Smith Industries HUMS: Changing the M from Monitoring to Management[1]

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Abstract—There is an on-going drive to expand the benefits achievable from Health and Usage Monitoring Systems (HUMS). In order to facilitate this expansion, the function of a HUMS needs to evolve from one of monitoring into that of management. This paper explains the differences between the two types of system and the benefits achievable from these. A number of examples are presented to illustrate the considerable amount of development activity being undertaken which has the common aim of producing a new generation of Health and Usage Management systems.

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1. INTRODUCTION

Smiths Industries Aerospace (SI) are a world leader in the implementation of Health and Usage Monitoring Systems (HUMS) and in the development of HUMS technologies. This paper describes how the "M" in HUMS is evolving from "Monitoring" to "Management". The significance of this evolution can be understood from the following definitions:

- Monitoring: To maintain regular surveillance over, or close observation over.
- Management: To organize, regulate, take charge of, take control of, make proper use of.

The last decade in the 20th Century saw the arrival of Health and Usage Monitoring Systems, first on helicopters and latterly on military fixed wing aircraft. This started in the United Kingdom (UK), with systems being fitted to helicopters operating in the hostile environment of the North Sea. The driver behind the introduction of these systems was a requirement to improve helicopter safety. The need to improve safety demanded a significant advance in the provision of health monitoring for the helicopter's engines, drive train and rotor systems. With its comprehensive vibration monitoring functions, this advance has been effectively provided by HUMS.

The first decade in the 21st Century will see a transition in emphasis from Health and Usage Monitoring to Health and Usage Management. The change is due to the fact that, having already demonstrated an ability to improve safety, there is now another clear driver of HUMS. This is the requirement for an effective tool to streamline maintenance, make this more cost effective, reduce an aircraft's logistics footprint, and improve aircraft availability. These goals cannot be achieved by simply providing a monitoring function, they require a management function.

2. HUMS CHARACTERISTICS AND BENEFITS

20th Century HUMS: Health and Usage Monitoring

A 20th Century HUMS can be characterized as follows:

- Monitoring: The emphasis is on providing diagnostic data to detect and diagnose faults to indicate a requirement for maintenance action.
- Health: The focus has been on improving safety by detecting faults which represent a hazard to airworthiness.
- Usage: The usage monitoring performed has been relatively simple and largely limited to an automating of the aircraft logbook.
- Data: While HUMS has provided a significant advance in the quantity and quality of data available on aircraft, this has largely remained in the form of data rather than being transformed into information.
- Stand-alone: HUM systems have mostly been stand alone systems in two respects - the HUMS ground stations have not been integrated with other aircraft maintenance management or logistics systems, and the HUMS outputs have not been fully integrated into the aircraft maintenance policy.

Despite the limitations of the above characteristics, current in-service helicopter HUM systems have provided significant safety and maintenance benefits.

Achieved Benefits—The UK Civil Aviation Authority (CAA) have gathered and analyzed HUMS data from the North Sea helicopter operators (reference [1]). They have obtained information on 63 airworthiness related arisings, where an arising is defined as an event which has led to significant maintenance action. HUMS successfully detected approximately 70% of these arisings. The CAA classified 6 of the arisings which were successfully picked

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up as potentially catastrophic and hazardous, and estimated that 1 or 2 of these would most probably have led to accidents if they had not been detected in time. The CAA have made the following statement (reference [2]):

"It is considered that the first generation HUMS, which added comprehensive vibration monitoring to existing health monitoring techniques, has already demonstrated the ability to identify potentially hazardous and catastrophic failure modes, and has already reduced fatal accident statistics."

The achieved helicopter maintenance benefits can be summarized as follows (reference [3]):

1. Simplified rotor track and balance procedures and reduced test flying for rotor track and balance.
2. Reduced airframe vibration levels, resulting in fewer avionic and other faults, and hence less maintenance and downtime.
3. Better planning of maintenance, as a result of being able to track developing HUMS indicator trends and take appropriate actions in a timely manner.
4. Better targeted maintenance as result of more accurate fault information.
5. As a result of the above items, reduced disruption to operations due to unscheduled maintenance and aborted flights.

21st Century HUMS: Health and Usage Management

This section looks at the characteristics and potential benefits of the next major evolution of HUMS - a Health and Usage Management System. A 21st Century HUMS can be characterized as follows:

- Monitoring: The emphasis is on providing diagnostic and prognostic data to predict requirements for future maintenance.
- Health: The focus is on giving early indications of potential problems for maintenance planning purposes.
- Usage: This key function will manage the usage of the aircraft and controls life expired component replacements.
- Information: The HUMS will convert monitoring data into information which facilitates the effective management of aircraft maintenance.
- Integrated: The HUMS will be an integral part of the aircraft maintenance management and logistics system, and the HUMS outputs will be fully integrated into the aircraft maintenance policy.

These expanded HUMS capabilities are targeted at the achievement of a level of benefit which goes well beyond that achievable with current in-service HUMS.

Target Benefits—The health and usage management function is aimed at providing the following additional benefits:

1. Significantly enhancing the ability to control and regulate aircraft maintenance by providing a new level of information on both the current and projected future health and usage status of aircraft.
2. Enabling greater flexibility to be built into maintenance cycles and simplifying recovery processes when there are deviations from established cycles.
3. Streamlining scheduled and unscheduled maintenance by providing accurate maintenance information and facilitating "maintenance credits", which are HUMS-facilitated modifications to scheduled component inspection, overhaul and replacement requirements.
4. Controlling component replacements due to life expiry (when and with what frequency) by regulating aircraft usage.
5. Reducing the logistics footprint by reducing spares holdings "just in case" something suddenly fails and communicating down the supply chain to facilitate "just in time" provisions of spares for deteriorating components.
6. Improving operational effectiveness by predicting maintenance free operating periods and allowing short duration increases in operational limits which can be safely compensated for in subsequent maintenance schedules.

Some of the above benefits may have already been claimed for HUMS but these cannot be fully achieved until systems can perform a true management function.

3. Smiths Industries HUMS Activities

The remainder of this paper will describe a range of SI's activities which are targeted on this next phase in the evolution of the HUMS concept - the move from monitoring to management.

SI has, over the last year or so, significantly strengthened their position as a world leader in HUMS. SI has created a world-wide network of companies with leading edge HUMS capabilities and technologies. SI's Data Management Systems organization (SI-DMS) has been strengthened by the addition of Signal Processing Systems (SPS) and Strategic Technology Systems Inc. (STSI). The company's position has been further enhanced by adding the combined forces of the HUMS specialists Stewart Hughes Limited (SHL) and MJA Dynamics (MJAD). SI-DMS is a world leader in the following areas:

- The number of HUM systems fielded
- The amount of HUMS in-service experience gained
- The range of HUM system options in-service and in development
- The development of leading edge HUMS technologies

SI-DMS are carrying out a range of activities related to the development of the management elements of HUMS. A selection of these activities, linked to the HUMS characteristics defined previously, are described to illustrate how a true health and usage management capability is being created.

4. DEVELOPMENT OF HUMS FUNCTIONS

While the terms Monitoring and Management may be considered to be related, evolving HUMS into a system with a comprehensive management function requires development in the three areas of:

1. Health and usage management technologies
2. HUM system implementation
3. Aircraft operational and maintenance policy and procedures

SI-DMS are actively engaged in development areas (1) and (2), and are working closely with a number of Aircraft and Engine Design Authorities on (3).

Monitoring - Diagnostics and Prognostics

A diagnostic function within an aircraft monitoring system is the identification of a developing fault based on detected symptoms. A prognostic function is the prediction of when aircraft maintenance will be required and parts will need to be replaced. The main focus of health monitoring has, to date, been on the provision of fault diagnoses. In contrast, the main focus of usage monitoring (which is considered here to include the monitoring of component loads and fatigue damage accumulation) is on the provision of a prognosis of when a component will require replacement.

The goal of a future health and usage management system is to provide both diagnostics and prognostics based on combined health and usage information. To achieve the desired benefits the system must provide early detection and diagnosis of developing faults and measurement of damage accumulation, then use Design Authority information to predict a safe operating period before any fault or damage propagates to a point at which maintenance intervention is required. This is an extremely demanding requirement and is expected to involve:

- The intelligent analysis of combined health and usage information.
- The input of Design Authority data and maintenance criteria.

Under a contract with the US Air Force Research Laboratory, MJAD and SHL are developing a demonstrator system for engine health management known as ProDAPS (Probabilistic Diagnostic And Prognostic System). This is a modular, open architecture, system which will accept different types of engine performance, health, usage and operating data. The system will use emerging technologies to analyze and fuse this data to provide early indications of developing faults and calculate damage progression to give a complete engine diagnostic and prognostic assessment. This is only possible because the companies are working closely with Pratt and Whitney on the project, so that the necessary Design Authority input can be provided. The demonstrator will be tested on engine data from both a ground based seeded fault test program and a series of flight tests. Assuming the demonstrator is successful, the next objective is to implement the ProDAPS in an on-aircraft system. The ProDAPS is described in more detailed in another IEEE Aerospace Conference 2000 paper, reference [4].

Health Management

One of the characteristics of HUMS is that it implements multiple health monitoring functions in one system, for example performance monitoring, vibration monitoring, oil system monitoring, and rotor track and balance. Traditionally, the data produced by each of these functions has been analyzed and interpreted in isolation.

Effective aircraft health management requires three elements:

1. The application of a comprehensive set of complementary health monitoring techniques. Different monitoring techniques are capable of detecting different types of fault, and there is no single technique which can detected all faults at which a HUMS is targeted. Therefore effective health management depends on the use of multiple monitoring techniques which have complementary fault detection capabilities.
2. The application of health monitoring techniques which can provide early fault indications. Health management relies on an ability to provide a sufficiently early fault indication to enable the planning of maintenance at a future time when the necessary spares are available and aircraft operations will not be not seriously disrupted.
3. The integration of the outputs from the different monitoring techniques to provide an assessment of the overall health of the aircraft.

Current in-service HUM systems go some way to meeting the first and second requirements, but not the third (examples of work on technologies and systems aimed at meeting this last requirement are given in this section). There is still considerable scope, however, for extending health monitoring capabilities to meet requirements (1) and (2) through the development of new monitoring techniques which can complement the established techniques. SHL have been developing and testing two such techniques, based on their electrostatic sensor technology.

The first technique, involving electrostatic monitoring of debris or particulates in the engine gas path at the intake and exhaust, has been developed over many years and validated on a large number of engine tests. Two systems have been produced which can be used either in isolation or, more effectively, in combination. These are the Engine Distress Monitoring System (EDMS) and the Ingested Debris Monitoring System (IDMS). The second technique, involving electrostatic monitoring of the oil system, is a more recent development and utilizes two distinct sensor types. The first is an Oil-Line Sensor (OLS), which is mounted in an oil line and can detect oil-borne debris including 'fine' and non-metallic particulate. The second is a Wear-Site Sensor (WSS), mounted adjacent to critical bearing and gear components, which provides advanced warning of component deterioration prior to any release of significant wear debris.

Both of the health monitoring techniques based on SHL's electrostatic sensor technology have been successfully demonstrated on a recent Joint Strike Fighter seeded fault engine test program. The techniques and the results of this testing are described in two further IEEE Aerospace Conference 2000 papers, references [5] and [6].

Usage Management

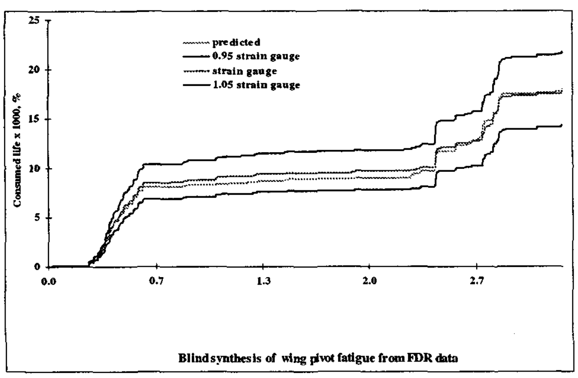
SI-DMS are undertaking two developments in different but related areas of usage management. These are a Fatigue and Usage Management System for the management of aircraft component fatigue lives and a Carefree Handling System for the management of aircraft operational parameters.

Fatigue and Usage Management System—In order to fully realize HUMS safety and maintenance benefits, MJAD has, over the last six years, proposed the introduction of probabilistic condition monitoring combined with effective information management. Developed by MJA Dynamics, the Fatigue and Usage Management System (FUMS™) is a probabilistic and prognostic model-based management system which extracts enhanced operational usage and maintenance information from Flight Data Recorder (FDR)-HUMS.

Sponsored by the UK MoD, MJAD has demonstrated the feasibility of probabilistic condition monitoring by synthesizing information from FDR measurements on both fixed and rotary wing aircraft (references [7], [8] and [9]). FUMS can synthesize such parameters as loads, stresses, Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF), creep and crack growth as well as temperature, torque, All-up-Mass (AUM) and Center of Gravity (CG).

FUMS can conventionally derive loads and fatigue damage directly from strain gauge data but can also synthesize loads, fatigue and other operational information indirectly from FDR data. Once trained, the FUMS mathematical network dispenses with the need for strain/load specific sensors and effectively provides 'virtual' sensing. Figure 1 illustrates an example of the indirect synthesis of structural component fatigue using FUMS compared to direct strain gauge derived fatigue.

Figure 1 Indirect synthesis of structural component fatigue



By providing an accurate FDR-derived prognostic capability FUMS can offer the following fleetwide operational and maintenance management benefits:

- Fatigue damage status, limitation and control leading to improved safety by providing advanced and accurate indication of excessive or unusual fatigue usage together with real-time structural integrity status for engines, transmissions, rotor system and fuselage. FUMS can also indicate defects growing under a low usage rate with undetectable symptoms.
- Optimized operational capability where the compliance of aircraft operations and usage profiles can be verified with Design Authority limits.
- Improved maintenance planning and scheduling through enhanced current and future usage assessment.
- Optimized spares holding resulting from direct information exchange with other logistics/maintenance management systems.
- Compatibility with existing HUMS. HUMS and FUMS complement each other. For example, accidental damage and maintenance induced faults can be detected by HUMS, and the effects of defects growing under normal usage conditions can be evaluated by FUMS. The architecture of FUMS provides HUMS with the management philosophy required for improving safety, reducing costs of ownership and increasing availability of aircraft (reference [7]).

Carefree Handling System—SHL has been working to extend the scope of HUMS to include helicopter carefree handling technology, which provides an aircraft operational management capability. Carefree handling is intended to tackle problems of high pilot workload and to manage operational parameters such as engine torque. Helicopter pilots must fly within strict limits related to the aircraft structure, aerodynamic conditions or control capabilities. These limiting parameters have traditionally been presented on gauges in the cockpit. However, during demanding maneuvers the pilots' attention is on the outside view, not on the gauges. The problem of workload grows when the pilot's attention is diverted by abnormal conditions. This may result in operational limit exceedances with the penalties of high maintenance costs and low mission effectiveness.

A carefree handling system has been developed under a UK Department of Trade and Industry (DTI) Advanced Flight Deck Technologies program. This comprises two main items: a collective lever cueing actuator and a carefree handling processor. The processor module used for the carefree handling system is SHL's Universal HUM Module (UHM), which was originally developed for HUMS applications. The carefree handling processor predicts future envelope exceedances and then calculates the appropriate cue. The processor implements a number of neural network torque prediction algorithms which predict the torque approximately 0.5 seconds ahead using current and past aircraft data. The cueing actuator provides a tactile cue to the pilot through the collective lever either in the form of a "soft stop" (CFH A) or a "stick shake" (CFH B) as shown in Figure 2. The system has been evaluated on a helicopter advanced engineering simulator facility under a number of different scenarios to test this through a full range of helicopter flying tasks. Figure 2 shows the subjective workload experienced by the pilots as recorded in a debrief questionnaire.

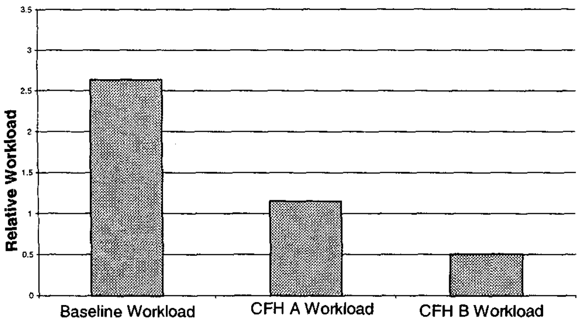


Figure 2 Relative workload

This clearly shows a very significant improvement for both variations of the carefree handling system over the baseline system, with the shaker showing the most improvement. In addition to reducing workload, the system is intended to aid the pilot in torque management, Figure 3 shows the duration of exceedances during a flyaway task.

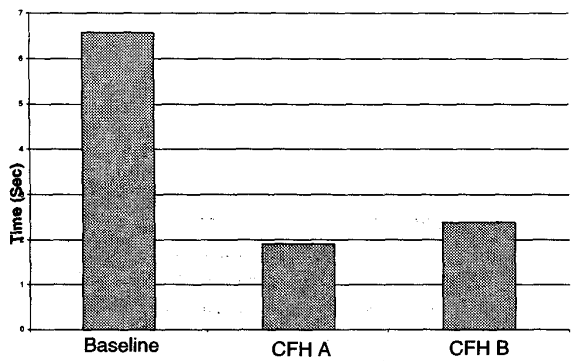


Figure 3 Duration of exceedance (Flyaway task)

In addition to approximately halving the torque exceedances during the flyaway task, the system also made a significant improvement in task performance. The results that have been produced to date clearly show the benefits of a carefree handling system in the 4 key areas of: workload, external situational awareness, task performance and torque management.

Management Information

Helicopter HUMS generate huge quantities of data. The current generation of in-service diagnostics are generally efficient at recognizing faults for which the HUMS has been manually configured. However, scope for both false and missed alarms with many current HUMS implementations remains high: operational effects can produce false alarms and there exists limited capability to detect previously unseen faults and automatically learn the characteristics of faults once they have occurred. In addition HUMS operators must frequently make decisions based on the interpretation of multiple data types. The problem of 'fusing' this data to reach a decision on the overall health of the aircraft is made more difficult by differing sampling rates and fault patterns between data types.

MJAD has successfully developed a range of Artificial Intelligence (AI) fault detection techniques to enhance the quality and fusion of HUMS derived data automatically and hence remove many current HUMS limitations (references [10] and [11]).

Two such AI fault detection techniques, namely Unsupervised and Supervised Machine Learning, are incorporated into the MJAD Pattern Learning Algorithm Toolkit (PLATO). The Unsupervised technique is a process that automatically detects atypical behavior and data trends without any prior knowledge for the reason for the behavior. The Supervised technique activates model-based pre-processing to remove operational effects and iterative classification processes to establish relationships between causes (mechanical faults) and effects (measurements). Processed data from multiple sources, such as vibration and oil debris in the case of diagnosing a gearbox fault, can then be 'fused' and corroborated to aid interpretation and final diagnosis.

Such techniques produce an enhanced diagnostic capability that offers the following fleetwide maintenance management benefits:

- Reduced manual management of large quantities of raw data.
- Reduced manual interpretation through automatic detection of significant trends.
- Reduced False Alarm Rate (FAR) through normalization of operational effects.
- Reduced Missed Alarm Rate (MAR) through enhanced and automatic diagnostics.
- Minimized depth of strip through enhanced and corroborated diagnosis.
- Improved maintenance planning and scheduling through improved fault isolation.

Integrated HUM Systems and Outputs

A health and usage management system must be integrated in the following respects:

- It must be integrated with existing computerized logistics systems to enable HUMS generated information to automatically update these systems and, where necessary, entries in the logistics system to update the HUMS.
- It must be integrated into the aircraft mission and defect information recording and maintenance planning workflows.
- Its outputs must be integrated into the aircraft maintenance policy, procedures and manuals.

SI-DMS are currently developing and implementing HUM systems which are, to varying degrees, integrated in all of the above respects.

GenHUMS—The Generic HUMS (GenHUMS) has been developed for the UK Ministry of Defence and is being installed on the Chinook fleet, with options for the Sea King, Puma and Lynx. The airborne and ground based system elements and interfaces are shown in Figure 4.

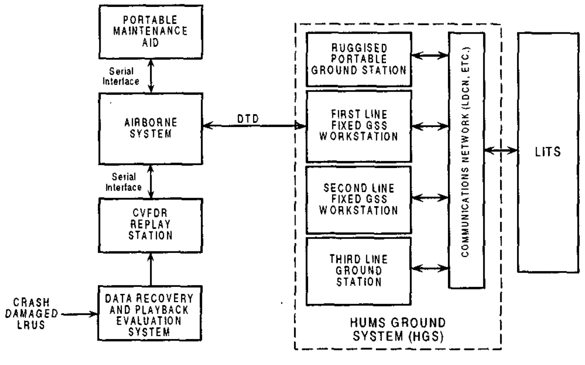


Figure 4 GenHUMS system elements and interfaces

GenHUMS ground stations are located at three different levels within the maintenance and support organization, providing management functions at squadron level, station level and fleet wide levels. The ground stations have the appropriate level of security classification to operate over the military local and wide area networks. The ground stations are also designed to have an interface with the RAF Logistics Information Technology Strategy (LITS) system. The system incorporates a rule base and rule editor for building diagnostics and a configurable facility to generate maintenance reports and actions.

Figure 5 shows how the GenHUMS is integrated with the pilot debriefing/briefing and maintenance recording processes.

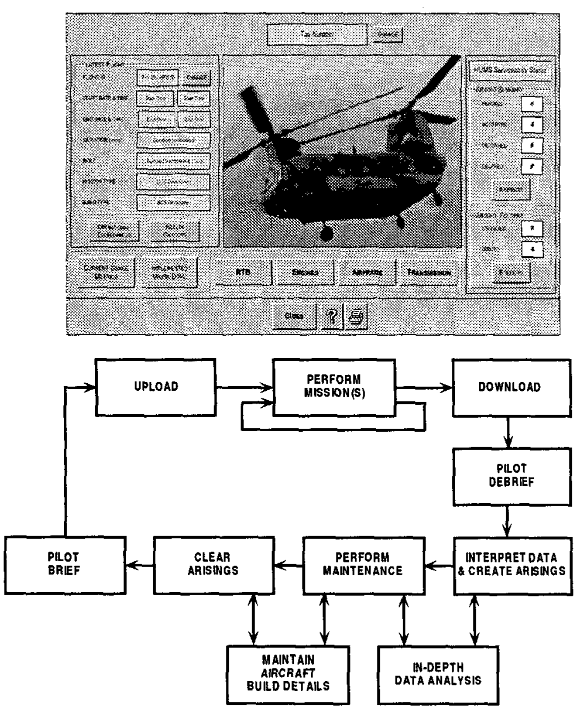


Figure 5 GenHUMS operation

BA609 HUMS—The Bell-Augusta 609 (BA609) is the first application of tiltrotor technology in a commercial aircraft. The BA609 HUMS is being developed in parallel with the aircraft and is directly derived from the GenHUMS system. Key HUMS features include airborne software and cockpit display unit certified to DO-178B Level B, and a new state-of-the art ground station that will be fielded on a portable computer provided with each aircraft.

The BA609 HUMS monitors the aircraft for exceedances, calculates usage, and monitors drivetrain components for condition indices. The ground station software, or GSS, provides direct links into the electronic maintenance manuals for the aircraft and engines. The aircraft dispatcher uses a "quick look" facility on the GSS to assess the aircraft operational status between flights without performing a time-consuming download of the entire data transfer media. Survey of the operational status of individual aircraft, groups of aircraft, or the entire fleet readily enables health trend identification and maintenance planning.

The BA609 HUMS GSS can guide the maintainer to the probable source of a discrete fault or exceedance and recommend solutions based on analysis of data and the condition indices. This fault-tree analysis is integrated with the maintenance manuals to provide efficient diagnosis and action planning.

Longbow Apache HUMS—A HUMS is currently under joint development for the Longbow Apache Helicopter by The Boeing Co., SHL and STSI. The system, which expands the capability of the current Maintenance Data Recorder (MDR), makes extensive use of the 1553 bus capabilities of the aircraft. Coupled with the existing capabilities of the Longbow Integrated Maintenance Support System (LIMSS), the expanded system will provide users with avionics diagnostics as well as traditional HUMS functionality without adding additional "boxes" on the aircraft.

The advanced diagnostic and data recording capabilities of the Longbow Apache have been upgraded in the U.S. AH-64D with the addition of the Longbow Integrated Maintenance Support System (LIMSS). The LIMSS replaces the limited data transfer cartridge with a maintenance data recorder (MDR). The MDR records up to 1700 fault indications, 210 warnings cautions advisories and exceedances, engine data, radar and TADS/PNVS data, and 175 safety parameters, with growth capability for 500 more parameters. LIMSS provides the maintainer with a Class 4, Interactive Electronic Technical Manual (IETM) on a portable computer, the Soldiers Portable On-system Repair Tool (SPORT). A fault diagnostics and ambiguity reduction program resides on the SPORT that interprets fault data downloaded from the aircraft and automatically directs the maintainer to the appropriate section of the IETM. The LIMSS offloads data from the aircraft to the SPORT via a 1553bus interface.

The Longbow Apache HUM system capabilities will include: rotor track and balance, engine and transmission vibration health monitoring, engine performance monitoring, airframe monitoring, aircraft, transmission and engine usage monitoring, exceedance monitoring, avionics diagnostics and voice recording functionality.

In addition to time based usage recording, Boeing is developing Structural Usage Monitoring System (SUMS) techniques that will analyze the data collected by MDR to give improved estimations of component lives based on the recorded flight data. These techniques have been developed and tested by Boeing on the Chinook helicopter and will be adapted for the Longbow.

5. CONCLUSIONS

The last decade in the 20th Century saw the introduction of the first true Health and Usage Monitoring Systems, these systems have now gained widespread acceptance.

The initial driver of HUMS was a requirement to improve helicopter safety. Now that this goal has been to a large extent achieved, HUMS is being adopted for both fixed and rotary wing aircraft with the objective of significantly improving aircraft maintenance processes. To achieve the new goal a new management function is required.

The first decade in the 21st Century will therefore see HUMS evolving into a Health and Usage Management System. Although it may appear to be a small step to change the M in HUMS from Monitoring to Management, this paper has shown that it can involve significant developments in both HUMS technologies and HUMS implementation.

The paper has presented a range of examples to illustrate how Smiths Industries - Data Management Systems are working towards the goal of providing comprehensive, state of the art, Health and Usage Management Systems.

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