available for consumer products, including both vehicle and non-vehicle systems. Similarly, Reichard et al. [7] provide a list of military projects in which the vehicle health information is incorporated within automated logistics systems. More specific examples of IVHM-like applications are provided by Fox and Glass [11], Hess and Fila [29], Bird et al. [8] and You et al. [30]. Three of the most mature IVHM applications in the literature are the DoD's 'Joint Strike Fighter', Boeing's 'Airplane Health Management' and GM's 'OnStar' (Table II). When selecting their examples, authors writing about IVHM seem to be attracted by the novelty, completeness and generic applicability of the approach rather than the degree of development. Hence, applications such as the US Navy's Integrated Condition Assessment System [32] are rarely cited, even thought this has been successfully deployed on over 100 ships.

Finding 4: There are a few examples of IVHM applications cited in the literature. Those that do exist tend to focus on demonstrating availability of the technology and, at the same time, to emphasise expectations from future developments.

Table II - Examples of mature IVHM-type systems

Organisation	Description	Link
US Department of Defense	Health management capabilities are being 'designed in' to the JSF aircraft and implemented within an integrated maintenance and logistics system.	www.jsf.mil
The Boeing Company	Boeing's Airplane Health Management solution uses remote analysis of real-time data to provide airlines and operators with customised maintenance decision support.	www.boeing.com
General Motors	The 'OnStar' telematics system monitors automobile performance in real time and presents a customised set of safety, security and convenience services to the driver.	www.onstar.com
NASA	IVHM systems being developed for the next generation of Reusable Launch Vehicle. IVHM will provide both real-time and life-cycle vehicle information to enhance decision making and maintenance.	www.nasa.gov
Smiths Aerospace & UK Ministry of Defence	Collaboration on a 'Fleet and Usage Management System' that will process heath and usage data to perform diagnostics, prognostics and life management on military helicopters and fixed wing aircraft.	www.smiths-aerospace.com/
US Navy	An Integrated Condition Assessment System for ships to integrate with remote support and provide system level monitoring and performance trending for condition-based maintenance.	www.idax.com
Lockheed Martin	Enhanced Platform Logistics System will provide ground vehicles with an embedded capability to monitor their own performance and provide predictive information allowing improved logistics support.	www.lockheedmartin.com

Drivers for IVHM: The IVHM literature is technical, the typical audience being system engineers rather than senior managers. The usual approach taken is to give a short discussion of the concept and then to describe specific IVHM solutions [9], [14], [27]. Despite their brevity, these introductory discussions typically contain a description of the benefits of IVHM, although a more detailed treatment of the potential drivers is given by authors who substantially focus on cost-benefit analysis [3], [26], [33]. For mission operations, adoption of IVHM can provide with adaptive control and improved survivability which enhances the probability of mission success [14]. Williams [1] claims that the benefits of IVHM extend into the area of fleet management, since vehicles in the fleet can be assigned to alternative missions according to changes in their condition and corresponding capabilities. For maintenance operations, IVHM provides value in many ways, including reduced need for inspection, advanced notification of maintenance requirements, reduced fault ambiguity, increased detection coverage and reduced repair time. Performing overhauls and replacements on-condition will maximise asset life [5], [34] and can also reduce wasteful removals of serviceable components due to the improved ability to isolate faults [3], [29]. There is a strong emphasis in the literature on the reduction of maintenance costs as one of the main drivers for IVHM [1], [6], [12], [19], [34]. While safety benefits of IVHM are also recognised, few authors see this as the ultimate goal of IVHM [8], [15], [35]. For support operations IVHM adoption is seen as part of a strategy for aftercare service providers to meet their obligations at a reduced cost [1]. Similarly, IVHM is claimed to provide strategic opportunities to the original equipment manufacturers of vehicle components because field performance data can be used to improve future designs [8].

Finding 5: IVHM technology has many potential drivers. To mission operations, it means maximising the exploitation of vehicle capabilities, to maintenance operations is it a release from time-based policies, and for support operations it allows a more aggressive on-demand management.

Barriers to the adoption of IVHM: IVHM brings with it significant economic and cultural challenges. Most authors [33], [1], [26] see the main barrier to the adoption of IVHM as the cost of hardware and software. Reichard et al. [7] indicate that this cost includes not only the development of the sensors and data processing, but also the penalty costs associated with additional weight, power, computing and communication resources. Also, many of the IVHM technologies have been developed relatively recently and in only a few cases on actual systems, making it difficult to carry out accurate cost-benefit analyses [10]. One of the earliest criticisms of IVHM was the possibility false alarms and other IVHM induced problems, such as sensor failures. These criticisms were supported by reported cases of inadequate or faulty sensors which caused premature termination of components or failure to detect faults in critical structures [12]. The costs and benefits of IVHM are directly related to how early in the design it is considered [5], [11], [27] and this requires a significant change in the way vehicle systems are designed [36].

Finding 6: The principal barrier to the adoption of IVHM is in the need to accurately assess the trade-offs between associated costs, risks and revenues.

Approaches to the design of IVHM systems: IVHM systems should be designed for a specific application and with consideration of the user's requirements. IVHM systems can vary in scope depending on the different subsystems and components of the vehicle [5]. IVHM technologies bring the greatest benefit when they are applied to the areas that have the most critical impact on vehicle performance and support costs [27], [33]. Even within the same industrial sector, effective IVHM design depends upon the specific business case, market segment and vehicle owner [8], [15]. The relationships between the designer and the users play a significant role in delivering an effective IVHM system. Bird et al. [8] and Scandura [15] both argue that successful implementation of IVHM requires knowledge of the factors that create value for several stakeholders such as maintainers, operators, OEMs and service providers in order to deliver the functionality that best reflects stakeholder priorities.

Finding 7: An IVHM system needs to be designed on the specific case from the client perspective; it needs to select the top degraders of vehicle performance and provide the functions that deliver the greatest value to the users.

IVHM design tools: Keller et al. [27] describe a suite of processes and software tools for IVHM development. An IVHM system may best be created as a series of layers performing different tasks within the overall IVHM function [8], [15], [21]. Aaseng [6] suggests a distribution of IVHM system components between the vehicle and the logistics infrastructure while Kacprzynski et al. [37] present a model for assessing IVHM sensor requirement specifications based on their financial and operational benefits. Most of these methods are tested through case studies however Tumer et al. [38] argue that they may need further development before they can be integrated into formal vehicle design practices.

Different tools have been presented for the development and implementation of software for IVHM but there is a strong generic flavour to these tools with many being based on the Open System Architecture for Condition-Based Maintenance (OSA/CBM) [27], [39]. Different authors have developed their own integration platforms for specific engineering environments, yet it is agreed that the open system architecture is an effective way to reduce costs, improve portability and increase competition in the market for IVHM solutions [40].

Finding 8: Some tools exist for designing IVHM systems, but these tend to lack in-depth evaluation of their compatibility with vehicle design practices. Better-established tools are available to develop software applications for IVHM; these are typically developed around a standardised architecture that gives them a strong foundation.

Future research challenges in the IVHM literature: Future research is suggested to leverage IVHM technology development across industrial sectors and organisations [12]. Bespoke methodologies are also required for the conceptual design stage to identify whether and how IVHM applications can be cost-effective [26] and the level of implementation that is most appropriate for the product or business [27]. Similarly, more quantitative methods are required to evaluate the safety benefits of IVHM and thus provide comprehensive decision support for vehicle owners [3]. Understanding the use of IVHM in the context of innovative service contracts such as performance-based logistics [25], [41] or product-service systems [42] is also a developing subject in the literature. Finally, it is recognised that more research is needed to develop, identify and present successful IVHM applications.

Finding 9: The IVHM literature shows that research is needed to coordinate knowledge development and improve methods and tools. More widespread adoption of IVHM will need an in-depth evaluation of its use within emerging models of servitization and a better understanding of existing applications.

CONCLUSION: Nine findings have been established from the literature currently available on IVHM. IVHM is a means of establishing current and predicted vehicle condition and using this information to enhance operational decisions. The concept originated in the aerospace industry in the 1970s, and most contributors have been from industrial, military and governmental organisations. IVHM systems consist of onboard and remote instrumentation systems and are used in a diverse range of configurations. A successful IVHM system needs to be tailored to a specific vehicle system and incorporate the functions that create value for vehicle users. Descriptions of successful IVHM applications demonstrate that the technology is mature, but the literature emphasises the expectations from future developments. Despite the many potential benefits of IVHM a serious barrier to adoption is the difficulty of accurately assessing the trade-offs between the associated costs, risks and revenues. While methods are proposed for designing IVHM systems, these have not yet significantly impacted vehicle design practice.

IVHM can improve both the cost-effectiveness of new and legacy vehicles by linking maintenance, operations, and logistics to the present and future health of the vehicle. However, the costs of the technology are potential barriers to widespread adoption. There is a need for consolidated tools and methodologies for the design of IVHM applications. A better understanding of the relationship between IVHM and emerging forms of service contracting would also facilitate a wider adoption of both. Recent advances in sensor, communication and software technologies have enabled a paradigm shift to take place in the way complex assets are designed, operated and maintained. Stringent health management requirements are being placed on the development of new vehicles [10] and IVHM offers an opportunity to improve the management of products thorough their lifecycles, extending beyond the field of vehicle systems to include any complex technical asset.

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