The Use of On-Board Condition Monitoring, Usage Monitoring, Diagnostics, Prognosis, and Integrated Vehicle Health Management to Improve Aircraft Availability and Mission Reliability

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ABSTRACT

Smiths Aerospace Electronic Systems is working on a number of research programmes focused on extending and improving the existing monitoring functions on aircraft into true ***Integrated Vehicle Health Management*** *(IVHM). Chief amongst these are:*

- *TATEM (Techniques and Technologies for New Maintenance Concepts), a 40M€ European Commission project involving 60 companies from a wide spectrum of aerospace organisations, including airlines, airframers, suppliers and research institutes; and*
- *AEPHM (Advanced Electrical Power Prognostics and Health Management), a joint USAF AFRL project with Boeing Phantom Work, St Louis.*

These projects show the increasing awareness and interest in IVHM and the role that it has to play in increasing aircraft safety whilst also reducing the operating costs.

There is no doubt that improvements in the maintenance process can contribute to both improved operability and increased aircraft safety. With ongoing force size reduction programmes and ever increasing operational demands aircraft availability and mission reliability have become increasingly important over recent years, these two factors when combined with maintenance related costs give the overall measure termed "Operability". Experience has shown that it is simple to keep any two of these three parameters under control but the true challenge for the future is to optimise all three to ensure that the correct numbers of mission reliable aircraft are available at the minimum cost.

Recent civil aerospace studies have shown that maintenance activities can account for as much as 20% of an operator's direct operating costs and have remained at this level for many years. Detailed analysis of this shows that there is clear scope for increasing the efficiency of the maintenance process. For example, it is estimated that line mechanics spend 30% of their time trying to access information to diagnose and rectify failures. Additionally, the occurrence of the need for unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner.

In a recent survey the incidence of human error in the maintenance task was estimated as being a contributing factor in 15% of aircraft incidents.

Existing aircraft systems tend to be limited in both their collection of data and the integration of the available data sources. This has tended to lead to a situation where the operator can become overwhelmed by the variety and disjointed nature of data sources and "not see the forest for the trees". Modern IVHM systems are working to overcome this problem by integrating all the condition monitoring, health assessment and prognostics into an open modular architecture and then further supporting the operator by adding intelligent decision support tools.

There have been two major enabling technologies that has allowed IVHM to become a real system and provide these clear safety and costs benefits for operators.

The first is the evolution of modern integrated aircraft architectures. In older systems all data produced needed to be communicated by dedicated connections, to dedicated onboard data storage media for post-flight analysis using independent ground-based systems. This leads to additional weight and complexity on the aircraft, and then slow and unconnected analysis of the data on the ground.

Modern systems, such as the Smiths Modular Processing System (MPS), selected for the Boeing 787, Lockhead C-130 AMP and Northrop Grumman X-47, provide a modular computing hardware platform and partitioned operating system that will host the software applications of the airplanes avionics and utilities functions. The system replaces the traditional, unique, standalone, computers that are fitted to common aircraft. This Modular Processing System enables the evolution towards a truly integrated data management system which will enable data to be communicated in a common format in a common physical and logical maintenance infrastructure. This will include onboard communication media, air-ground communications media, air and ground computing resources and data storage and access devices.

The second major evolution is the publication of open standards for IVHM systems, the leading standard, which is being used on both TATEM and AEPHM, is the Open Systems Architecture for Condition Based Maintenance (OSA-CBM). This was developed under a NAVAIR Dual Use Science and Technology programme that completed in 2002. This published standard allows multiple companies to work together to produce the software components for an optimised IVHM system and ensures that all of the data is available in a single location, and format, for the operator.

The AEPHM programme is used as an example of an IVHM system, where microprocessors embedded in digitally controlled power distribution systems, as well as in the digital controllers within these systems, provide an unprecedented, affordable and inherent opportunity to monitor an electrically powered vehicle's systems health. Data transmitted to, and from, these controllers can be used to characterize the system and component operating signatures, thereby enabling advanced diagnostic and prognostic capabilities, through diagnostics, prognostics and decision aiding algorithms.

The AEPHM architecture supports system level fusion of evidence and state information from multiple sources to improve estimates of degradation. Phase I of the program was completed with an end to end, hardware-in-the-loop (electric actuator, fuel pump, fuel valve, arc fault, and power distribution unit) demonstration with on-line data generation to show the integration of the technology into a realistic setting.

1.0 INTRODUCTION

The concept of modern Integrated Vehicle Health Management (IVHM) Systems can be directly traced back the original Health and Usage Monitoring Systems (HUMS) developed for helicopter during the 1980s and 90s.

The concept of Prognostic Health Management (PHM) for engines has been widely embraced but the remainder of the aircraft still lags some way behind and this paper will look at how IVHM could help improve availability and how systems such as the Smiths Aerospace Common Core System (CCS) will allow this to happen.

Figure 1, shows how early warnings of failed components allow the ground crew to prepare for the arrival of the aircraft and hence reduce the time required for turn-around. It also shows how, if the fault can be detected at an early stage, the need to perform maintenance at the turn-around might be eliminated. Whilst these potential benefits are well understood and have been written about for many years [1], no comprehensive health management systems are yet in service, this paper will look at the reasons for this and showcase recent work which demonstrates that the technology is now finally ready for such a system to work in practice.

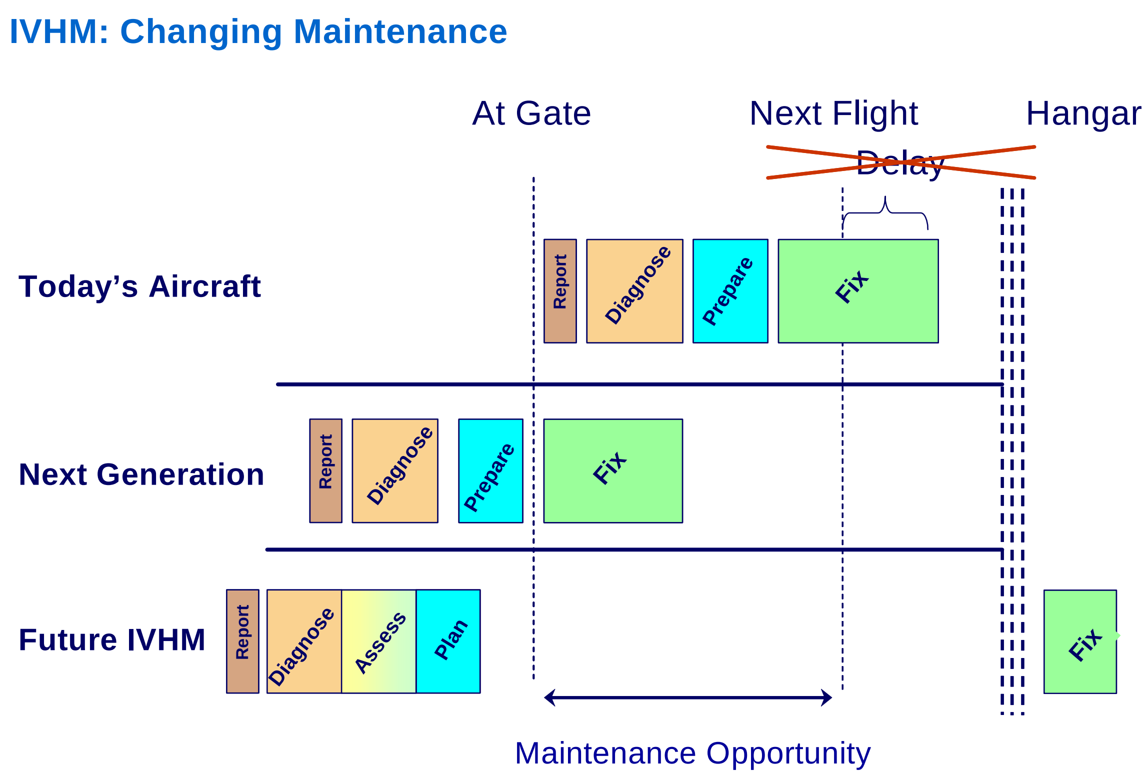

Figure 1: The effect of IVHM on TAT.

2.0 PROBLEMS OF SYSTEM BY SYSTEM PHM APPROACH

Historically Health Monitoring Systems have been implemented on "where necessary for safety" basis. This has created a situation where an aircraft may have several separate Health Monitoring Systems for specific parts, classically the engines on fixed-wing aircraft and the drivetrain on helicopters.

This approach has led to several significant problems when attempting to scale this up to the whole aircraft, namely:

- Weight: For most PHM systems most of the weight is classically in the wiring, so scales as a factor of both aircraft size and the number of systems monitored.
- Cost: Buying and installing **separate** monitoring systems for each aircraft system would be an enormous investment and undertaking. Any such installation would undoubtedly require the aircraft to be out of service for sometime, hence further increasing the costs. As a baseline it currently costs up to £100,000 ($180,000) to buy and fit a helicopter HUMS to cover the drive-train.
- Complexity: By purchasing independent monitoring systems for each aircraft system the operator could have to deal with multiple ground stations and interfaces and train their personnel to use all of these separate systems. Also, it is highly probable that these systems could, and at times would, provide contradictory results.

These have often been cited as the reasons why there has not been more widespread uptake of Health Monitoring Equipment. One of the first programmes to invest in a comprehensive IVHM system was the Joint Strike Fighter (JSF), where mission readiness and availability requirements have driven the need for IVHM.

3.0 MODERN AIRCRAFT SYSTEMS

One of the biggest changes in the design of modern aircraft systems has been the development of Integrated Modular Avionics systems. These systems such as the Smiths Aerospace Common Core System (CCS) selected for the Boeing 787 provide a common avionics platform on which multiple applications can be run in parallel. This has provided a major breakthrough in terms of both hardware and especially software with these common systems providing a suitable platform for running numerous applications with different requirements and criticality levels without needing a separate “box” for each system.

As part of this seed change in the design of systems, aircraft have implemented high speed digital buses such as IEEE-1394B, on JSF, and AFDX, on 787 and A380. The Smiths Remote Interface Unit (RIU), Figure 2, variants of which have been selected for both JSF and 787, allows up to 200 signals to be collated near to the point of generation and streamed onto these buses hence reducing the wire count by up to 2 orders of magnitude.

Figure 2: Smiths RIU.

Once these signals have been collected by the RIU they can be made available in the central CCS in a standard format making any storage, processing and further distribution much simpler.

4.0 CONCEPT OF IVHM

These modern systems have finally allowed the realisation of IVHM as the RIU / RDC and CCS combination has tackled the major challenges identified above.

- Weight: The RIU / RDC has eliminated the excessive wiring that would have been required for multiple individual systems. Also the CCS allows the IVHM software and algorithms to be run alongside the other airborne software avoiding the need for dedicated IVHM hardware, even extending as far as utilising the aircrafts normal communication methods, a major breakthrough compared to the dedicated PCMCIA card readers classically required in the cockpit for helicopter HUMS.
- Cost: By utilising the existing aircraft hardware in terms of both processing and network capability the cost of installation now becomes one of sensors, something that modern "virtual sensing" techniques are tackling, and software which can be installed without significant aircraft downtime.
- Complexity: By transmitting all of the data over common buses and to a common core the complexity is greatly reduced and this has been tackled even further by developments such as the Open Systems Architecture for Condition Based Maintenance (OSA-CBM) initiative [2-5]. The maintenance technician can now expect one coherent interface to the entire maintenance system. Current research is looking at taking this even further to provide a "Process-Oriented" structure to the data displayed at the point of need [8].

In addition to this it has also placed all of the data in one place which has opened up the possibility to see the bigger picture of how the aircraft is performing, this truly is a case of the "the whole is greater than the sum of the parts".

However to realise a workable system still requires an open software architecture where airframers, equipment suppliers and specialist PHM companies can provide the tools to turn this data in to information, knowledge and finally actions. This is where developments such as OSA-CBM are allowing the further realisation of these systems.

The goal of OSA-CBM is "to facilitate the integration of PHM components from a variety of sources. OSA-CBM is striving to build a de-facto standard that encompasses the entire range of functions from data collection through the recommendation of specific maintenance actions".

OSA-CBM has now been published as a Machinery Information Management Open Systems Alliance (MIMOSA) standard, defining an open architecture for implementing IVHM systems. It is a cross industry standard, which, for aerospace, has been implementations in development by Boeing Phantom Works, Smiths and the TATEM project. The OSA-CBM framework is shown in Figure 3, and full documentation, UML models and XML schemas may be downloaded from the MIMOSA and OSA-CBM websites [2,4].

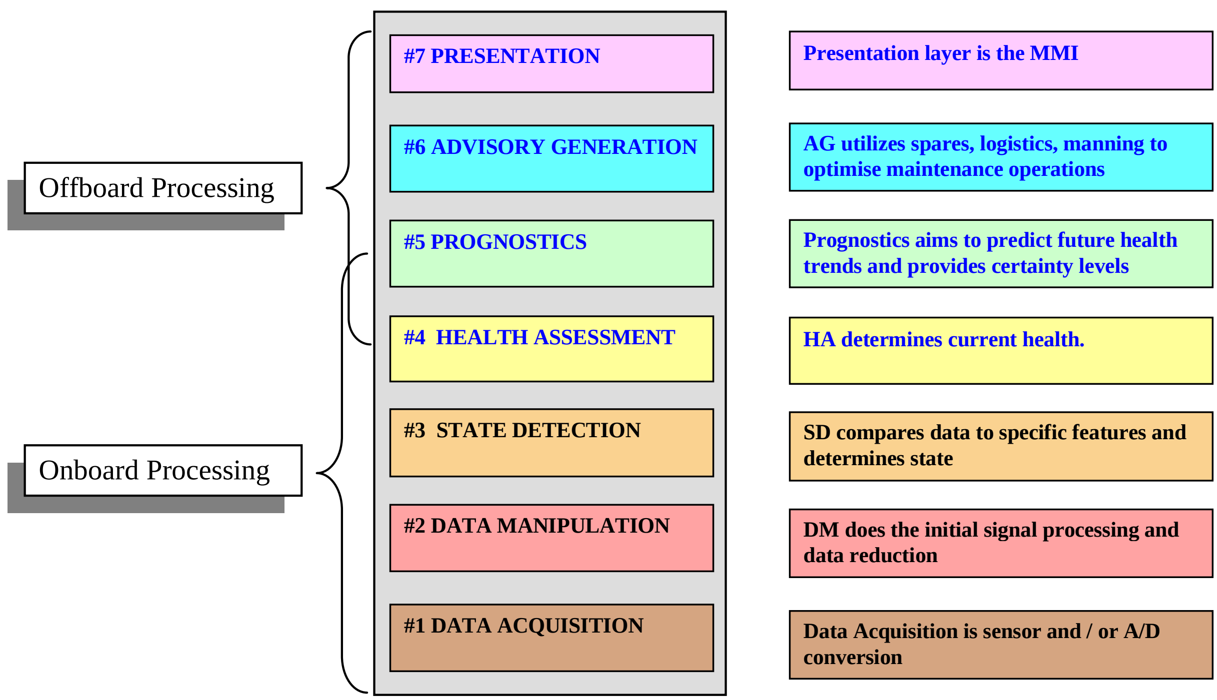

Figure 3: OSA-CBM.

The combination of the RDCs to remove the dedicated sensor wiring, common computing platforms such as CCS and the maintenance software architectures such as OSA-CBM have now made it possible to have the benefits of PHM without the pain, and this is the true concept of IVHM.

5.0 AEPHM

5.1 Introduction

As an example of a future IVHM system application for a military aircraft and the use of the generic approaches described above, this paper will look at the Advanced Electrical Power Prognostics and Health Management (AEPHM) programme.

The Aircraft AEPHM program was a Dual Use Science and Technology (DUS&T) program being sponsored by the Air Force Research Laboratory (AFRL-PRPE) Power Division. Boeing Phantom Works in St. Louis was the prime contractor for the AEPHM program with Smiths Aerospace as the principal subcontractor.

The objective of the program was to demonstrate health management technologies that will enable condition based maintenance and thus improve the availability of military aircraft, and analogously, the dispatch reliability of commercial aircraft. Aircraft electrical power distribution systems receive increasing focus on safety concerns in both civilian and military aircraft. The trend toward more electric aircraft is accelerating the incorporation of flight-critical electrical components such as actuators, fuel/hydraulic pumps, valves, or fans. Methods to accurately predict impending failure of electrical loads and to predict/protect against arcing faults in aircraft wiring will improve flight safety in addition to enabling more predictable aircraft operation.

The outline of the AEPHM programme can be seen in Figure 4.

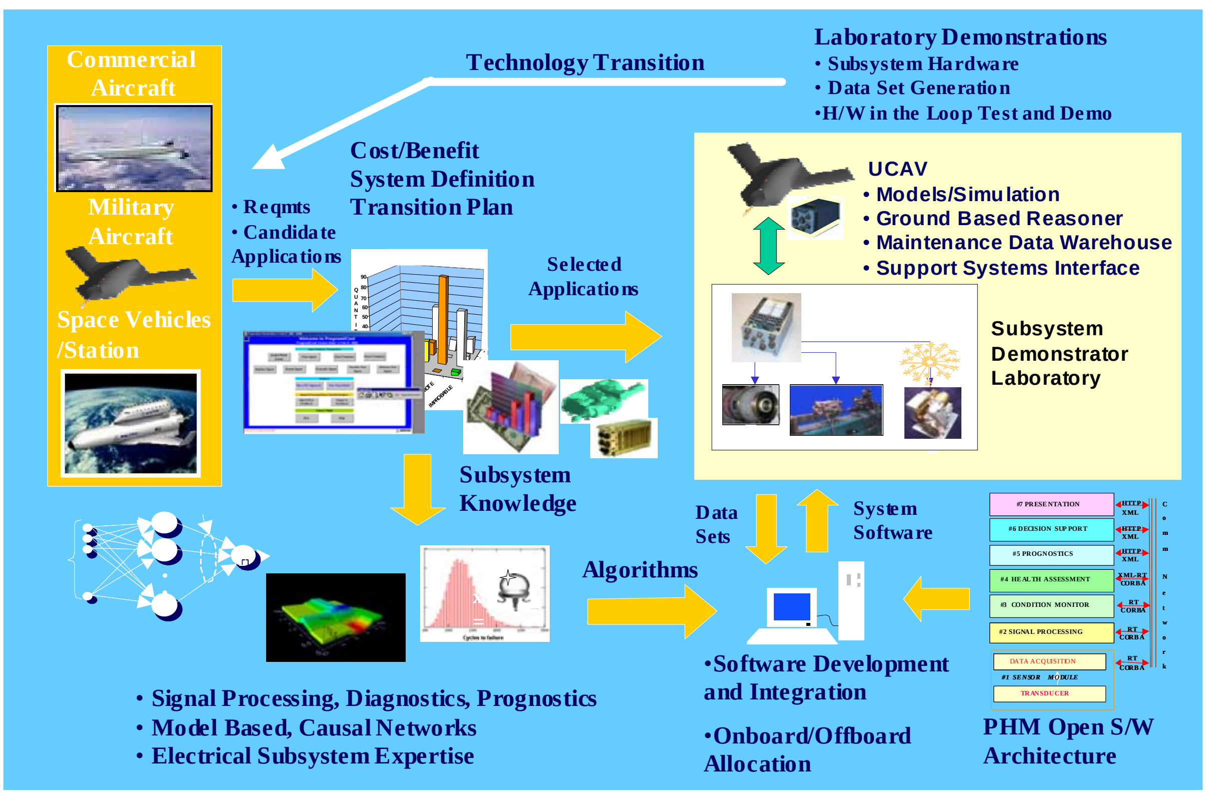

Figure 4: AEPHM Overview.

A major objective of the AEPHM program was to identify the data needed to achieve a desired level of health management and explore economical approaches to access the required data. The key element in this effort was the modification of a Power Distribution Unit (PDU), see Figure 5, to support health management data acquisition and processing. A modified Smiths Aerospace PDU was used in the demonstrations to access data on electrical loads and perform health management processing.

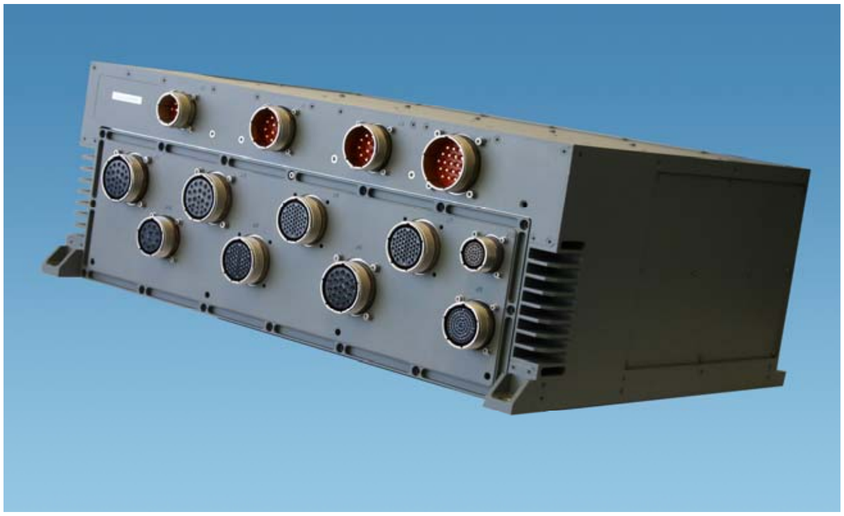

Figure 5: Smiths PDU.

Prognostics and health management (PHM) applications for electrical subsystems were identified, algorithms developed and integrated into an PHM demonstration system that would support the operator/commander, logistics and maintenance functions. The program demonstrations were implemented based on an open software architecture to facilitate integration of multiple components. The primary focus for the design and demonstrations to determine the potential value of AEPHM technology, were electrical systems like those used now being implemented on advanced, more electrical, unmanned combat aircraft. The program strongly emphasized the characterization of faults/degraded modes using seeded faults and accelerated wear tests to develop realistic diagnostic and prognostic models.

The first phase of the AEPHM program that was completed in July of 2005 resulted in a demonstration of health management for actuators, fuel pumps and valves, and arc fault protection (AFP). The second phase of the program has gone onto address generator health management.

The AEPHM system is based on characterization of degraded modes using test fixtures to emulate realistic operating conditions and collect data. Electro-Mechanical Actuators (EMA), fuel pumps and fuel valves were tested in the Boeing Subsystem Demonstration Laboratory. Arc and wire fault testing and data collection was performed in Smiths Aerospace laboratory facility in Cheltenham, UK, [6].

Electrical actuation was a key area of interest because of its pervasive use on UAVs. The actuator selected for experimentation and demonstration was a 135 VDC brushless motor unit, Figure 6. This model has previously been used for flight control applications for UAVs and has dual motors powering a drive train that includes bearings, a gear drive and a ball screw.

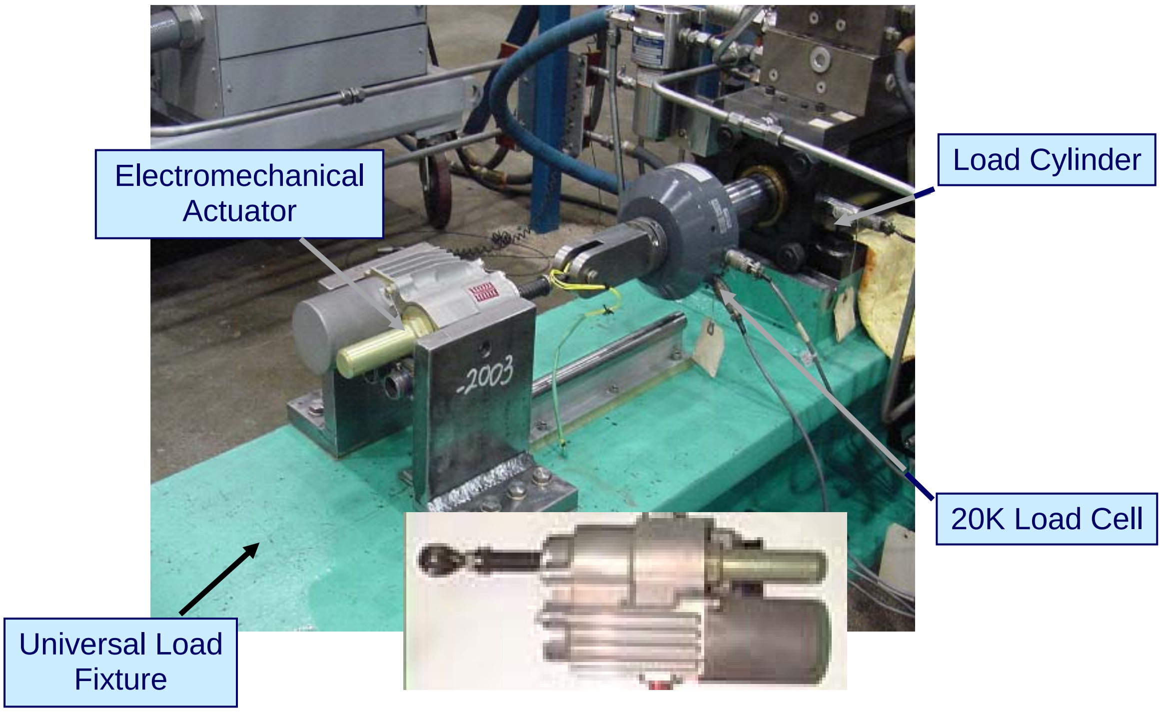

Figure 6: AEPHM Actuator Test Rig.

The motivation to develop PHM for electrical actuator was 1) to avoid gear, bearing or ball screw failures that would lead to an in-flight actuator mechanical jam and negatively impact safety and mission reliability and 2) improve mission availability and reduce support costs by implementing prognostics for motor and mechanical drive.

Data collection to characterize actuator fault modes consisted of performing accelerated wear tests in the actuator test fixture with defined load scenarios or profiles. Four actuators of various levels initial of wear were subjected to a combination of accelerated life tests and targeted fault insertions. The actuators that were run to failure were physically examined after the failure to verify the type of fault or degradation that had occurred.

Based on the extensive data collected from these tests four actuator PHM health indicator algorithms were developed: torque efficiency, freeplay, motor performance and vibration analysis. Figure 7, shows the results of load independent motor performance algorithms for 5 degradation states at 2 load settings. This algorithm showed how the degradation of the motor coils could be measured from data available with the Smiths PDU and calculated independent of the load on the actuator.

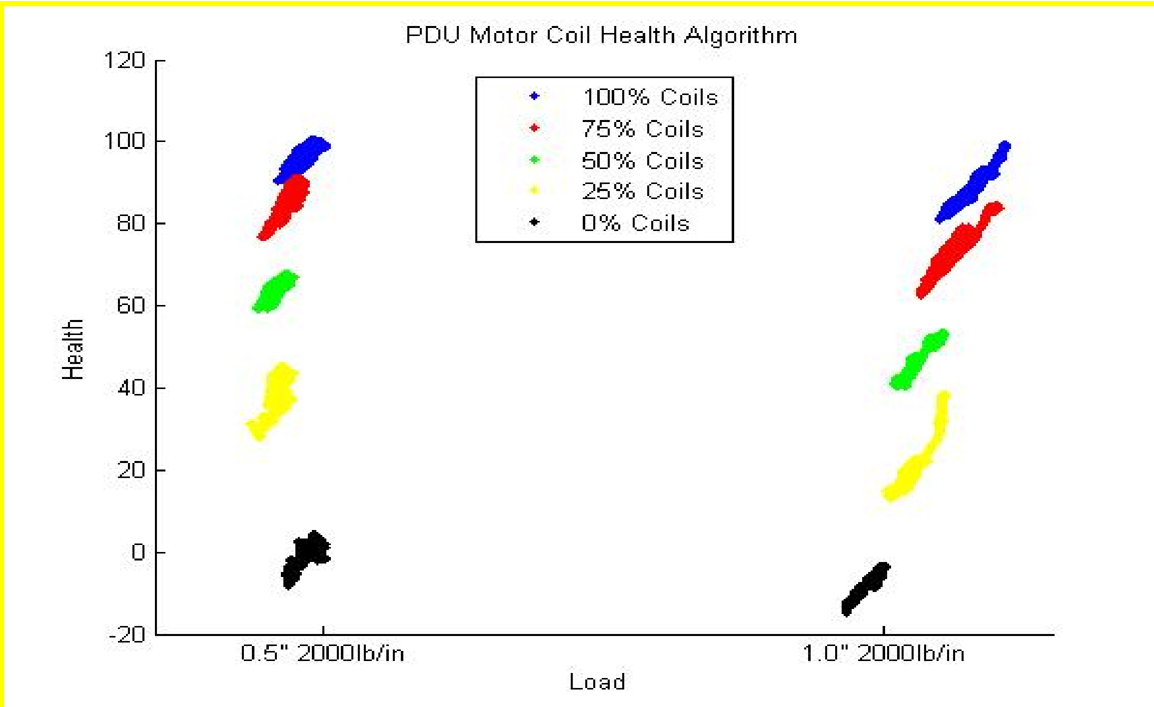

Figure 7: Smiths Load Independent Motor Performance Algorithms Results.

The objective of the fuel system PHM was, as in the case of actuation, to avoid in-flight failures and improve mission availability by reducing downtime. A 270 VDC transfer pump, Figure 8, was used in the tests. Fault modes associated with catastrophic fuel pump failure (bearing failure, dry running, foreign object) were characterized, as recommended by manufacturer, by artificially loading the pump by controlling a valve on the output side.

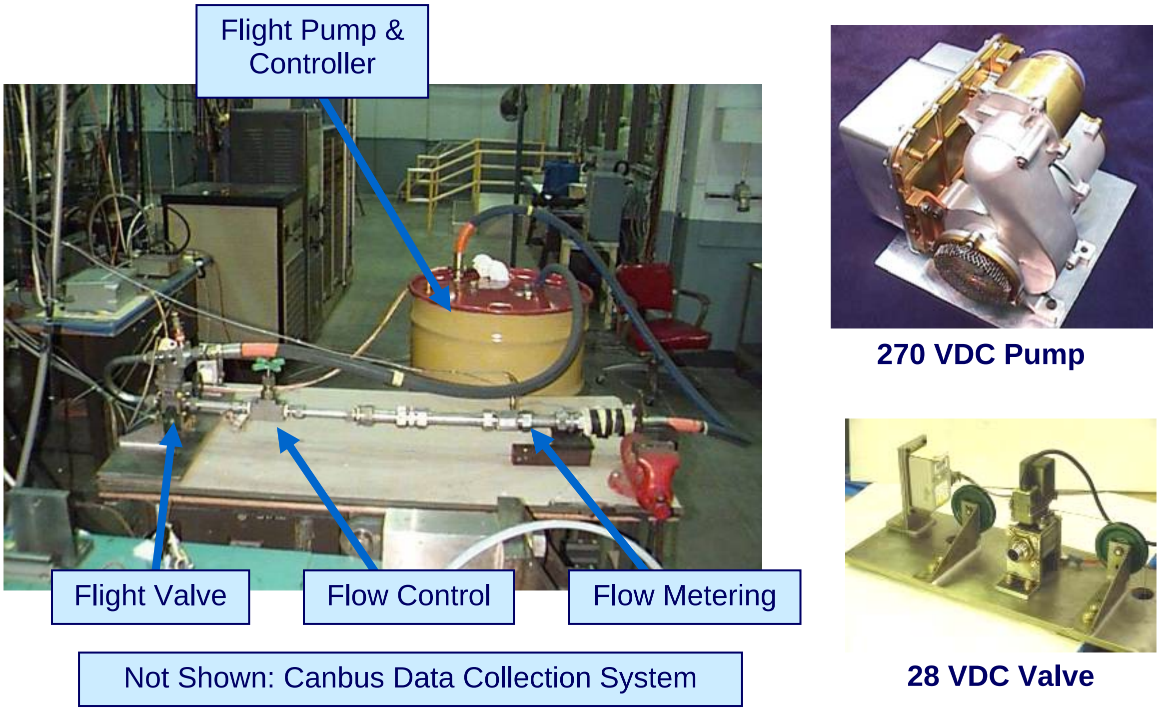

Figure 8: AEPHM Fuel System Test Rig.

Data to characterize the pumps faults was collected using the capabilities of the PDU and a pump PHM health indicator was developed, see Figure 9. Since pump control is based on constant power, it is not possible to detect this reduction in motor RPM from the control signal interface with the pump.

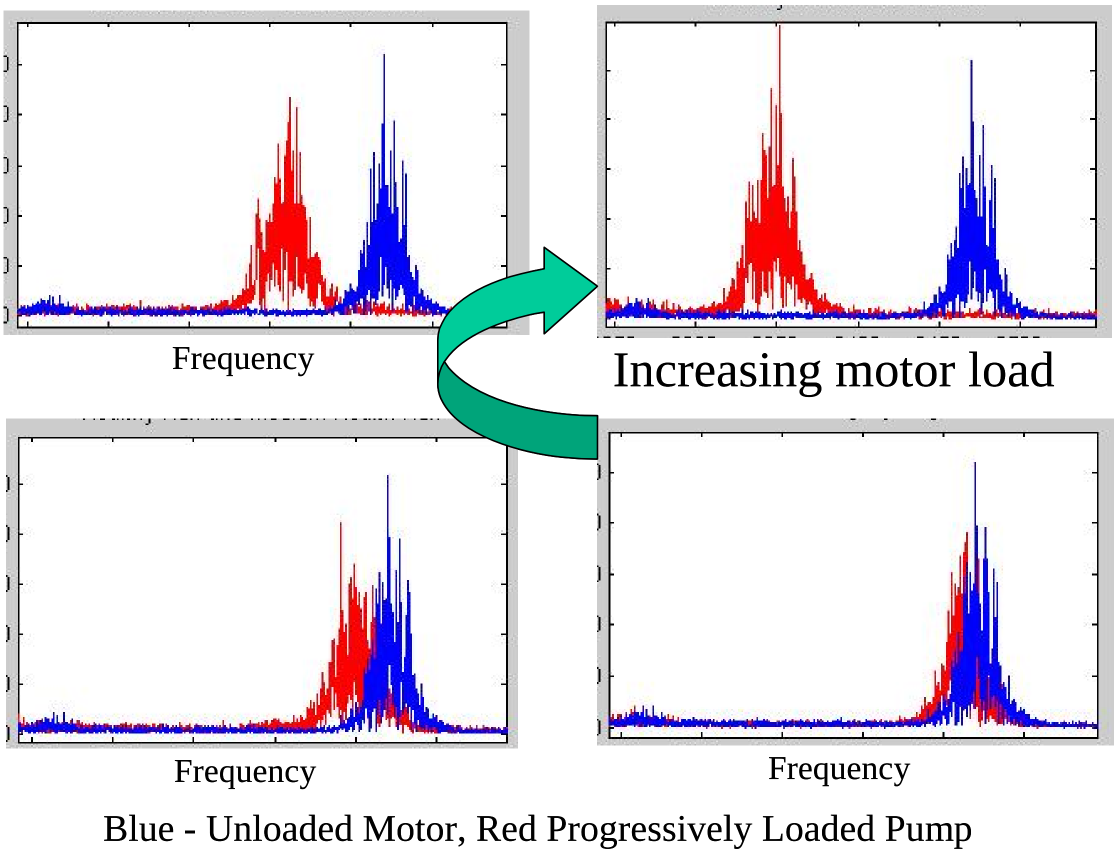

Figure 9: AEPHM Fuel Pump Results.

In a similar fashion, failures that would cause electrically actuated fuel valves to bind during opening or closing were investigated. Motor performance was characterized by loading an arm attached to the valve. Two algorithms were developed to detect conditions that load the motor. Both algorithms were based on the slope of the time versus current curve required to close or open the valve. One used data available to the vehicle management system and the other data from within the PDU. Both algorithms yield similar results; being able to trend an increasing load placed on the valve.

Each of these areas of work showed the benefits that can be achieved without the need to add extra sensors to vehicle.

5.2 System Integration and Demonstration

The algorithms that generate indications of actuator and fuel system health as well as the trending and prognostic algorithms were integrated into an end to end (sensor to decision aiding for the operator or maintainer) system demonstration as shown in Figure 10. The system was configured to run using hardware inputs or stored scenario data.

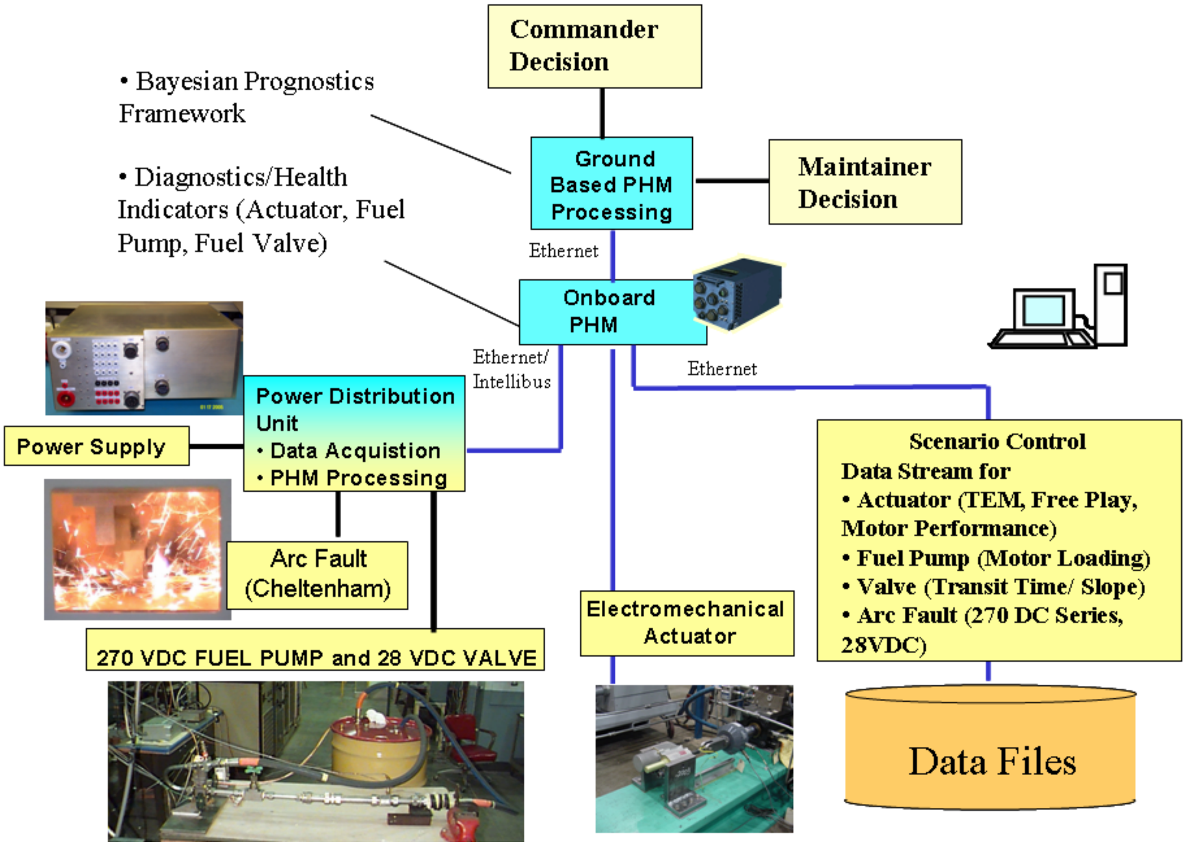

Figure 10: AEPHM System Integration.

System modules were configured in accordance with the Open System Architecture for Condition Based Maintenance (OSACBM) standard. The demonstration scenarios included the generation of gray scale health indicators for the actuator, pump and valve and trending and prognostic projections for the actuator bearing failure and fuel pump as the motors were progressively loaded.

In regard to data handling, it is envisioned that the health indicators for the various subsystems would be generated based on onboard processing and downloaded to ground based processing capability which would trend and prognosis system health as well as provide the necessary projections to decision aids for the maintainer and operator.

The full test facility for arc fault existed only at Smiths Facility in Cheltenham, UK. Similarly the hardware laboratory to support actuator and fuel system hardware in the loop existed only in the Boeing Subsystem Laboratory. However, data streams from all systems were available for 'integrated' demonstrations.

The AEPHM program established the feasibility of detecting and trending actuator and fuel system degradations as well as the role of the PDU as an effective device for implementing arc fault protection and as a means to perform data collection and processing in support of electrical system PHM.

The actuator and fuel system health indicators and trending/prognostics were based on a handful of test cases. Even this handful was sufficient to show a definite trend to failure that can be used in the short term to aid in the avoidance of in-flight failures. For actuators, further work is needed to refine these indicators and health projections under various conditions as well as to differentiate between component degradation modes (e.g., bearing, ball screw and gear). The challenge here will be to determine whether additional sensors (e.g., accelerometers) are needed to achieve this differentiation.

5.3 Reasoning with Design Data

A Failure Mode and Effect Analysis (FMEA) can serve many purposes and is commonly used in the design of a new system to identify possible component failure modes and failure rates, their effect on sub-components and criticality, and to test the impact on system functionality. A FMEA can be an effective way of capturing the a-priori diagnostic knowledge of a new design. A FMEA will describe the system components, the ways in which these components can fail along with expected failure rates, and can be extended to include events or detecting tests that are expected to be triggered given a component's failure mode for design testability analyses. This design data may contain hundreds or thousands of propositions describing the causal associations between components, failures and detecting tests.

The knowledge captured by a FMEA and testability analysis can be utilized in the early construction of a diagnostic reasoning engine. If it is acknowledged that: there will be a need to update and adapt knowledge acquired through infield experience, there will always be inherent uncertainty in the true state of events and their fault isolation capabilities, and there will be a need to provide outputs or take inputs to be fused with other diagnostic sub-systems; then the Bayesian approach to diagnostic inference has to be a prime candidate. Notwithstanding some of the practical difficulties that can impact the construction of a Bayesian inference engine, it is virtually unrivalled in terms of a theoretically sound and generic approach to reasoning with multiple (and possibly conflicting) pieces of evidence.

Out of the range of Smiths work in this area [7], this paper focuses on Smiths work on a Boeing fuel system shown in Figure 11. The major components include the:

> transfer tanks, wing tanks, engine feed tanks, pumps, valves, plumbing that includes pipes and t-connections, power distribution units and remote interface units.

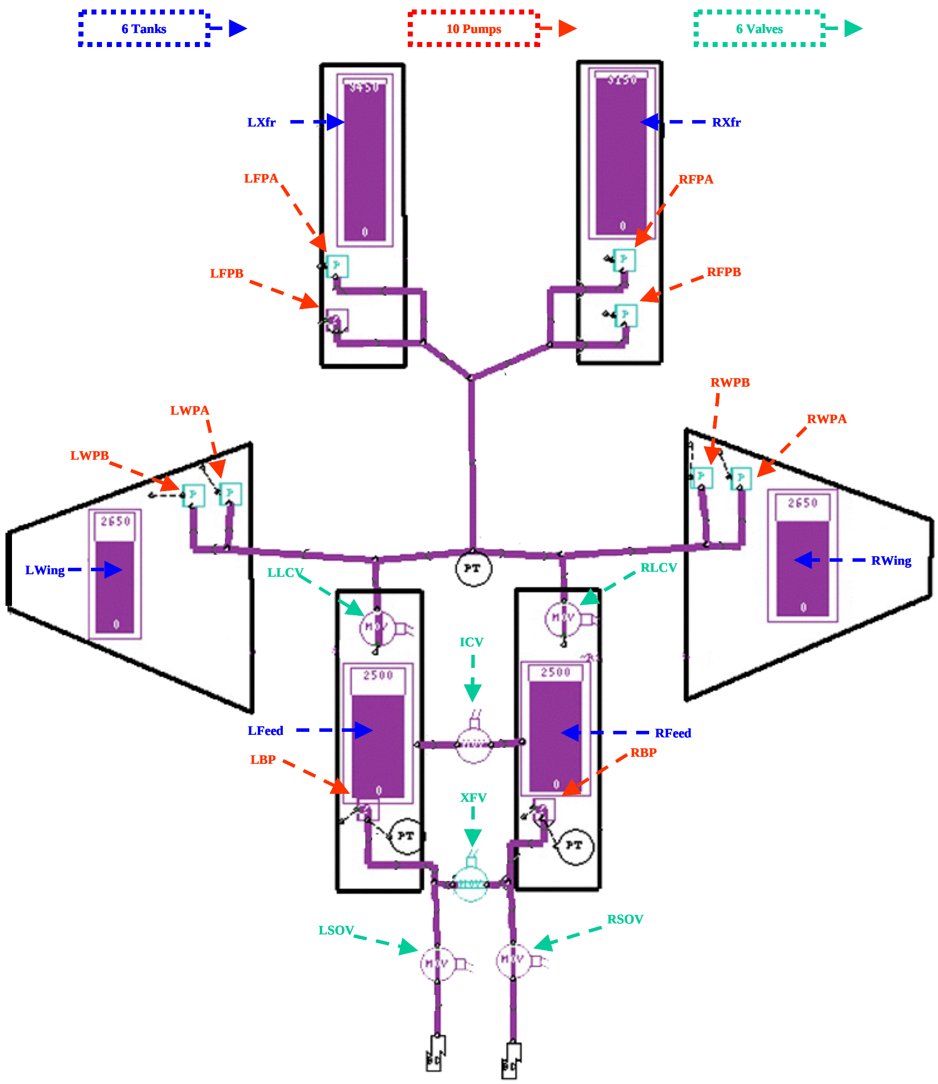

Figure 11: AEPHM Fuel System for Diagnostic Reasoning.

The components are grouped into major subassemblies:

> left and right transfer tanks, left and right wing tanks, left and right engine feed tanks, transfer plumbing, interconnect and crossfeed, and right and left engine feeds.

The structure of the causal network is simple. The failures causally connect to detecting tests and their probability of occurrence is determined from the failure rate information in the FMEA. The failures also connect directly to their parent component, which in turn can be connected to other components through the component hierarchy. The causal network allows the modelling of the probability of a test being triggered given multiple failure combinations. The statistics for such a model are not contained in the design data, and indeed it is hard to imagine the collection of sufficient data from in-field experience that would allow such combinations to be reliably modelled. Therefore noisyor gates are used to constrain the causal network's model to those probability estimates contained in the FMEA.

The large size of the network required the development of some novel techniques in dynamic restructuring to exploit the current information scenario to identify network substructures that can compile and inference independently whilst reaching the same conclusion as though the network were kept complete.

Causal networks have fundamental benefits over logic type reasoning systems. First, is the ability to perform non-monotonic reasoning which is fundamental for correct diagnosis. Another is that partial state evidence can be entered. For example, a valve might have states open, closed and partially open. When entering evidence for this valve it might not be possible to define its true state but it may be known for example that the valve is definitely not closed. Causal networks can also be adapted with in-field experience to learn updated probability distributions. The causal network can also suggest when evidence is not consistent (e.g., a sub-system failure has led to false indications on tests).

In summary, the diagnostic knowledge contained in a FMEA and other design data can be automatically mapped into a causal network. This causal network provided a sound representation of the knowledge that exists prior to in-field experience. The parameters of the network can then be updated as in-field experience is acquired. This allows optimal diagnostic reasoning to be automatically and directly produced from required design data, thereby removing the need for the manual development of the aircraft and system "diagnostic fault tree".

5.4 Summary and Conclusions

The AEPHM program established the feasibility of detecting and trending actuator and fuel system degradations as well as the role of the PDU as an effective device for implementing arc fault protection and as a means to perform data collection and processing in support of electrical system PHM.

Actuator and fuel system health indicators and trending/prognostics were developed that can be used in the short term to aid in the avoidance of in-flight failures. For actuators, future work is needed to refine these indicators and health projections under various conditions as well as to differentiate between component degradation modes (e.g., bearing, ball screw and gear).

An integrated end to end Health Management solution was demonstrated using public standards for software module interfacing and data transmission.

6.0 WHERE NEXT FOR IVHM?

Projects such as TATEM [8] and AEPHM have shown that operators could gain substantial benefits from a truly Integrated Vehicle Health Management solution, these include:

- ✓ Optimisation of maintenance intervals.
- ✓ Leaner maintenance regimes / reduced activity and shop-time.
- ✓ Reduction in spares inventory.
- ✓ Fewer unscheduled activities.
- ✓ More technically advanced and integrated a/c and systems.
- ✓ Support for the increased use of electrical systems.
- ✓ Less 'Technical data'….and more 'Technical Information'.

- ✓ And, in the future could even help organisations achieve:
  - ✓ Greater flexibility of organisations and processes.
  - ✓ Greater organisational integration and collaboration.

However, for these benefits to be achieved the developers of these systems must understand the needs of the end users. The target for any such system designer should be how does this help to achieve:

> *"the right qualified person is at the right place at the right time; with the right tools, the right parts and the right information; doing the right economically opportunistic maintenance, seamlessly integrated throughout the organization as well as the external value chain network"*

Smiths experience in developing both Health Management and other large integrated solutions has led to the following recommendations for IVHM system designers:

1) **Understand the operators need for an Integrated "End to End" solution.**
   - Develop solutions based on operators needs!
2) **Use and support Open System Architectures for IVHM Solutions.**
   - Accept that no one organisation can expect to provide the whole solution.
   - Use an architecture that allows for future developments and changes.
3) **Ensure the architecture is open, and simple to use for the other solution providers.**
   - Respect that 3rd party organisations need to be able to retain their IPR.
   - Ensure support for integration of 3rd party, and Operator developed enhancements.

Smiths and Boeing Phantom Works are continuing their close working relationship beyond the AEPHM programme to develop extensions to the OSA-CBM tool chain to help meet these needs [9].

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