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The effect of current military maintenance practices and regulations on the implementation of Integrated Vehicle Health Management technology

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Abstract: Health monitoring tools can be used to diagnose failures and estimate the remaining useful life of certain components, generating information that can be used to improve the management of logistics and maintenance activities in what is known as Integrated Vehicle Health Management (IVHM). The work presented here analyzes the effect of military practices and regulations on the benefits that can be expected from installing health monitoring tools on military aircraft. The findings on the impact of the military environment on short-term and medium-term goals of maintainers and operators are key to produce an accurate and reliable Cost-Benefit Analysis (CBA) for IVHM technology. The results of this work are based on information obtained through the use of a questionnaire to gather the knowledge of experts in the field and by studying military standards. Secondary benefits of implementing IVHM have been studied in detail to provide a guide of which are really relevant when working on a CBA and which can be ignored. The transition from current Condition Based Maintenance (CBM) practices included in military standards to the use of continuous health monitoring tools is also discussed. The effect of current outsourcing practices, such as availability contracts, is taken into account in the analysis of these issues.

Keywords: From PHM and CBM+ considerations to Maintenance, Maintenance Related Services, Service Improvement, Asset and maintenance management, Cost-Benefit Analysis, Maintenance Costs, Maintenance Policies, Standards, Program Costs.

1. INTRODUCTION

In order to reduce maintenance costs and increase the availability of a vehicle, diagnostic and prognostics can be used to generate information to be used to make decisions regarding maintenance and logistics. Advances in automated decision making can also be applied to reduce the need for human intervention. When these tools are implemented in conjunction to improve the performance of the support infrastructure we talk of Integrated Vehicle Health Management (IVHM).

The capabilities of health monitoring tools have improved significantly in recent years, making industrial applications possible. As a consequence, several Cost Benefit Analysis (CBA) procedures for IVHM have been proposed to determine the improvements in support cost and vehicle availability (Leao et al., 2008; Banks and Merenich, 2007; Hoyle et al., 2007). Some have even gone further by proposing methodologies to optimize the design of certain tools from a CBA perspective (Kacprzynski et al., 2002).

Calculating the decrease in maintenance cost and time is crucial to justify the investment on a certain tool. Quantitative methods focus on three main areas:

- Reducing maintenance time using diagnostic tools.
- Deferring jobs until they can be carried out along other scheduled activities using prognostics.
- Reduce the stock of components and delays by improving logistics (Khalak and Tierno, 2006).

As a result, CBAs for IVHM technology are carried out considering the following areas (Banks et al., 2009):

- Coverage of the health monitoring system
- Cost of development and implementation
- Cost of operation of the new IVHM system
- The expected range of missions to be flown
- The expected scheduled maintenance operations

However, the knowledge that can be inferred from the exponential increment of data generates all sorts of additional benefits. These tools can be used to, among other things, enforce quality policies (Benedettini et al., 2009), to reduce costs in manufacturing, testing and certification phases (Scandura, 2005; Trichy et al., 2001), to react automatically to a fault (Kurien and R-Moreno, 2008); and to generate all sort of benefits for stakeholders that are not directly involved in manufacturing, supporting or operating the vehicle (Wheeler et al., 2009). It is important to realise that some of these secondary benefits can be used to develop new business practices with the potential to reshape the way cash flows through the aerospace sector (Hess et al., 2006).

At the same time, regulations already in place impose numerous limitations to the benefits these systems can bring. Many scheduled checks and replacement of components must be followed regardless of the indications of a health monitoring tool. As a consequence, in many cases it is necessary to wait until they are proven reliable to modify the standards being followed. Only once this point is reached it is possible to start to perceive a return on the investment.

Although it is possible to enumerate the multiple advantages and disadvantages of installing health monitoring tools on an aircraft, it is necessary to determine which are really relevant for each platform. Evidently there are major differences in the way stakeholders perceive these issues for different vehicles, specially taking into account how the goals change from civilian to military platforms (Williams, 2006). We focus on military aircraft and the effect of the support system put in place by military organizations on the use of IVHM technology.

1.1 Outsourcing

The maintenance of military aircraft has been increasingly outsourced, mostly to companies or divisions that are part of aircraft or engine manufacturers and act as maintenance service providers. Originally, these maintainers carried out scheduled activities of high technical complexity and workload, also known as depth maintenance activities. Air forces remained in charge of daily operations to ensure the airworthiness of aircraft between flights in what is normally known as forward maintenance. In recent years forward maintenance has started to be outsourced to a higher or lesser degree for some platforms, even with contractors deployed overseas.

The complexity of the contracts between air forces and maintainers means that there are nearly as many outsourcing formats as contracts. One of the extremes corresponds to those agreements where the maintainer charges the operator for every single job (meaning there is no incentive to reduce maintenance costs). On the other hand, availability contracts ensure the operator is charged based on the availability of the vehicle, regardless of the cost to the maintainer.

Stakeholders' objectives depend on the characteristics of these contracts since they define the way maintenance costs are allocated and availability objectives achieved. The observations made here are intended to include those issues IVHM will face in the near future; the relevance of some of them to specific platforms will depend on the details of the agreement between the maintainer and the operator.

1.2 Regulations

The benefits of predicting the failure of a component or reducing the time necessary to diagnose a problem are obvious, however current military regulations my undermine some of them. Barriers to install onboard IVHM tools or the continuance with standardise maintenance practices made redundant with new health monitoring tools are some of the regulatory obstacles that reduce the chances of technically sound tools being implemented.

Both NATO and British Ministry Of Defence (MoD) standards were studied to identify the most problematic areas. Given the similarity of the practices between major western air forces and the uniformity of some procedures imposed by NATO, the findings mentioned are relevant to several nations.

1.3 Questionnaire

In order to obtain information on the frequency of certain maintenance activities and the amount of resources and time dedicated to them a questionnaire was prepared. The questionnaire was then used to gather the opinions of experts on maintenance of military aircraft. The objective was to get information that could be used to infer the relative importance of the numerous benefits and challenges often mentioned in the literature and to identify those that could be missing.

The results from the questionnaire are not exact figures extracted from the analysis of maintenance logs of a specific type of aircraft. Experts provided approximate average values for the range of vehicles operated by a modern air force that comprises aircraft with a wide range of ages, sizes and roles.

2. FOCUSING ON THE RIGHT MAINTENANCE PHASE

The ultimate goal of IVHM is to defer as many maintenance activities as possible so they can be carried out when the impact on the availability of the aircraft is the lowest possible. In essence corrective maintenance jobs would be transformed into predictive maintenance tasks. Additionally, flight servicing between missions could be accelerated by reducing the time necessary to determine the condition of the aircraft. However, the use of health monitoring tools has proven to be counterproductive on some cases (Swearingen and Keller, 2007; Keller et al., 2001), making the flight servicing longer and more unpredictable, with the latter possibly being the most disruptive side-effect.

There are two main flight servicing regimes followed by most air forces in the world. The first consists of Before Flight (BF) servicing, After Flight (AF) servicing and Turn Round servicing for those cases when the AF is still valid and the aircraft can be deployed after a set of preventive maintenance tasks. The second regime consists of Technical Flight Servicing (TFS), which is valid for a defined period; and Daily Flight Servicing (DFS), which comprises those tasks necessary to ensure the aircraft can be deployed at any time during the following 24 hours.

For the last two decades there has been a continuous increase in the coverage of Built In Test Equipment (BITE) used on board aircraft. At the same time, the introduction of digital avionics and data buses enabled the storage and continuous monitoring of an increasing number of parameters. Consequently, the number of components and subsystems with some degree of diagnostic capability has grown.

However, as increasingly complex subsystems started to be monitored and the interactions between them became more numerous and intricate, the reliability of the BITE was affected. Consequently, false positives or false alarms have become a major source of problems in modern aircraft.

As for the parameters being monitored, many of them were given thresholds that produce a fault code if reached or crossed. Since military aircraft are often operated at the limit of their capability, it is not uncommon to have to go through numerous fault codes after each flight. These arisings need to be checked by experienced personnel and sometimes require further checks to discard certain faults as the cause for the code being flagged.

As a consequence, the duration of post flight servicing has not only increased but also become more unpredictable. This represents a major problem for mission planning, especially for those squadrons that fly the same airplanes several times per day.

Thus, in the short term IVHM technology is more likely to produce benefits if it is aimed at increasing the reliability of diagnostic systems already in place and to speed up the analysis of the numerous occasions thresholds are crossed.

3. ANALYSIS OF SECONDARY BENEFITS OF IVHM

3.1 Flight Tests

Most CBAs focus on the how computer aided diagnoses improve the efficiency of maintenance jobs by reducing the time necessary to identify and isolate a fault. If a prognostic tool is being considered, the deferral of the job until it can be carried out at more convenient time is regarded as the main benefit. In some cases the increase in the number of missions completed successfully is also taken into account in the analysis. However, the effect of flight tests is rarely mentioned in the literature and is missing from most comprehensive quantitative CBAs.

Flight tests are common practice for diagnosing problems or for checking that a job on some critical system (e.g.: helicopter rotor) was completed correctly. The decision to use a health monitoring tool on a certain component is normally based on the frequency of failure of the component, the time necessary to repair it and its cost. However, flight tests can be necessary on cheap reliable components which are not normally regarded as candidates for the use of IVHM. Perkins (2011) showed how the cost of replacing a rotor bearing on a Chinook is largely driven by the cost of the test flight, which is several orders of magnitude higher than the cost of replacing the part. If the maintenance of the vehicle is outsourced, the cost or loss of availability due to a test flight might not be considered critical by the maintainer, but it still affects the operator.

While the cost of a flight test can be easily calculated, the allocation of the cost and the analysis of the effect of the test on the availability of the vehicle might not be that simple. Depending on the requirements the test can be carried as part of a routine flight (known as Partial Test Flights, PTFs) or it might need a specific maintenance flight (known as Maintenance Test Flights, MTFs). It is not uncommon for test flights to be repeated because additional work or adjustments need to be made (e.g.: helicopter rotor balancing). Diagnostic and prognostic tools have the potential to reduce the duration of certain test flights or even eliminate them, but computer models which simulate both maintenance operations and fleet management are necessary to quantify the improvement on availability.

According to the answers to the questionnaire, approximately only 10% of test flights are MTFs, which can lead experts to believe that analysing the potential of IVHM to improve costs and downtimes in this area is not worth the effort. However, the answers also showed that about 70% of PTFs are not carried out in combination with a routine flight, effectively having the same impact as an MTF. This shows that operational demands play a major role in the way flight tests are planned.

The benefits of IVHM rely on the correct and efficient use of the information health monitoring tools produce by maintenance and mission planners. This issue illustrates how important it is to determine whether the data generated by a diagnostic or prognostic tool will be put to use in order to make sure the estimated return on investment is accurate enough.

3.2 Training

It is often claimed that the use of computer based diagnosis and electronic documentation can help to reduce the amount of time personnel dedicate to training. While this claim is evidently true, it was not clear to what extent this would produce a significant improvement in personnel availability and productivity.

According to the answers to the questionnaire, it is estimated that, over a year, nearly 10% of the total man-hours are spent on training, 50% of which are dedicated to learning on check, damage evaluation and failure diagnosis. Therefore, the gain of man-hours due to a reduction in training by the use of diagnostic tools would be, at best, 5%. Nevertheless, there is potential to make important savings if less experienced personnel (with lower salaries) can be dedicated to more complex tasks thanks to the use of IVHM.

3.3 Administrative tasks

Regarding the personnel working in the technical offices, it is estimated that 30% of their total man-hours are spent on administrative and logistic affairs, meaning that the use of automated decision making tools could help to reduce not only the delays, but also the fixed costs of personnel. Currently, less than 25% of the time left is dedicated to activities aimed at improving the efficiency of the maintenance process, part of which is spent analysing historical maintenance data, something that could be significantly reduced if IVHM data-based tools are implemented.

The questionnaire helped to shed some light on the effect administrative task have on the availability of personnel with hands on the aircraft. Of all the delays affecting maintenance tasks between 10% and 15% are delayed because the necessary personnel are not available. Most of the delays come as result of the maintenance tasks requiring more time than that available between missions. Therefore, little improvement can be expected from focusing on micromanaging workers, given the complexity of such task, compared to what can be achieved by using IVHM to improve the performance on logistics and administrative tasks. Especially taking into account that approximately between 10% and 15% of maintenance personnel's time is dedicated to administrative tasks, a proportion that can be reduced as the different IVHM tools become more integrated with logistics.

3.4 Auditing

Maintenance practices of legacy aircraft must be reviewed to take into account any unforeseen changes in the way they are operated, their components degrade or the way they impact the support systems of other platforms. Structural, systems and propulsion audits are carried out to verify the airworthiness of the aircraft and that the operational and maintenance costs are under control. Normally, the first set of audits starts 15 years after the aircraft was declared in service or at 50% of its expected operational life. In most air forces these audits are to be repeated every 10 years.

These audits are exhaustive and can take years to complete resulting in a significant expense. The analysis of historical maintenance data is the core activity of these audits and requires going through numerous documents to put the information together before any kind of analysis can be performed. Health monitoring tools can store the same information in digital format making it accessible at any time much faster than it used to be. Additionally, they allow for much more component-specific information to be stored, improving the detail of the analyses that can be carried out. Furthermore, data mining techniques can be used to detect trend hidden in the data that would be missed in a conventional audit.

3.5 Quality policies

Most maintenance organizations that work on the support of military aircraft, either subcontractors or ministries of defence, meet the basic requirements of ISO 9001. This quality policy is to be applied to both fixed and rotary wing aircraft.

In case an issue regarding the quality of any of the activities or systems involved is detected it must be reported immediately through the generation of an occurrence report. The quality of an activity is considered to be compromised when normal fault reporting cannot be applied, problems with the technical information have been detected, problems regarding the information contained in reports are found or when there is suspicion of a deficiency in the management of the quality policy (UK Ministry of Defence - Military Aviation Authority, 2010a; UK Ministry of Defence - Military Aviation Authority, 2010b).

Time is normally an important factor when these occurrences are investigated since most organizations expect that the report must have been received, the matter must be studied, and subsequent action recommended, within 7 working days.

Health monitoring tools can help on two main areas regarding this matter. First, they provide additional data that can help to better understand the issue in a format that allows for all sort of computer-based analyses to be carried out. Second, they are time-saving tools that accelerate the generation of occurrence reports and investigation of the problem. And third, a comprehensive health monitoring system implemented on the whole fleet can be used as the basis to partially automate the detection of deviations from the quality policy by detecting abnormal fault rates.

3.6 Logistic Information Systems

A Logistics Information System (LIS) comprises electronic information tools used for the management of the logistics operations capable of performing any combination of the following functions (UK Ministry of Defence, 2010):

- Administrative
- Financial
- Asset management
- Maintenance management

Although there are LISs already in place to a higher or lesser degree in most modern air forces in NATO, currently they are normally limited to electronic tracking of orders and stock, with no automation based on the information from IVHM systems.

The integration of logistics with the use of health monitoring tools is key to ensure the success of an IVHM system, but it is important to keep in mind that, according to the answers received to the questionnaire, about 10% of the times an aircraft is not available for a mission the cause is a logistics or administrative delay. Although this shows that an improvement in the management of logistics can have a noteworthy impact on the availability of the aircraft, it is necessary to keep in mind that the cost of developing and implementing these technologies is high and might not justify an increase in availability that might not reach 10%.

3.7 Data transfer and management

Most health monitoring systems currently in use, such as HUMS (standard in all modern helicopters) or Typhoon's Integrated Monitoring and Recording System (IMRS), rely on some sort of Portable Maintenance Data Stores (PMDS) to download the data. PMDSs are memory cards that are removed after each flight and then taken to a ground station. Although sometimes it is possible to read the arisings onboard through some kind of Maintenance Data Panel (MDP) installed on board of some aircraft, it is still necessary to download the information from the PMDS to carry out an analysis with enough depth.

All the steps involved in this part of the process can take several minutes, especially in those cases in which the data are first sent to a centralised system and then they have to be requested from the ground station again, increasing the amount of time wasted. This must be acknowledge in the CBA to make sure the time gained through installing an IVHM tools does not end up wasted transferring the data.

4. CURRENT CBM STANDARDS AND IVHM

Most air forces have been using Condition Based Monitoring (CBM) for some systems for long enough to become part of their regulations. As a result, these practices will not be abandoned automatically if a continuous health monitoring tool is installed on a vehicle since that would be in violation of the regulations. Consequently, there is not saving associated with the use of a new tool that performs the same function as one of these CBM procedures. Furthermore, the cost of development and implementation of such tool cannot be justified unless the accuracy of the new tool exceeds that of the current procedure considerably.

It is possible to develop an IVHM tool to replace a CBM technique that is currently part of the military standards if the objective is to advocate for the derogation of the standard once the tool is proven reliable. However, this introduces a significant delay in the profitability of the project and is a significant risk that must be taken into account in the CBA.

The following CBM procedures are the most common and widespread among nations that are part of NATO.

4.1 Vibration Control

Vibration monitoring is a widespread method to assess the health of all sorts of rotating equipment and it is used on aircraft engines, transmissions and even structures. Forward maintenance organizations must measure the vibrations after maintenance activities such as rectification, fitting major assemblies, events that may have affected the natural frequency of some systems (e.g., heavy landing, bird strike) or if the crew reports an abnormal vibration in the aircraft.

Special groups are in charge of analysing data gathered by systems such as HUMS and provide technical assistance to the operating units. Any diagnostic tool that uses vibrations as an indicator of a fault will probably be affected by these regulations and should try to make the most of the means available to reduce development and operational costs.

4.2 Wear Debris Monitoring (WDM)

Those systems that use some sort of lubricant can be subjected to debris monitoring to detect excessive friction or abnormal loading that, eventually, can lead to the failure of the system. WDM is specially suited for rotating machinery and hydraulic systems in which the content of metallic particles in the oil can very useful for the detection or prediction of faults.

Spectrometric Oil Analysis Programme (SOAP), Magnetic Detector Plug (MDP) and filter debris assessment, and The Wear Debris Management System (WDMS) are the techniques normally used. Normally, the samples are analysed using a centralised system which will remain operative if a new IVHM tool performs the same function.

4.2 Hydraulic Fluid Monitoring

The cleanliness of hydraulic fluid is defined by NATO standards (NATO, 2006) and must be monitored regularly. Particles, water and other contaminants must be monitored to ensure the integrity of the hydraulic system is not compromised by the use of inadequate fluid. Some of the different techniques that can be used for this purpose are: CM20 particle counter, Patch testing, Filter Examination, Compar testing, HIAC particle counter, etc.

As with WDM, a set of laboratories specialised on making these analyses is already in place, reducing the profitability of an IVHM that tries to replace their function.

5. CONCLUSIONS

This work sets the basis for a deeper analysis of the secondary benefits of using IVHM on military aircraft. Although the main target of CBAs regarding IVHM technology is to quantify the direct impact of using a set health monitoring on the time and cost of maintenance tasks, as it has been shown here, there are all kinds of additional aspects that must be taken into account to make an informed decision.

Some of the secondary benefits often mentioned in the literature have been proven to have little impact on maintenance costs or the availability of the aircraft. On the other hand, the study of current military practices and regulations has helped to discover some additional benefits that are worth analysing in more detail.

During the life of an aircraft, audits are to be carried out periodically. They can be carried out quite deeply and an important amount of resources may be allocated to perform them. If they were to be combined with a viability analysis this would reduce its cost and, what is more important, would take advantage of a "time window of good faith" during which operators and OEMs are more willing to share information than under normal circumstances.

Any tool developed to bridge the gap between the diagnoses and predictions generated with IVHM tools and the logistics systems will have to take into consideration the characteristics of the current LIS and how regulations impose certain constrains on the automation of the management of the logistics. Nevertheless, this presents an important advantage for the developer, since regulations provides a framework on which some requirements are already defined.

Since there some data gathering systems already being used by air forces such as HUMS there is a record of different parameters during several flights. Therefore diagnostic and prognostic algorithms should be based on the data already provided by these systems. In case the objective is to retrofit this technology on legacy aircraft, it seems logical to take into account the limitations imposed by the existing recording systems on the quantity, resolution and accuracy of the parameters fed to any IVHM tool.

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