# State-of-the-art in integrated vehicle health management

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## 1 INTRODUCTION

The concept of integrated vehicle health management (IVHM) is an evolution of diagnostic and prognostic systems [1, 2]. The goal is to implement an advanced prognostics and health management (PHM) strategy that enables continuous monitoring and real time assessment of vehicle functional health, predicts remaining useful life of fault or near failure components, and uses this information to improve operational decisions. Here, maintenance operations benefit from reduced occurrences of unexpected faults as the health management system will provide early identification of failure precursors while, simultaneously, condition-based maintenance (CBM) is enabled, which can enhance availability, mission reliability, system life, and affordability (e.g. references [1] and [3] to [5]). Similarly, command and control functions rely on an improved awareness of vehicle condition and vehicle situational capabilities, and so also safety, utilization, vehicle turnaround, and the chance of mission success can increase [2, 6, 7].

For some authors, the scope of an IVHM system also includes logistics management. The underpinning expectation is that the availability of continuously updated and detailed vehicle health information can be used to automatically trigger logistics actions. An example of an extended IVHM system that comprises both the vehicle and its support infrastructure is the US Department of Defense (DoD)'s Joint Strike Fighter (JSF) programme [4, 8]. The JSF programme is leading the development of next generation strike weapon systems for the US Navy, Air Force, and Marine Corps. Here, the vehicle is being designed with a fully functional PHM system that performs fault detection, isolation, and reconfiguration across numerous components and subsystems (e.g. airframe structures, engine, electronics, hydraulics, fuel, and electric power systems). The PHM system also relays aircraft status data to a distributed information system that processes PHM calculations together with other information about the vehicle and the logistic cycle and, if maintenance is required, informs the supply chain infrastructure of the need for parts, tools, test equipment, manpower, and support facilities.

IVHM is a potentially valuable strategy for the manufacture and management of vehicle platforms. Currently, there are deep financial uncertainties in both military and commercial vehicle markets and therefore intense pressure to reduce costs [6]. Hence, much attention is being given to the operational and support activities that contribute a very large proportion of the lifecycle total ownership costs of modern vehicles [9, 10]. Commercial aerospace experience has shown that nearly 95 per cent of aircraft lifecycle costs are attributable to maintenance activities [11]. Similarly, the US government records have historically shown that the cost of operating and supporting a vehicle may exceed the initial purchase price as much as ten times [12]. In this climate, it would appear that the new generations of vehicle platforms will undergo substantial changes and will integrate distinctive technological progress to improve in-service operations. The current vision is that new and legacy vehicles should be provided with advanced technology-based intelligence functions that should enable more informed decisions on the design, usage, maintenance, and support [13, 14]. This is entirely consistent with the adoption of an IVHM philosophy that uses merging and strong coupling of interdisciplinary trends from the engineering sciences, computer sciences, and communication technologies to achieve the cheapest possible and most effective asset utilization.

The concept of IVHM has been discussed for some time (see Reichard et al. [7], Bird et al. [11], Baroth et al. [13], Fox and Glass [15]), yet the applications appear limited. Although many potential benefits are evident, obstacles have been reported to arise from the need to develop the IVHM technologies and then to accurately evaluate the challenges and risks of IVHM adoption (e.g. reference [16]). However, a concerted and coordinated research programme could address many of these obstacles and provide a platform of tools and principles that enable a wide scale adoption of IVHM by manufacturers and owners of vehicle systems. Such research requires a thorough and precise understanding of the existing knowledge and so the purpose of this article is to describe the state-of-the-art of IVHM.

The study in this article has taken the form of a systematic literature review. The methodology consisted of targeting relevant publication databases, searching these using a wide range of keywords associated with IVHM, and then reviewing each article identified. The outcome of these reviews was the extraction of a set of key findings. Hence, the article is structured as follows. First, the search strategy is described and applied to the identification of the relevant publications. Then, the key themes emerging from these publications are analysed and the related findings are presented. Finally, the results of the analysis are summarized and conclusions are drawn.

## 2 RESEARCH PROGRAMME

### 2.1 Aim, scope, and research questions

The aim of the research presented in this article has been to identify, interpret, and summarize the literature currently available on IVHM. The scope of this study has been to put together the publications that are relevant to IVHM within a wide range of industrial sectors. The word 'vehicle' in the IVHM acronym has been therefore related to any type of vehicle systems, ranging from spacecrafts to aircrafts, cars, trucks, ships, trains, helicopters, submarines, tanks, and so on. However, only articles that explicitly relate to the context of vehicle systems have been included, whereas those that refer to PHM of technical assets in general are tailored to stationary applications (e.g. machinery applications) and have been avoided. Similarly, articles discussing individual aspects of IVHM (e.g. sensor strategies, data processing techniques, and communication technologies) or IVHM functionalities in isolation (e.g. subsystem-level health management and health monitoring applications) have been excluded unless direct relevance to the topic of IVHM could be established. For example, a publication that is clearly within the scope of this review is that of Ofsthun [17] that compares the challenges that IVHM systems have to face in the aerospace and in the automotive sector.

The authors' initial approach to this study has been to consider the following questions.

1. What is an IVHM system, and how is it commonly defined?
2. How does IVHM differ from conventional vehicle design and operation practices, and what are the consequences?
3. Where are the leading examples of IVHM application? Where are the enablers and inhibitors of technical
4. 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 the existing literature may not be sufficient to allow these to lead directly to key findings.

### 2.2 Search strategy

The search strategy was developed by first defining the relevant data sources, time frame, and keywords. Initially, a wide selection of databases was identified, covering journals, conference proceedings, books, technical reports, and articles from trade journals. These databases included IEEE, Scopus, Compendex, Inspec and Aerospace, and High Technology Database, along with the more traditional library cataloguing systems.

The time frame for the study was chosen initially to include only the literature published between 2000 and 2008. However, as research progressed, this was naturally extended as a consequence of crosschecking citations.

The search was approached by identifying a range of keywords and key phrases that could be relevant to IVHM. The concept of IVHM embraces a very broad set of aspects, and so quite a wide range of search strings were necessarily used. These tended to address the various philosophies that can be implemented through IVHM systems, such as: PHM, total health management, health monitoring integration, logistics automation, system-level assessment, integrated diagnostics, autonomous maintenance, intelligent maintenance, informed maintenance, and on-board maintenance. Keywords were also run, which related to technical features that are typically associated to IVHM physical components. Example of these include: intelligent sensing, self-diagnosis, self-reporting, and embedded prognostics. The word 'vehicle' was often combined as an additional keyword to ensure some direct association of the publications to the field of IVHM.

Several sector-specific searches were also conducted by replacing the keyword 'vehicle' with the names of the main sectors where IVHM is being applied (e.g. aerospace, aviation, automotive, navy, railway, and military) and corresponding vehicle types (e.g. spacecrafts, aircrafts, cars, trucks, land vehicles, ships, submarines, and trains). Moreover, separated searches were conducted which focused on concepts associated to IVHM for particular vehicle types. These used key phrases such as autonomic logistics (AL) for the military aviation sector, HUMS for the helicopters sector, remote diagnostics and maintenance or telemetry for the automotive sector, and autonomous or intelligent vehicle for the space sector.

Finally, an internet search was executed using a similar process to that used for the library databases. The results of these searches combined to provide the following results.

### 2.3 Results and analysis

The search strategy initially identified a large list of well-known works. However, each publication was downloaded and quickly checked so that those that appeared to be outside the scope of the review were straightforwardly excluded. Following this screening, the list of hits was reduced tosome90 publications that were retrieved for more accurate examination. The abstracts of these publications were carefully analysed and a brief summary of the contents was extracted. By doing this, 39 publications were identified, which appeared to be suitable for review as part of this research. Subsequent cross-checking of references increased the list to 48, and it is the analysis of these publications, together with complementary references from previous studies of the authors, that forms the basis of the findings in this article. These are now discussed in detail.

## 3 GENERATION OF KEY FINDINGS

The literature review process allowed 11 key findings to be established. This section presents each in turn.

### 3.1 Definition of IVHM

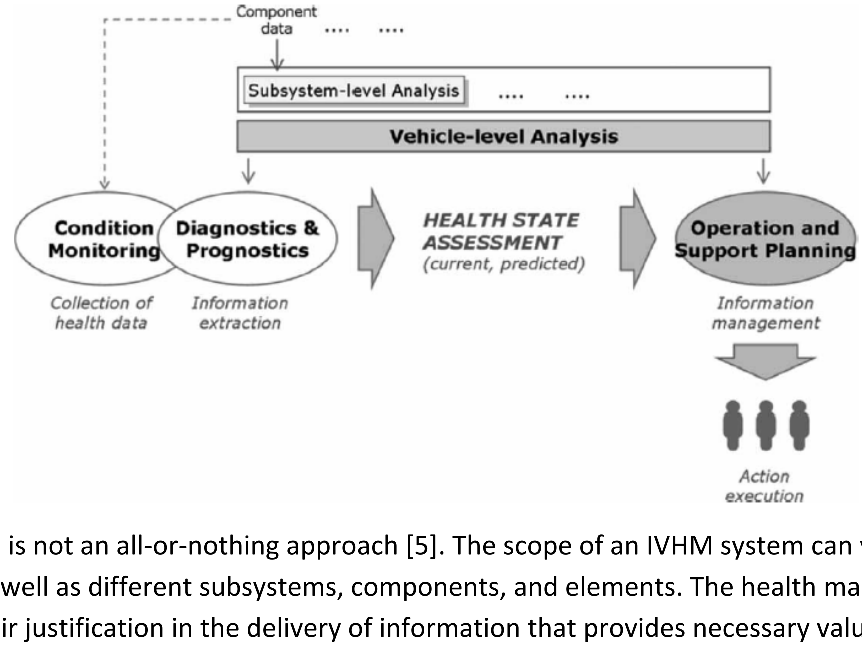
There is no unanimously or even generally accepted definition of IVHM [11, 18], yet various authors have proposed their own illustration of the concept (Table 1, [6, 13, 18–24]). By comparing the various interpretations, the concept of IVHM can be generalized as 'the capture of vehicle condition, both current and predicted, and the use of this information to enhance operational decisions, support actions, and subsequent business performance'.

Figure 1 shows how an IVHM system that is intended to operate. Health data are collected from vehicle components, structures, and elements and used to make diagnoses and prognoses of the present and future health of the vehicle. This information is further processed to formulate appropriate operation and support actions and presented to the people who should decide and execute the actions. Here, the first critical issue is that information regarding vehicle condition must be acted upon to generate reactive plans rather than merely processing health data and presenting them for later manipulation and use. This differentiates the idea of health management from health monitoring, in which there is no requirement to specify the use of the data that is collected [13, 25]. The second critical issue is in the notion of integration. The health management system will consider the vehicle as a whole; it will merge all vehicle functions rather than be implemented separately on individual subsystems, components, and elements [22, 26]. In comparison to the classical approach of using loosely coupled federated systems, the single IVHM system will help streamline isolation of route cause of failures as well as facilitating improved decision-making in fault conditions. On these bases, an IVHM system can be considered as an advanced vehicle instrumentation system that enables cost-effective ultra-high system availability, thereby ensuring operation safety. In a wider sense, the IVHM proposition can be seen as a quality management tool, in that it systematizes continuous improvement of new and legacy vehicle systems in response to changing users' needs and requirements [25].

Table 1 Definitions of IVHM

| Author | Definition of IVHM |
|---|---|
| NASA [19] | ‘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 [6] | ‘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. [13] | 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. [20] | ‘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 lifecycle costs’ |
| Price et al. [21] | ‘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’ |
| Wilmering [18] | ‘The unified capability of an arbitrarily complex system of systems to accurately assess the current state of member system health, predict some future state of the health of member systems, and assess that state of health within the appropriate framework of available resources and operational demand’ |
| Paris et al. [22] | ‘The process of assessing, preserving, and restoring system functionality across flight and ground systems’ |
| Jakovljevic and Artner [23] | ‘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. [24] | ‘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’ |

Fig. 1 The IVHM strategy



Intriguingly, the IVHM is not an all-or-nothing approach [5]. The scope of an IVHM system can vary and include different functions as well as different subsystems, components, and elements. The health management technologies have their justification in the delivery of information that provides necessary value to its users (maintainers, operators, Original Equipment Manufacturers (OEMs), service providers, and so on) [11, 26] and so informational needs of these users determine the functionalities to prioritize for cost-effective implementation. Similarly, although fulfilling total integration of its components, the ‘Integrated’ aspect of IVHM can only include some vehicle subsystems. Clearly, the IVHM technologies bring the greatest benefit when they are selectively applied to the areas that have the most critical impact on vehicle performance and support costs [27, 28]. Therefore, the most appropriate extension of the system depends upon the business case, the specific market segment, and user of the technology [11, 26]. This exploration of the definition of IVHM leads us to summarize:

> *Finding 1:* An IVHM is a condition monitoring system that delivers value in supporting efficient fault detection and reaction planning. It offers a capability to make intelligent, informed, and appropriate decisions based on the assessment of present and future vehicle condition. The IVHM logic is premised on integrating vehicle components and subsystems to increase the level of health state determination and improve the ability to formulate responses. These systems tend to be customized as they focus on the functions that deliver the greatest value to their users and on the key components and subsystems that have the most relevant impact on vehicle performance.

### 3.2 Evolution of the IVHM concept

The acronym IVHM is only used in the aerospace sector. However, several authors have suggested that the same functions provided by an IVHM system can be found in vehicle types other than aircraft and spacecraft, including helicopters, land vehicles (automobiles, trains, military ground vehicles), and maritime systems (ships and submarines) [11, 13, 17, 26]. This research has focused on such cross-sector interpretation, although there is also a broader view in the literature that is to see potential applications of IVHM to non-vehicle systems, like production machines, industrial process plants, or power generation plants [5, 14].

IVHM was first conceptualized by NASA. The first publication found was a report written in 1992, entitled 'Research and Technology Goals and Objectives for IVHM' [19]. This report stated IVHM as the highest priority technology for present and future NASA space transportation systems.

The concept of IVHM is said to date back to the early 1970s [6, 19], although there is no evidence of this in the literature of those years. The literature on IVHM has been mainly published after 2000, with earliest articles appearing at the end of the 1990s. Since 1997–1998, the number of articles on IVHM grew steadily, peaking between 2001 and 2002 and afterwards between 2006 and 2008.

Conferences have been the most popular dissemination route for research on IVHM, with the 'IEEE Aerospace Conference' being the leading one. This conference, along with similar technical conferences (e.g. the 'Digital Avionic Systems Conference' or the 'AIAA Space Exploration Conference') has been the forum for discussion about the principles, applications, and developments of IVHM. Almost no articles have been published in journals while some relevant articles have appeared as special reports, typically from government agencies and military organizations. Collectively, these articles have covered a range of aspects of IVHM, with approximately 35 per cent describing the potential impacts or cost-benefit analyses (e.g. references [10], [15], and [29] to [31]), 15 per cent discussing design approaches (e.g. references [26] and [32] to [34]), and ~25 per cent focusing on examples of either fielded or under development IVHM systems (e.g. references [8], [11], and [35]). Other topics are related to technology evolution and integration (e.g. references [22], [36], and [37]), logistic support (e.g. references [38] and [39]), and development planning (e.g. references [6], [13], [16], [19], and [40]).

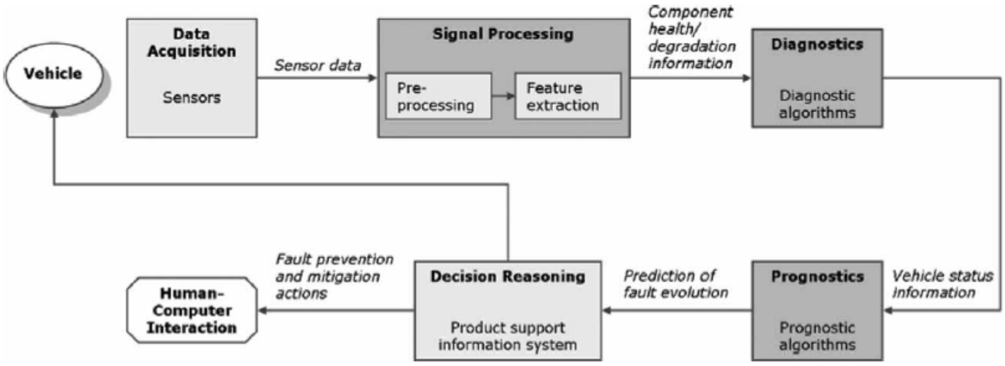
In terms of affiliation, the authors tend to be associated with manufacturing organizations of IVHM equipped vehicles, OEMs of IVHM components, or prime contractors responsible for integrating the systems (e.g. references [6], [11], and [26]). The largest contributions come from NASA, The US DoD, the Boeing Company, and Honeywell Corporation. There have been relatively few contributions from academic institutions, and those that exist have originated in the research centres of US universities, such as the 'Applied Research Laboratory" at Pennsylvania State University or the 'Intelligent Control Systems Laboratory' at Georgia Institute of Technology (e.g. references [14] and [27]). This exploration of the origins of IVHM leads us to summarize:

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

### 3.3 Technology principles for IVHM systems

Figure 2 illustrates the basic functional architecture of an IVHM system. Here, the first step is the use of sensors to measure state awareness variables that are indicative of potential failure modes. In addition to conventional sensors used for monitoring and control (e.g. temperature, speed, and flowrate sensors), sensor devices that are specifically tailored to health management applications (e.g. strain gauges, ultrasonic sensors, acoustic emission sensors, and proximity devices) [41] are available. Although sensor suites tend to be specific to the application domain, a few developmental sensor technologies are taking central stage in the IVHM domain. These include micro and fibre optic technologies that reduce sensor size, weight, and support requirements [19, 42] together with increasingly advanced smart sensors that have opened up the possibility for widespread introduction of embedded sensor systems [13]. Similarly, the availability of a specific protocol (IEEE 802.11) is fostering an intensive use of wireless sensor networks, which ensure quick and accurate information transfer with significant space savings [14, 43].

Fig. 2 Architecture of an IVHM system



Sensor data are preliminarily processed to remove artefacts and noises and then manipulated to extract fault features. The techniques commonly used to ‘clean’ the types of data derived from IVHM sensors include, e.g. low-pass filtering and time synchronous averaging. Fast Fourier transform and short time Fourier transform-based methods are very popular approaches in the extraction of condition indicators, while wavelet theory finds extensive application as both denoising method and feature extractor [14].

The diagnostic module analyses fault features to detect, identify, and isolate impending and incipient failure conditions. Diagnostic information is combined with historical data in the prognostic module and is used to generate an estimation of the time to failure of components and subsystems. Concerning the enabling techniques, both model-based and data driven reasoning have been used in IVHM applications [20, 44, 45].Being based on the construction of a mathematical model of the physical system, model-based reasoning can be performed according to a variety of approaches, ranging from Lagrangian dynamics, Hamilton dynamic, and approximation methods as some of the most common model-based diagnostics techniques, to physiscs-based, autoregressive moving average and particle filtering methods as examples of typical prognostics schemes [14]. Conversely, data based reasoning relies on training construct models of the system (e.g. artificial neural network and expert systems) with known fault patterns. Popular methods for pattern recognition in IVHM systems include statistical correlation/regression methods, fuzzy-logic classification, and neural network clustering techniques [44]. Nevertheless, prognoses of failure conditions are often executed by just analysing the statistical form of historical data according to experience-based techniques, typically the Bayesian probability theory or Weibull modelling [20].

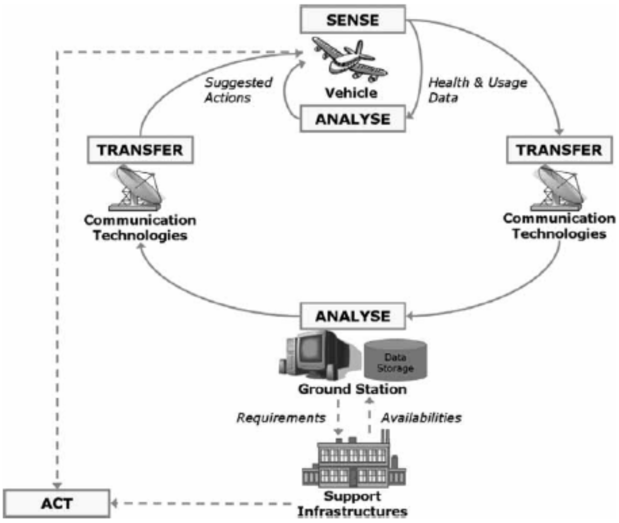
Finally, the diagnostics and prognostic information is turned into product support actions through an information system that transmits selected information to the automatic recovery systems onboard the vehicle and to technology enabled support managers. At the current state of practice, there is no well-established set of candidate methods for IVHM support planning, thus meaning that any modelling strategy or optimization routine can be applied. This exploration of IVHM technology principles leads us to summarize:

> *Finding 3:* IVHM involves synergistic deployment of sensor technologies and reasoning techniques all the way through to the development of a proactive decision support capability. Most of the IVHM-related technologies are available from other types of applications, yet these need to be implemented according to specific strategies.

### 3.4 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. Here, for example, consider an aircraft. As illustrated in Fig. 3, the IVHM system requires appropriate sensors to be positioned on critical components of the aircraft, monitoring the relevant subsystems (e.g. engine, propulsion, avionics, and structures) and state variables (e.g. temperature, pressure, speed, flowrate, and vibrations). The data collected by sensing devices are analysed onboard the vehicle. At the same time, health and usage data are also transmitted to a ground support centre where additional data analysis capabilities are deployed. In this case, wireless networks or more simple communication technologies are used to send the data from the aircraft to the remote support centre so that analysis can still be performed in-flight.

Fig. 3 Example of an IVHM system



Less critical data can be stored on the aircraft during the flight and accessed postflight at the ground station. Within the onboard and ground-based systems, vehicle health state is monitored continuously and predictions are made regarding the remaining life. Then, if appropriate, actions are suggested to minimize the effect of faults or to repair/replace the failing components. In addition to this, planning and execution of actions can be arranged in conjunction with the support infrastructure which provides recovery and maintenance support.

This example illustrates the typical configuration of an IVHM system. However, the systems described in the literature fit into a spectrum. At one end of the spectrum, all health management functions are incorporated onboard the vehicle, and at the other the data processing is entirely carried out with remote resources. Incorporating health management functions onboard, i.e. increasing vehicle autonomy, is motivated by a reduced dependence on data communication and therefore reduced operation costs and quicker response capabilities to unexpected events [6, 22]. On the other hand, diverting the analysis of health data to a remote support centre provides enhanced fault forwarding, troubleshooting, and historical information support while reducing the amount of instrumentation and computer resources that need to be furnished onboard the vehicle [11, 33, 35].

The preferred IVHM solution tends to depend on the complexity of the vehicle, mission challenges, and operational environment, and is therefore largely sector-specific. For example, the increased mission duration, distance, and therefore the cost and delay of communication in space flight are leading the space industry to aim for the highest level of vehicle autonomy [5, 22, 46]. By contrast, the automotive industry is trying to minimize the number of sensors needed to cover an automobile and implement remote diagnosis and maintenance systems [35]. This exploration of the configurations of IVHM systems leads us to summarize:

> *Finding 4:* An IVHM system will integrate onboard and remote hardware and software resources to collect, monitor, and analyse vehicle health data. The system can be seen in a range of configurations, dependingontheamountof analysis that is performed onboard the vehicle or alternatively diverted to the remote support.

### 3.5 Examples of IVHM applications

Examples of IVHM applications are quite rare in the literature. A few initiatives have been currently undertaken in diverse industrial sectors to deliver IVHM type systems, yet most of these systems are still under development. Baroth et al. [13] give an overview of the leading applications across the automotive, space, military, and commercial aviation sectors. Janasak and Beshears [2] discuss health management systems currently offered with different consumer products, including both vehicle and non-vehicle systems. Similarly, Reichard et al. [7] provide a list of military projects in which the information generated by the vehicle health management function is being incorporated within automated logistics, planning and scheduling systems. More specific examples of IVHM associated applications are provided, e.g. by Hess and Fila [8], Bird et al. [11], Fox and Glass [15], and You et al. [35]. Some of the most relevant IVHM applications, as highlighted in the literature, are the DoD's 'JSF', Boeing's 'Airplane Health Management (AHM)' and GM's 'OnStar' (Table 2). Under the JSF programme, the DoD is developing a sophisticated IVHM logistics and maintenance system, while Boeing and GMare seen as IVHM leaders with their commercial packages offering IVHM maintenance decision support. When selecting their examples, the authors dealing with IVHM seem to be attracted by the novelty, completeness, and generic applicability of the schemes, rather than a careful consideration of the degree of development. Hence, applications such as the US Navy's 'Integrated Condition Assessment System (ICAS)' [47] are rarely cited, even though this is successfully fielded on over 100USNavy ships. This exploration of the applications of IVHM leads us to summarize:

> *Finding 5:* 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 emphasize expectations from future developments.

Table 2 Examples of IVHM applications

| Organization | Description | Link |
|---|---|---|
| US DoD | The US DoD is developing the 'JSF'. Health management capabilities are being 'designed in' to the aircraft and implemented within an integrated maintenance and logistics system | http://www.jsf.mil |
| The Boeing Company | Boeing commercialises an AHM solution that uses remote analysis of real-time airplane data to provide airlines and operators with customised maintenance decision support | http://www.boeing.com |
| General Motors | General Motors offers the 'OnStar' telematics system that monitors automobile performance in real time and makes available to the driver a customised set of safety, security, and convenience services | http://www.onstar.com |
| NASA | NASA is developing various IVHM systems for the next generation of Reusable Launch Vehicle, crew and cargo transfer. IVHM technologies will be used to provide both real-time and lifecycle vehicle information which will enable informed decision making and maintenance | http://nasa.gov |
| Smiths Aerospace and UK Ministry of Defence | Smiths Aerospace and the UK Ministry of Defence are collaborating to evolve a 'Fleet and Usage Management System', a ground-based fleet management framework that, on the basis of processing health and usage data, will be able to perform advanced diagnostics, prognostics, and life management on military helicopters, airplanes and engines | http://www.smiths-group.com |
| US Navy | The US Navy is installing an ICAS on its ships that integrates with remote support to provide system level monitoring and performance trending for CBM | http://www.navy.mil |
| Lockheed Martin | Lockheed Martin has been commissioned an 'Enhanced Platform Logistics System' by the US Marine corps. This will provide Marine Corps ground vehicles with an embedded capability to monitor their own performance and provide with predictive information allowing CBM, improved logistics support and more efficient fleet management | http://www.lockheedmartin.com |

### 3.6 Benefits of IVHM

The literature about IVHM tends to be very technical, the predominant audience consisting of system engineers rather than senior managers. The approach most frequently taken is to give a short discussion of the concept and then to describe specific IVHM solutions, applications, or support tools (e.g. references [20], [22], and [28]). These introductory discussions are typical to emphasize the benefits of IVHM, although a more in-depth assessment of the potential advantages is available from those authors who substantially focused on cost-benefit analysis (e.g. Byer et al. [3], Banks et al. [27], and Hoyle et al. [31]).

For mission operations, adoption of IVHM can provide with adaptive control and improved survivability. Probability of mission success is enhanced as, e.g. the single integrated system can compensate for failures in one subsystem by adjustments in another [10, 22]. Safety also benefits from IVHM since the accurate and detailed assessment of health data, both current (diagnostics) and future (prognostics), supports early identification of failure onset and enables replacement of critical components before they can cause an accident [15]. For mission operations, the potential to assess the actual capabilities of the vehicle against the requirements of the mission is said to help maximize vehicle utilization through 'fix-orfly' decisions, maintenance programmes, or mission reconfiguration. In addressing the issue of the role of IVHM in supporting efficient vehicle turnaround, Williams [1] states that benefits of IVHM extend well 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 is seen to provide value in many ways, including reduced need for inspection, advanced notification of maintenance requirements, reduced fault ambiguity, increased detection coverage, reduced time for repairs (since the IVHM system will diagnose and isolate failures and also check out the repair actions), and reduced wasteful removals of serviceable components (e.g. reference [10]). Performing overhauls and replacements on-condition will maximize asset utilization and component life [5, 36] as maintenance actions will be only undertaken when the actual condition deteriorates. Moreover, automation of monitoring and analysis functions minimizes the need for human input and this will directly translate into increased reliability, maintainability, and reduced manpower costs [3, 5, 19].

For support operations, adoption of IVHM is claimed to improve responsiveness and enable more aggressive management since fault alarms can be available with sufficient lead time to arrange effective on-demand actions [4]. Similarly, logistic field operations will benefit from the opportunity to extract continuously updated information about part usage and resource engagement, which will increase supply reliability [8]. Finally, IVHM is envisioned as a mechanism to support the design of vehicle products as field data can be made available to theOEMsof vehicle subsystems and components, and hence used to design modifications and upgrades which can improve availability, reduce costs, and minimize environmental impact [11]. This exploration of the benefits of IVHM leads us to summarize:

> *Finding 6:* The IVHM technology has many potential benefits. To mission operations, it means maximizing the exploitation of vehicle capabilities, to maintenance operations it is a release from time-based policies, and for support operations it signifies a more opportunistic management.

### 3.7 Drivers for IVHM

Most authors see IVHM as a reliability and maintainability concept, and so essentially refer to the need for safe and cost-effective vehicle operation as essential driver for IVHM development (e.g. references [1], [6], [11], [13], [20], [26], [36], and [48]). In addition, many linkIVHMwith automating logistics coordination (e.g. Reichard et al. [7] and Banks andCrow[38]) and realizing new and revolutionary logistic support concepts, such as the Marine Corps Coherent Analytical Computing Environment, the Navy's Sense and Respond Logistics Program, and especially the DoD AL [4, 49]. However, the most intriguing prospects come from those authors who see the ultimate instantiation of IVHM as a competitive proposition for aftercare service providers (e.g. Williams [1], Vachtsevanos et al. [14], and Hess et al. [50]). They essentially refer to an increased viability for performance-based arrangements, where comprehensive aftercare services are offered to end users who actually pay a flat rate for set level of product performance [51, 52]. In these scenarios, investing in IVHM capabilities is seen to help reduce technical risks and achieve higher profit margins in the long term. This exploration of the drivers for IVHM leads us to summarize:

*Finding 7:* IVHM development has been substantially driven by end-user pressures to reduce maintenance costs, improve safety of vehicle operations, and facilitate logistics management. In addition to this, IVHM is being increasingly developed as a strategy for performance-based service providers to meet their obligations at a reduced cost.

### 3.8 Barriers to the adoption of IVHM

The adoption of IVHM brings with it significant economic and cultural challenges.The majority of authors (e.g. Williams [1], Banks et al. [27], and Hoyle et al. [31]) see the main barrier to the adoption of IVHM as the cost of the hardware and software that is needed to perform the IVHM tasks. Reichard et al. [7] indicate that this cost includes the development, qualification, and implementation of the sensors and data processing software, and also the penalty costs associated with additional weight, power, computing, and communication resources. In addition to this, many of the technologies (such as sensing, diagnosis, prognosis, and so on) have been developed relatively recently and in a very few cases on actual systems, thus making it difficult to carry out accurate cost-benefit analyses [14].

A cultural change is necessary for the user of an IVHM equipped vehicle to accept the shortcoming of the potential for false alarms and other IVHM induced faults, such as sensor failures. This is one of the earliest criticisms to IVHM, supported by many reported cases of inadequate or faulty sensors that caused premature termination of components or failed to detect problems in critical structures [13]. Similarly, the cost and potential of IVHM are directly related to howearly in the design it is considered (e.g. references [5], [15], [28], and [50]) and this requires a paradigm shift in the way vehicle systems have traditionally been designed [53]. Hence, we summarize:

*Finding 8:* The principal barrier to the adoption of IVHM is the need to accurately assess the trade-offs between associated costs, risks, and rewards.

### 3.9 Guidelines for effective IVHM design

The design of IVHM systems needs to be approached as a system engineering process [13, 18]. Since many complex interrelated decisions are required to deliver an effective system, it is imperative that a disciplined methodology is employed during the design process and a collaborative environment is created where domain expert can share data and applications [54]. Cost-benefit analysis is leading design practices [31]. The IVHM systems are specifically intended to improve the overall vehicle operational characteristics, yet it has to be proven that achievable benefits exceed the cost of developing, implementing, and using the technologies [19].

In many cases, the existing low-level systems set the stage for the development of an advanced and fully integrated IVHM system. Examples of these include on-board diagnostics systems that are commonly installed on cars and light trucks to provide diagnostics failure codes for a number of vehicle subsystems [35] or central maintenance computers that are used on commercial aircrafts to performfault consolidation and root cause analysis, direct the maintainer towards the faulty system, and recall the appropriate repair procedure [11]. It is important that a synergy is realized between theIVHMsystem and these low-level systems and, as well, with vehicle instrumentations that are designed with other functional purposes (e.g. control) so that these can share sensors and data processing capabilities [22, 55, 56].

To interface and integrate the various components of the IVHM system, design engineers should make use of open system architectures (OSA) that are unanimously recognized to be extremely effective in reducing costs, improving portability, and increasing competition in the market for IVHM solutions (e.g. references [56] to [58]). The available open system standards include AI-ESTATE and IEEE 1451.2 [14], yet the most important one is the ‘OSA for CBM’ that provides a framework for facilitating interchange and integration of CBM components from different sources (e.g. references [24], [34], [37], [57], and [59]). From this we summarize:

*Finding 9:* The design of an IVHM system needs to be approached as a system engineering process and in a cost-benefit perspective. The IVHM system must be constructed into the host vehicle and in connection with the other instrumentation systems. The components and elements within the system must be integrated according to an open system standard, typically the OSA/CBM architecture.

### 3.10 Tools for designing IVHM systems

The tools proposed in the literature for the design of IVHM systems can be generalized as system-level methodologies that look at either optimizing use of the different technology resources or assisting in their allocation across the extended system.

Within the first category, a failure modes, effects, and criticality analysis (FMECA) study is strongly recommended during the early stages of the design process to link the candidate failure modes to their severity, frequency of occurrence, and testability (e.g. references [50] and [55]). Advanced FMECA approaches are available, which analyse failure symptoms and may also suggest the sensor suites and diagnostics and prognostics technologies that are most appropriate for the IVHM system [14, 27, 37, 54]. At the same time, a strong generic favour is shown in the literature towards the use of trade studies as a methodology to identify the most balanced technical solution among a set of viable options. Specific trade-studies approaches are available to assist designers of IVHM systems. For example, Vachtsevanos et al. [14] propose a formal framework that applies the integrated product and process design methodology for the selection of the best alternative technologies for PHM components, sensors, and algorithms. Similarly, Banks and Merenich [60] propose a software application to support the exploration of the technical and economic performances associated to different designs solutions, and Keller et al. [28] present a design platform where a simulation model is combined with several cost/benefit models to support cost/benefit trades. Use of simulation for technology related trade-offs is also proposed by Kacprzynski et al. [54] and Ge et al. [61], while analytical cost-benefit models are proposed by Byer et al. [3], Banks et al. [27], Wilmering and Ramesh [29], and Banks et al. [62].

Tools for resource allocations have instead typically the appearance of system architectures which suggest the distribution of IVHM functions across technological components of the system, such as the software framework described by Swearingen and Keller [56] for developing modular IVHM architectures based on the OSA/CBM standard. Other examples include the framework described by Paris et al. [22] which modularizes IVHM functions and integrates them into avionics, health management, and control components, or the architecture given by Aaseng [6] for distributing the typical IVHM functions of an aircraft platformbetween the vehicle, the operations support, and the logistics infrastructure. This exploration of the tools for IVHM design leads us to summarize:

> *Finding 10*: Various tools have been developed to supportIVHMdesign. Overall, these implement a wide range of approaches for the solution of technologyrelated trade-offs and assist in the definition of the most appropriate architecture of the system.

### 3.11 Future research challenges in the IVHM literature

The existing literature explicitly identifies research challenges for IVHM development. Future work is suggested in the area of leveraging IVHM technology development across industrial sectors and system developers [13, 56]. Bespoke methodologies are also required that can be applied during the conceptual design stage to reveal whether the IVHM applications can be cost-effective [10, 31], and to evaluate the level of implementation that is most appropriate for the single product or business [28]. Similarly, more quantitative methods are called for, to evaluate the safety benefits that IVHM can bring and thus provide comprehensive information on which vehicle owners can base decisions [3]. Understanding the support that IVHM can give in the context of innovative manufacturing business models, such as performance-based logistics [29, 55, 63] or product service systems [64], is also a growing subject in the literature. Finally, it is recognized that there has been insufficient work carried out to identify and present successful IVHM applications. This leads us to summarize:

> *Finding 11:* The IVHM literature highlights that systematic research initiatives are 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 the emerging stream of manufacturing servitization and a better understanding of the existing applications.

## 4 CONCLUDING REMARKS

The aim of the research presented has been to identify, interpret, and summarize the literature currently available on IVHM. The investigation has focused on the literature explicitly related to the context of vehicle systems. A more informed prospect could therefore be achieved in the future by also considering research dealing with other types of engineering systems. Moreover, although it is recognized that the viability of IVHM systems is tightly coupled with recent technological strides (e.g. increased processing power, wireless communication, and smart sensing) [18], the article has not intensively addressed the technology side of IVHM applications. There are two main reasons for this: (a) IVHM includes a large number of subdisciplines (e.g. sensor technology, signal processing, and control techniques), and therefore it involves a very broad and multi-disciplinary field of knowledge [5, 14, 24]. It would have been difficult, if not impossible, to capture and summarize in a single article all the essential elements of traditional and emerging technologies that can have an impact on IVHM systems; (b) technology advances do not represent the real innovation with IVHM. As observed by Bird et al. [11], many of the IVHM enabled improvements find their routes in operational and process innovation rather than in any individual innovative technology. It is through system-level integration and transition from health monitoring to management that IVHM realizes new ways to provide value to an extended set of end customers. Similarly, what creates the business case for IVHM is not technical innovation; rather it is a novel financial approach to asset lifecycle [29]. On the other hand, the article has taken a very wide view of IVHM in that it has carried out a cross-sector investigation as so contributed to a general understanding of the concept which can overarch all potential application domains.

On this basis, 11 findings have been established. In summary, IVHM is a capability to capture vehicle condition, both current and predicted, and use of this information enhance operational decisions, support actions, and subsequent business performance. The concept was originated in the aerospace sector in the 1970s, and to date most contributors have been from industrial, military, and governmental organizations involved with developing IVHM systems. Although substantially driven by end-user pressures to improve cost-effectiveness of maintenance and support activities, IVHM is being increasingly developed as a competitive proposition for aftercare service providers. An IVHM system will involve synergistic deployment of sensor technologies and reasoning techniques, tackled to the provision of a proactive decision support capability. It will consist of onboard and remote instrumentation systems, and can be implemented in a diverse range of configurations. To be effective, an IVHM system needs to be designed according to an open system standard and to be constructed into the host vehicle. Several tools are available to support IVHM design, which assist in the solution of technology-related trade-offs and in the definition of the most appropriate architecture of the system. There are a few examples of successful IVHM applications in the literature. These demonstrate that the technology is mature, but also tend to emphasize expectations from future developments. Despite many potential benefits related to IVHM, a serious barrier to adoption results from the problem of accurately assessing the trade-offs between the associated costs, risks, and rewords.

These findings support the view that IVHM has the potential for improving safety and cost-effectiveness of new and legacy vehicles by linking maintenance, operations, and logistics to the present and future health of the vehicle but that the cost and complexity of the technology are perceived as potential inhibitors to widespread adoption. The principal issues concern the lack of consolidated tools and methodologies that can guide an early assessment of the most appropriate level of IVHM implementation. An in-dept evaluation of the use of IVHM within emerging forms of service contracting and a better understanding of the existing applications would also facilitate a wider adoption of IVHM.

The conclusions of this review provide a platform on which to base future work. A true paradigm shift is taking place in the way complex assets are designed, operated, and maintained. Stringent enhanced diagnostics, prognostics, and health management requirements have begun to be placed on the development of new applications [14]. IVHM follows and interprets this trend by specifically integrating component, subsystem, and system level strategies to deliver the richest possible information and decision support during vehicle field performance. This is enabled by the recent advances in sensor, communication, and software technologies and seems to be a significant opportunity to improve the management of the product through its lifecycle, which extends well beyond the field of vehicle systems and potentially includes any complex technical asset.

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