From HUMS to PHM: Are We There Yet?

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Abstract

Over the last fifteen years, military aircraft Health and Usage Monitoring Systems (HUMS) have morphed from simple data acquisition systems, mostly hardware centric, to more complex software-rich integrated health management (HM) systems. The latest application to fifth generation military aircraft has propagated the concept of Prognostics and Health Management (PHM). This paper provides a discussion on the attributes, benefits and challenges of novel military aircraft health management systems. Factors affecting successful implementation of prognostics and Knowledge Discovery with aircraft Big Data are further explored.

Keywords: Big Data, Data Analytics, Health Management, HUMS, Knowledge Discovery, Military Aircraft, PHM, Prognostics.

Introduction

There is no doubt that Health and Usage Monitoring Systems (HUMS) for military aircraft have come a long way over the last fifteen years. The first HUMS Conference, in 1999, discussed the challenges, benefits, and latest technologies for emerging helicopter HUMS. Retrofit of HUMS was the main avenue for employment of these systems; interestingly, data fusion and prognostics, which remain novel today, were also presented [1].

The Joint Strike Fighter (JSF) Prognostics and Health Management (PHM) system is the first military aircraft application where Prognostics and Autonomic Logistics are mandated. There is a significant shift from a sensor and data-centric monitoring capability with HUMS, to an information-rich and integrated asset management focus with PHM. In the current era of fifth generation aircraft, and the proliferation of Unmanned Aerial Systems (UAS), the requirements and expectations from health management systems are becoming more demanding. In the context of this paper, the term health management (HM) systems refers to the wide range of aircraft health, and usage, monitoring and management systems that apply to all military aircraft including UAS.

Background

In 2000, the Australian Defence Force (ADF) explored the idea of retrofitting a basic engine monitoring system to the F-111 aircraft; for the analog-era platform it would have been a cutting-edge addition to support sole operator flying yet the difficulty of retrofitting and retirement plans did not justify it. Of the ADF helicopters operating at that time, the Sea King (Mk 50/50A) and Seahawk (S-70B-2), did not have Original Equipment Manufacturer (OEM) HUMS. They were retrofitted instead with hardwired sensors and cables to facilitate Rotor Track & Balance (RTB), and gearbox and engine vibration checks using carry-on ground support equipment as part of routine maintenance. DST[1] developed a vibration monitoring system that was utilised for the Mk 50/50A, and later replaced with a commercial unit when it became obsolete [2-3].

Later additions to the ADF rotary wing fleet were delivered with HUMS, as OEMs started introducing these at production. The most recent helicopter addition, the Seahawk ROMEO (MH-60R), was delivered with the Integrated Mechanical Diagnostics System (IMDS) that combines a significant number of sensors with data fusion for advanced health indications. For the ADF fixed wing aircraft, the structural usage component of the HUMS has been equally important to health monitoring.

[1] Previously known as DSTO.

Normally, several ground HUMS components would be implemented to support different aspects of aircraft maintenance, and often that required further refinement to become operationally suitable [4].

Ontology

There are numerous descriptions for HM systems in the aerospace domain. The term HUMS has traditionally been applied to helicopters but also adopted for fixed wing aircraft as well as recently to land vehicles. Integrated Vehicle Health Management (IVHM) and Integrated System Health Management (ISHM) terminology is widely used by NASA and DOD. The space domain pioneered the development of HM concepts for fault accommodation and automation; these concepts are becoming relevant now in support of novel UAS. Although PHM refers specifically to the JSF application, it has received a much wider adoption as a concept.

The ontology of HM systems is not standardised and this adds some confusion when attempting a common understanding of the objectives, functionality, and issues among aircraft users and sustainment stakeholders. There are many publications that cover architecture, objectives, methods, and tools in this field [5-8] including latest research in the field of PHM [9].

HM systems record and process aircraft health (and usage) data, and convert it to useful actionable indicators that support maintenance, integrity and safety of the aircraft; integrated HM systems also aim to minimise the operational and sustainment cost. The six blocks of functionality in a condition monitoring system, which relate well to HM systems, are described in ISO-13374 as data acquisition, data manipulation, state detection, health assessment, prognostics assessment and advisory generation [10]; *state* and *health* also would address the life and usage aspects of health. For the JSF, PHM consists of three broad components: diagnostics, prognostics and health management (see *Fig.1*).

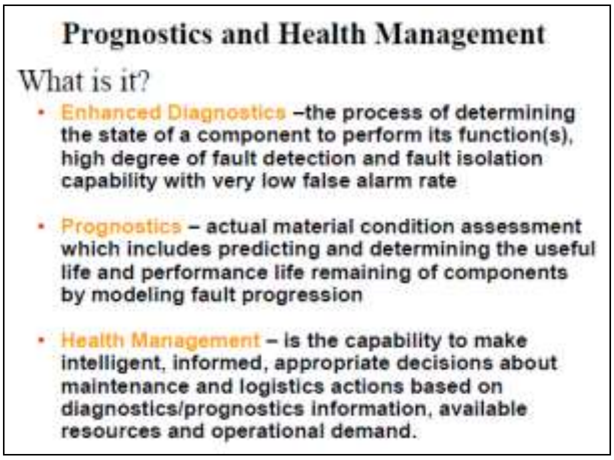

Fig.1: JSF PHM definitions [11]

Benefits

The benefits from aircraft HM systems range across many stakeholders. Traditionally, the most tangible benefits have been in the facilitation of maintenance which affects safety and availability (see *Table 1*). Fleet managers rely heavily on HM systems to provide asset state visibility for mission planning. Broader projected benefits include O&S cost reduction, which has been a major driver for the JSF program [24]. The benefits of HM systems from an operator's perspective have been described in several papers [2-4, 12-15].

The US Army has been a strong advocate of HUMS stating many benefits: 52% less unscheduled Maintenance Man Hours/Flight Hour, 48% less mission aborts and 5% increase in Operational Readiness Rate [12]. The UK Chinook experience with a retrofitted HUMS, showed significant reduction in RTB testing time, 20% more accurate flight hour recording compared to pilot reporting, and proactive airworthiness benefits when incidents that could have caused aircraft loss were avoided [14]. Significant reduction in maintenance effort, increased aircraft availability, savings in fuel costs and engine hours were attributed to the implementation of a propeller balancing solution [4]. A noteworthy claim is that a battalion fitted with HUMS increased availability by 27% compared to one without a system [15]. Recently, the Federal Aviation Administration granted life extensions for a helicopter Main Rotor Hub using HUMS data through individual aircraft usage monitoring [16].

Table 1: Stakeholder benefits of aircraft health management systems

Pilot/ Operator	Maintainer	Integrity Manager	Fleet Manager	O&S Stakeholder	Other
Report health state to pilot. *Improve flight safety by identifying fault prior to failure.*	*Identify and correctly isolate faults.* *Reduce Could Not Duplicate /Return Tested OK & false alarms.* *Reduce workload.* *Eliminate maintenance testing time/ flights.* *Plan /optimise Maintenance.*	*Track actual life/usage.* *Compare against design spectrum.* *Enable relifing.* *Confirm asset airworthiness.*	*Asset status awareness.* *Assess fleet mission capability.* *Increase availability.* *Support Mission Planning.* *Enable Force Life Management.* *Enable MFOQA* *Increase Sortie Generation Rate.* *CBM+*	*Identify R&M trends.* *Identify degraders.* *Support spares planning.* *Support PBL.* *Support Training.* *Support Knowledge Discovery & continuous improvement.*	*Support incident /accident Investigation.* *Support R&D*

HM system capabilities

An indication of the range of aircraft HM applications, from the component level to aircraft and fleet is shown in *Table 2*. Traditionally, several off-board HM systems would be in place to achieve the full scope; In contrast, with the JSF, off-board PHM resides in one ground system, the Autonomic Logistics Information System (ALIS).

Table 2: Health management applications at component, aircraft and fleet levels.

COMPONENT-LEVEL	AIRCRAFT-LEVEL	FLEET-LEVEL
Diagnostics/Built-In-Tests	Corrosion monitoring	Fleet trending
Usage / Life tracking	Exceedance monitoring	Force Life Management
Mechanical Diagnostics	Flight regime recognition	Performance Metrics
Gas Path Debris Monitoring	Individual Aircraft Tracking	Knowledge Discovery
Performance Trending	Loads Monitoring	MFOQA
Prognostics	Operational Usage Monitoring	PBL data gathering
Blade health monitoring.	Mission Capability assessment	
RTB /Propeller Balancing	Maintenance management	

Novelty of HM systems and remaining challenges

Compared to traditional HM systems, and using the JSF PHM system as precedent, the new generation of military HM systems will aspire to be well integrated, with comprehensive functionality, be interoperable, cyber secure, and produce actionable condition indicators (see *Fig.2*). In addition, effective data management will become important to enable O&S cost improvements besides the traditional safety, maintenance and availability benefits. Data telemetry and autonomous information systems will become more widely adopted.

The fundamental characteristics of a good HM system are summarised in *Table 3*. Unfortunately, acquiring all these great attributes is a difficult and expensive endeavour. The factors that contribute to achieving the attributes of *Table 3* are shown in *Fig.3*. Within the constraints (or catalysts) of policy, requirements definition, program management and acquisition strategy, the onus is on the HM system OEM and also the user to achieve the desired HM system capability. In major DOD acquisition projects, the role of the Program Office therefore becomes significant.

During System Development and Design, the HM system architecture, functionality, and initial performance are finalised. In order to achieve a HM system that is fit for purpose, relevant (to user needs), cyber-secure, mature, interoperable and affordable, the military user becomes an important player as the OEM cannot fully appreciate the operator needs, environment and constraints.

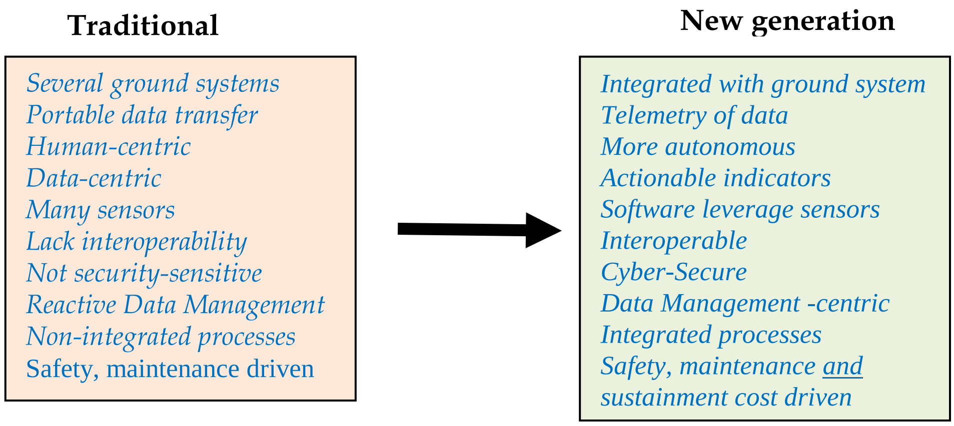

Fig.2: Traditional versus aspiring aircraft health management system attributes

Table 3: Characteristics of a good aircraft HM system

Fit for purpose
Integrated
Robust
Reliable
Relevant
Maintainer/User-friendly
Mature
Scalable
Supportable
Cyber secure
Interoperable
Work as advertised
Affordable

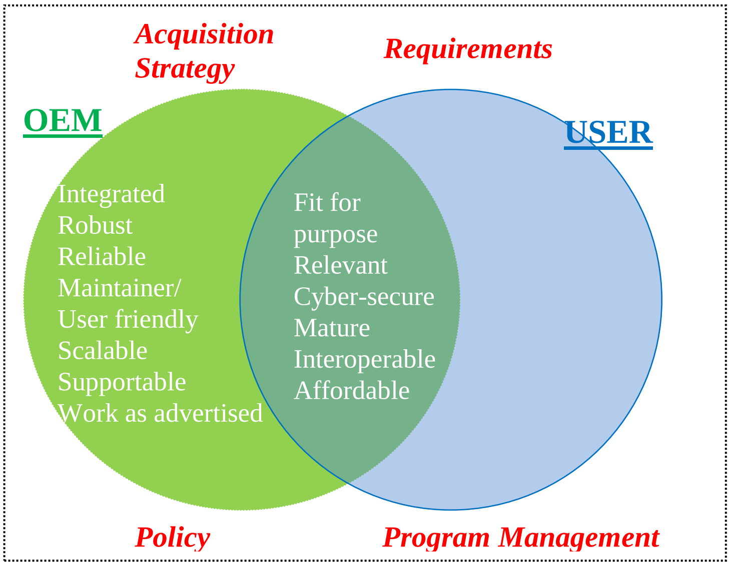

Fig.3: Circles of influence for desirable attributes of HM systems

It has been a common experience, that HM systems are immature when first fielded; this is true for novel as well as legacy systems. As HM systems are mostly software, the maturation aspect is critically dependent on field experience and continuous feedback loop. A mature HM system has low false alarms, refined algorithm thresholds, and is fully functional (see *Fig.4*). The greater the technological innovation of a HM system, the longer the maturation period will be once fielded; unfortunately this creates angst among the users of the systems and impacts on level of buy-in overall.

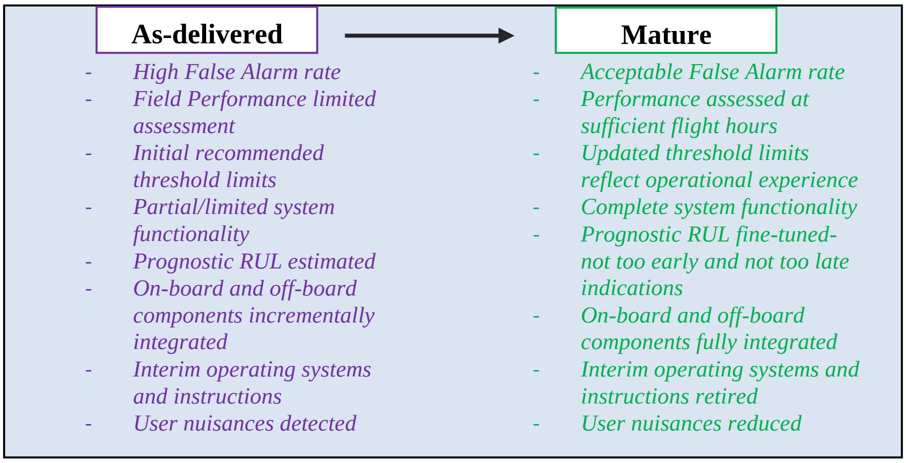

Fig.4: The path to maturation for HM systems

The following specific challenges affect current new generation of novel HM systems:

- Issue of cybersecurity
- Need for interoperability
- Complexity of agile software development
- Enduring issue of system integration
- Maturity of prognostics
- Management of 'Big Data'

In the context of the military, the importance of cybersecurity and interoperability is self-explanatory. The agility of the software development process has been an issue wider than the HM application; the software development model commonly used in defence aerospace, the V-model, is known to not respond well to inevitable changes in design. Integration of software sub-systems between aircraft and ground remains the Achilles heel of HM systems. Two of the listed challenges, prognostics and Big Data, remain a focus of the aerospace research communities.

Prognostics. Also described as predictive diagnostics, prognostics remains an emerging field with a low TRL. It has been called "new, hard, often risky technology" [19]. Most papers in the field of prognostics [9] describe proof of concepts and practical field applications are lacking. The evolution of mechanics system diagnostics to early prognostics for helicopters set the groundwork for the JSF prognostics vision [17-18]. There has been considerable discussion on the challenges of applying prognostics for the JSF [18-21]. A major challenge for system prognostics remains the determination of Remaining Useful Life (RUL). Military aircraft applications are mostly usage-based prognostics. In the absence of tangible indications of system degrading health, monitoring the usage in the field together with expert knowledge of damage and degradation allows health predictions to be made.

Several factors contribute to successful implementation of prognostics in the aerospace field that go beyond the novelty of the applied prognostic model itself (see Fig.5). As this is an emerging field, policy, user buy-in and a resourced plan for maturation are major factors for successful adoption of prognostics and the related shift in maintenance concept to opportunistic maintenance.

Aircraft Big Data. The types of data generated in support of aircraft HM include data produced during flight, data processed on the ground and extended sustainment data (see *Fig.6*). According to Gartner's definition, "*Big data" is high-volume, -velocity and -variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight and decision making"* [22]. Three further Vs have been used, veracity, value and visibility [23]. An interpretation of the 6V properties for military aircraft data is shown in *Table 4*.

Of these, value, visibility, veracity and volume rank highest in importance for military aircraft applications (see *Table 4*). The issue of data visibility is significant as often data is in propriety format or stored on OEM databases not fully accessible by stakeholders. Although the volume of data generated off the aircraft has increased by two orders of magnitude from early HUMS systems that typically recorded 5MB per flight hour [14], data storage capacity has also improved. The challenge with Big Data is in how best to achieve *enhanced insight and decision making*.

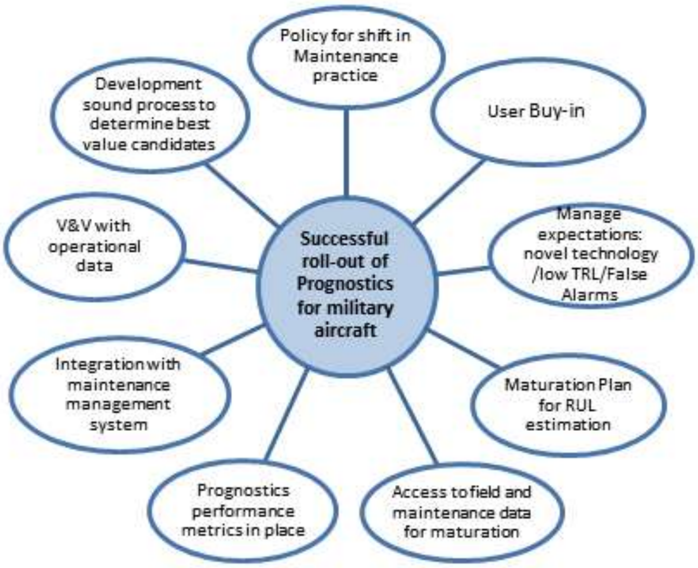

Fig.5: Factors affecting successful implementation of prognostics for military aircraft.

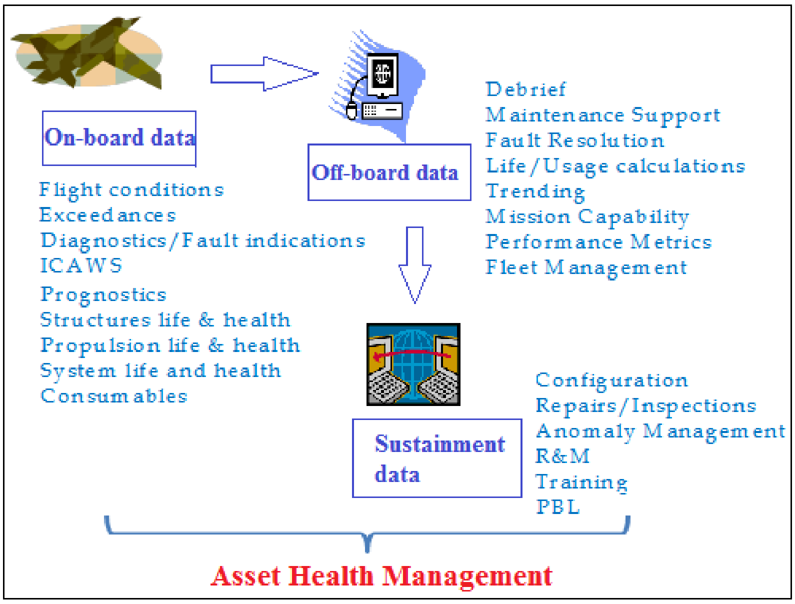

Fig.6: Types of data generated in support of aircraft health management

Table 4: The 6V properties of aircraft HM Big Data

PROPERTY		Military aircraft interpretation
VOLUME	Size of data	On-board: HIGH(nominal 500MB per flight hour i.e. fleet data ~TB) Off-board: LOW (exceptions e.g. borescope images)
VELOCITY	Rate at which produced	On-board: HIGH (1-100Hz, high frequency aircraft parameters e.g. loads). Off-board: LOW
VARIETY	Range of formats and representations	Raw (binary) and processed format. Structured (on-board) and unstructured (off-board) e.g. pilot/maintainer comments, inspection/repair information. Numerical, text and images.
VERACITY-	Uncertainty due to data quality	Data integrity issues: data recording, loss, filling, synchronisation, corruption, compatibility issues.
VALUE	Economic or political	HIGH: flight safety critical, mission-critical, airworthiness relevant, security-relevant, O&S cost or PBL-relevant.
VISIBILITY	Access and viewing of data	HIGH (desired)-access to flight or historical data for re-lifing, incident investigations etc. Not usually streamlined.

Data mining and Knowledge Discovery for aerospace applications are not new concepts [5, 31]. The JSF program advocated Knowledge Discovery, the capability to data mine and extract useful information and trends from vast amounts of data from several data sources across a fleet, for fleet sustainment continuous improvement and maturation. Currently, the popular term Data Analytics is used to describe a similar concept and a rapidly growing field [25]. Several aircraft OEM are adopting Data Analytics for sustainment, availability and reliability improvements, and also as a service to the user [27-30]. Under Performance Based Logistics (PBL), and with access to vast fleet data, this can enable providers to improve sustainment at a reduced cost.

Several elements need to be in place in order to successfully achieve a Knowledge Discovery capability (see *Fig.7*). Fundamental design elements are the architecture, management of the 6V's of Big Data, and data mining techniques i.e. Data Analytics. In the military aerospace domain though, the ownership, rules of engagement and supporting policy, and also data security need to be addressed first before this capability becomes widely adopted.

Fig.7: Factors affecting successful implementation of Knowledge Discovery.

Conclusion

Military aircraft health management systems have become software-centric and data-rich complex systems, and a fundamental part of cost effective aircraft asset management. The new generation of health management systems have many aspirational attributes, from integrated, robust and scalable design, to meeting requirements for interoperable, cyber secure and affordable systems. Key factors for successful employment of prognostics in the aerospace field have been presented. The characteristics of mature health management systems and the strong dependency on field feedback have been discussed. In the era of Big Data, the use of Data Analytics in support of Knowledge Discovery for military aircraft sustainment is now being explored; key factors for successful implementation have been provided.

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