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(R) Guidelines for Integrating Typical Engine Health Management Functions Within Aircraft Systems

RATIONALE

AIR4061B has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

SAE Aerospace Information Report (AIR) 4061 provides best practice guidelines for the integration of Engine Health Management (EHM) system functions within aircraft systems to include both its main engine(s) and any Auxiliary Power Unit(s) (APU). This document provides an overview of some of the functions EHM typically integrates, offers some system variations encountered with different aircraft, and suggests general considerations involved with integration. It presents a sample EHM parameter coverage matrix to show the types of parameters with which a typical EHM system might interface, offers insight into signal and data processing and retrieval, and offers a view of typical EHM parameter requirements by function. Where practical, this document delineates between military and commercial practices.

1.1 Purpose

This AIR provides guidelines for the integration of engine health management system functions with other aircraft systems and subsystems. It supplements ARP1587 by providing additional guidance on best practices for general EHM functional integration with typical commercial and military aircraft systems. This document assists aircraft and EHM system designers by offering guidelines for physical and functional integration.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada), Tel: 724-776-4970 (outside USA), www.sae.org.

ARP1587 Aircraft Gas Turbine Engine Monitoring System Guide

AIR1828 Guide to Engine Lubrication System Monitoring

AIR1839 A Guide to Aircraft Turbine Engine Vibration Monitoring Systems

AIR1871 Lessons Learned from Developmental and Operational Turbine Engine Monitoring Systems

AIR1872 Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines

AIR1873 Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines

AIR1900 Guide to Temperature Monitoring in Aircraft Gas Turbine Engines

AIR4174 A Guide to Aircraft Power Train Monitoring

AIR4175 A Guide to the Development of a Ground Station for Engine Condition Monitoring

AIR4176 Cost Versus Benefits of Engine Monitoring Systems

AIR4985 A Methodology for Quantifying the Performance of an Engine Monitoring System

AIR4986	Engine Electrostatic Gas Path Monitoring
ARP5293	Safety Considerations for Lasers Projected in the Navigable Airspace
AIR5317	A Guide to APU Health Management
AS5391	Health and Usage Monitoring System Accelerometer Interface Specification
AS5392	Health and Usage Monitoring System, Rotational System Indexing Sensor Specification
AS5394	Health and Usage Monitoring System, Advanced Multipoint Interface - Specification
AS5395	Health and Usage Monitoring System, Data Interchange Specification

2.2 GLOSSARY

ACARS	ARINC Communication Addressing and Reporting System
A/D	Analog to Digital
AIR	Aerospace Information Report
AIRCOM	Air to Ground Communication
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio, Inc.
ARP	Aerospace Recommended Practice
BITE	Built-in Test Equipment
CAS	Calibrated Air Speed
CDP	Compressor Discharge (or Delivery) Pressure
CRC	Cyclic Redundancy Check
CRT	Cathode Ray Tube
D/A	Digital to Analog
ECU	Engine Control Unit
EGT	Exhaust Gas Temperature
EMI	Electromagnetic Interference
EHM	Engine Health Management
EPR	Engine Pressure Ratio
ERFE	External Radio Frequency Environment - High Energy Radio Frequency

GMT	Greenwich Mean Time
HP	High Pressure
IAS	Indicated Air Speed
LRU	Line Replaceable Unit
MRO	Maintenance Repair Operations
PLA	Power Lever Angle
RAM	Random Access Memory
RPM	Revolutions Per Minute
SAT	Static Air Temperature
S/O	Shutoff
TAT	Total Air Temperature
TLA	Throttle Lever Angle
T/R	Thrust Reverser

3. GENERAL INTRODUCTION

Engine Health Management is a term that has more recently been adopted to cover the overall system aspects associated with both the engine's health and the engine's usage. From hardware to software and from diagnostics through to prognostics, the principal functions of engine health management are to assess engine condition by gathering event data to perform diagnostics, gathering data for trending and performance analysis, and gathering data to assess life usage of life-limited parts. This information is then used to provide operational maintenance decision support.

Use is often made of engine variables which are primarily sensed for other purposes (e.g., engine control or flight deck display), as well as additional parameters incorporated specifically for engine health monitoring. Integrating EHM within the Airframe's existing systems is dependent on several influencing factors including communication networks, signal interferences, power requirements, etc. A number of different solutions and levels of sharing, between the engine and aircraft-mounted hardware, can be found both in-service and/or under development. Over time, further developments are expected to stretch the boundaries even more.

The continued technological growth in the area of digital systems and data buses serves to provide cost benefits when adding engine health monitoring capability through partial or total integration with other on-board systems. Utilization of such digital and data technologies within the integration of EHM functions should result in fewer Line Replaceable Units (LRUs), reduced design, implementation, and Maintenance and Repair Operations (MRO) costs, and lower weight. Additional drivers to consider during the aircraft level integration of digital EHM system architectures include:

a. Data segregations between flight critical information and pure health management information (data)

b. Data transmission capabilities for the network

c. Data storage environmental conditions and capabilities inside/outside controlled environments

d. Technology readiness of the planned implementation solution

A growing trend has been to perform as much signal conditioning of engine parameters as possible on the engine or at the sensor to reduce the number of wires within the engine/airframe interface. Engine mounted controllers, for example a FADEC, represents an on-engine integration solution.

Retrofit of engine health management capability into an existing vehicle has its own limitations. This should not deter the designer from investigating these possibilities. Functional integration may indeed be the only hope for implementing some level of engine health management in a cost-effective manner, for EHM offers the users a variety of other benefits and opportunities to better manage their aircraft. The job of the EHM system integrator is to determine the optimum architecture that meets the system's goals.

Figure 1 shows the Engine Health Management functions, as represented in the circles of the functional flow diagram. It provides a general description of the interfaces, represented by the diagrams arrows, between the aircraft and engine/APU functions. Also included are some functional growth areas for EHM. Other SAE documents, found in the reference section above, may contain further details of EHM as it applies to specific equipment. For example, SAE Document AIR5317 Guide to APU Health Management discusses EHM as it applies to the APU. The primary functions are detailed in this AIR.

Figure 2 illustrates possibilities for integrating functions within typical airplane systems. Additionally, the sections of this AIR that discuss the integration issues to be considered for the various functions are provided.

4. GENERAL CONSIDERATIONS

4.1 Introduction

The guidelines for the integration of propulsion health management system functions with other aircraft systems and subsystems are applicable for legacy system installations as well as new development aircraft. A cost benefit analysis geared towards exposing the economic feasibility of introducing and integrating the propulsion health management system with the legacy installation or with the new design aircraft will be the determining factor for many integration issues. Exposing the desired use of the propulsion health management system and identifying the propulsion subsystems whose health monitoring will provide economic and safety benefits to the operators is required to develop an accurate cost benefit analysis. As such, this analysis shall include the following topics.

a. The use of Life Limited Parts in the engine or APU has an inverse impact on both safety and maintenance costs. Current practice has accepted a high maintenance cost to maximize safety. The cost benefit assessment should consider means to reduce the maintenance costs associated with Life Limited Parts while maintaining equivalent or improved safety with respect to these components (refer to AIR1872).

b. Due consideration should be given to reductions in the operational cost as well as reduction in maintenance and repair costs. Metrics such as in-flight shut downs, dispatch reliability, gate turn times, UER rates, asset availability, reduced secondary damage due to timely engine removal for cause, etc. would be used to quantify the benefits. In the MRO category, shop turn times, inventory levels, maintenance labor hours, various maintenance intervals such as mean time between removals (MTBR), shop visit rates and costs, etc., would be considered.

c. Factors such as reduced cost due to enhanced workscope planning, directed engine teardown, better module matching, and inventory management should be considered.

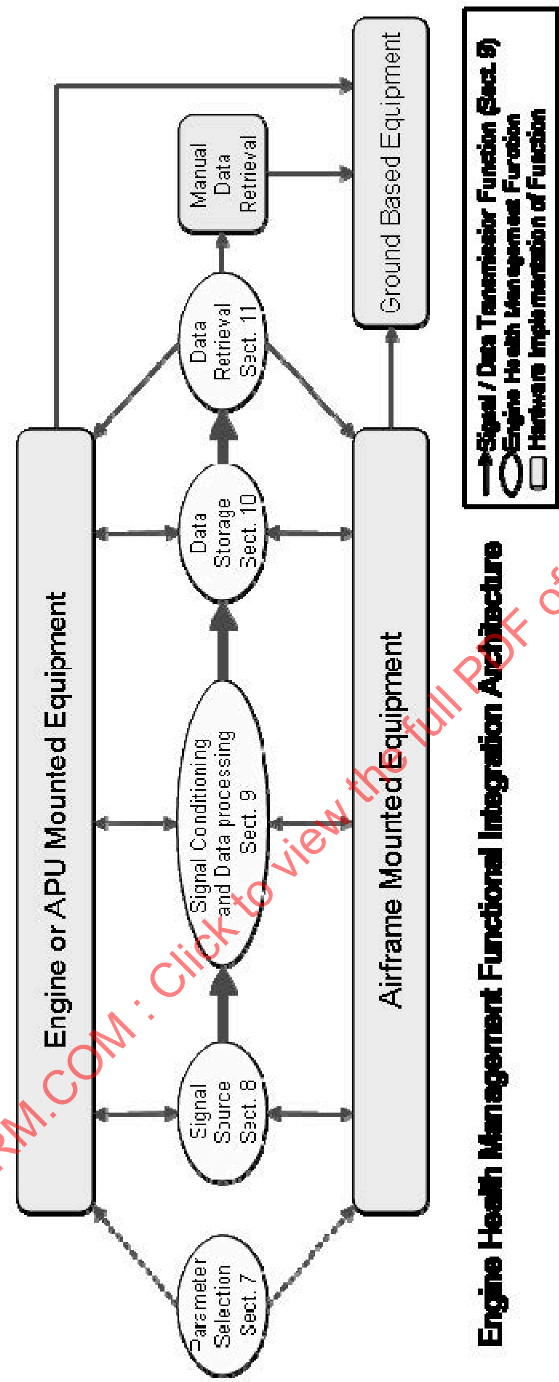

FIGURE 1 - EMS ELEMENTS AND TYPICAL INTEGRATION CANDIDATES

Section Reference						
	Section 8	Section 9.1	Section 9.2	Section 9.3	Section 10	Section 11
EHMS Function	Signal Source	Data Transmission	Signal Processing	Data Processing	Data Storage	Data Retrieval
Hardware & Software Implementation of EHM function	Crew Input	Hand Carry			Written Record of Displayed Data*	
	Engine / FADEC	Visible Display	Engine / APU Mounted Controller			Write to Physical Media
	EHM Sensors	Electric Wire	Engine / APU Mounted Health Monitoring Unit		Removable Hard Drive	
	Aircraft Sensors	Wired Network Databus			Airplane Mounted Hard Drive	File Transfer Via Wired Network*
	Health & Usage Data		Airplane Mounted Controller			File Transfer Via Wireless Network*
	Sensor / LRU Configuration Data	F/O Network Databus		Airplane Mounted Health Monitoring Unit		
	BIT	Wireless Network Databus				Data Streaming via Wireless Network*
Trade Study And Certification Considerations	Labor Costs Erroneous Data Transcription HIRF/EMI Transceiver Complexity Bus Bandwidth Bus Protocol Overhead Power Supply	Environmental Effects on Component Reliability and Performance Signal Accuracy Resolution Sensor Reliability Redundancy Power Supply	HIRF/EMI Sample Rate Filtering Power Supply	Processor Rate Partitioning Power Supply	Volume Partitioning Reliability Redundancy Power Supply	Costs of Data Transcription Bandwidth

* - May be Eng/APU or Airframe Mounted Hardware

FIGURE 2 - EMS INTEGRATION RELATIONSHIPS

A thorough analysis of this kind would create a good foundation for the selection of the appropriate sensors and analytics that will form the elements of a beneficial EHM system.

Following the creation of the cost benefit analysis, the development and documentation of User Requirements will guide the design and development of the propulsion health management system. A systematic approach is essential for effective management of the integration process. From the propulsion health management system user requirements document and the available documents of candidate on-board systems, a list of potential function assignments for these systems is identified.

A Systems Engineering approach is recommended for effective integration of the EHM system with other on-board systems. The systems engineering approach will draw from the user requirements to create the operational and functional requirements for the EHM system. The operational and functional allocation of the EHM system shall be structured to maintain the criticality of all interfacing systems and subsystems. When integrated into the propulsion system, the EHM system shall be considered part of the propulsion subsystem. The criticality allocation for the health management system shall take into consideration its eventual utilization for maintenance. Where the health management system is integrated with cockpit displays, controls or other systems and/or has implications for dispatch, appropriate considerations shall be accorded to the criticality assignment. Early deliberation with the qualifying entity is encouraged.

The user requirements must define the use of the propulsion health management system. These requirements will establish a list of supporting functions. Normal engineering design and development practices shall be employed to insure that the EHM system maintains the required integrity and security of the data acquired and/or transmitted. The combination of functional requirements and integrity/security design practices will guide physical implementation and/or allocation of functions to various systems. These decisions are to be well documented, for example, as part of the EHM system interface control documents or systems description document.

4.2 Functional Interactions

A basic guideline is that the functional interactions of the propulsion health management system with other aircraft/propulsion systems should not adversely affect the aircraft and propulsion system operation. The health management system boundaries shall be established with appropriate consideration for all the aircraft systems with which it interfaces. Special consideration shall be given to maintaining the criticality and reliability of those systems and their interfaces. The aircraft/propulsion system operational and mission scenario shall be used to establish the desired maintenance of the system interface and data integrity. Consider data captured in a high integrity system and transferred to a lower integrity system where it is stored. This lower integrity system could then download the data during a powered but benign state of the propulsion system operation. However, some capability would need to be included in the process if the original high integrity of the data is to be maintained. For example, the data could be encapsulated with a Cyclic Redundancy Check (CRC). Figure 2 shows possible propulsion health management system integration relationships to be studied.

4.3 Isolation

Safety considerations may dictate functional independence, among the various components of an integrated set of subsystems, to protect against effects of common mode signals, coupling and crosstalk, bus interactions, and failure propagation. A system safety hazard analysis should be conducted to insure that the appropriate isolation is accorded to the interfacing safety critical items and the functional independence of the integrated systems. For legacy systems, integration diligence must be exercised to insure that established levels of RF emissivity and RF susceptibility are not compromised. Ground paths and lightening protection schemes should be analyzed for compliance with acceptable specifications.

4.4 Environmental Effects

If the EHM system is non-critical, relaxed protection standards for tolerance against environmental factors such as lightning, electromagnetic interference (EMI), external radio frequency environment (ERFE), high and low temperatures, and steady state and vibratory mechanical loads may apply. However, care must be taken to ensure that critical systems, e.g., flight controls and engine controls, are not compromised. Should high protection standards become necessary for shared parts of the EHM, e.g., amplification of an EHM signal within a control system box, the cost-effectiveness of sharing will need careful examination. Often, recommendations, guidelines, and or regulations have been established by both commercial and military agencies (FAA, JAA, DGAC, DOT, DOD, etc.)

4.5 Maintainability

Integration of EHM functions with other aircraft systems may impact maintainability. In the U.S. commercial aviation arena, governing agencies, like the FAA, have regulations or guidelines governing such things as continuous maintenance. EHM system Designers should consider the following aspects:

a. Maintenance personnel should be provided with a single information source. If, for example, the maintenance staff has to consult built-in-test equipment (BITE), EHM, flight logs, and warning computers separately and then has to correlate this data, they may be tempted to use only one source and not use all available information.

b. Fault-finding is often carried out by a process of elimination. Integration may reduce the number of LRUs and improve fault isolation capability.

c. The elimination of multiple data sources will remove possible disagreements at the possible expense of added complexity and/or masking defects.

d. Physical integration of EHM functions with other systems that require complex installation procedures may cause problems. An operator may be reluctant to perform maintenance just to clear an EHM fault.

e. Physical integration of EHM functions with other systems will likely require that these systems provide self-test capability for the added functions.

4.6 Reliability

The use of other systems to perform EHM tasks and process EHM data could adversely affect the reliability of these systems. It will be necessary to evaluate the effects of integrating the EHM functions both in hardware and software. The evaluation could result in integration design constraints and may lead to a decision that some elements of the EHM system not be integrated.

4.7 Electrical Power

Consideration must be given to a number of characteristics of the electrical power system. Typically, an aircraft electrical power distribution system comprises multiple independently protected distribution buses. Each bus has a particular characteristic when an engine fails, or an electrical generator drops out, ranging from transient disturbances to complete electrical power loss. Interruption of electrical power should not result in the loss or corruption of EHM data. Additionally, data related to a particular engine should not be corrupted by the failure of that engine or its associated subsystems.

Consideration must also be given to the possibility of low voltage or the absence of power generated by a main engine when monitoring that engine during start or shut down. The highest integrity bus is frequently battery-direct or on the emergency AC bus. These buses may be available for power during starting but often have severely restricted load capability.

Where the EHM uses multiplexed data distribution buses, close attention should be paid to the data bus power source. The times when power disturbances are most likely to occur, such as during engine start or shutdown or during load switching, are some of the most important to monitor. The use of redundant data bus structures fed from alternate power sources may be considered to enhance the integrity of the EHM. Providing power to the EHMS after an engine is shut-down to complete EHM processing activities (signal processing, data transmission and storage, etc.) should be considered.

Many sensors rely on electrical power to provide excitation or secondary services such as heaters. In the development of system power architecture, care should be taken to evaluate the effect of power loss on sensors.

4.8 Data Bus Sharing

When considering the sharing of system data buses, consideration should be given to the following:

a. Bus integrity

b. Bus capacity/data rate

c. Bus configuration and routing

4.8.1 Bus Integrity

Most modern aircraft, commercial and military, have flight critical data buses. The integrity of these buses, and the systems connected to them, must be carefully maintained. It may be possible to transmit engine health management data on these buses or to pick off data that are already on the bus, but the sources and destinations of the data must comply with the bus interface requirements. In some cases a bus may be "off limits" entirely.

4.8.2 Bus Capacity

The capacity of a candidate bus to handle the extra data needed for engine health management function must be evaluated. The primary considerations are:

a. Availability of labels or addresses for the EHM data

b. Impact on growth margin for the primary bus users

c. Resolution and update rate requirements of the EHM and primary user data.

4.8.3 Bus Configuration and Routing

The selection of a bus for transmitting EHM data should consider bus configuration and routing. The primary considerations are:

a. Ability of the bus structure to accept additional terminals.

b. Ability of the bus protocol to accept additional terminals and labels.

c. Impact on Electro-Magnetic Interference (EMI), External Radio Frequency Environment (ERFE), and lightning protection of additional wiring or re-routing of wiring.

d. Impact on cost and weight of additional wiring or re-routing of wiring.

4.9 Software

Software integration should be considered at the earliest opportunity. The design of both the software and the hardware that runs it need to trade benefits of integration against the mission criticality of the function provided by the software. Section 4.3 provides topics to consider from a partitioning perspective. For functional integration, factors to consider are:

a. Commonality of routines such as input and output (Reuse Capability)

b. Computational capacity

c. Timing requirements/duty cycle

d. Memory capacity

e. Common language

f. Operating systems

g. Reprogrammability

h. Software quality and configuration management requirements

4.10 Future Architectural Concepts

Current industry trend is the integration of propulsion health management systems with other aircraft health maintenance systems such as central maintenance computer (CMC) into a centralized web-based, network-centric integrated system. The current emphasis has been to combine on-board aircraft maintenance with ground-based predictive management functions. In keeping with this trend, the propulsion health management system could be integrated with the aircraft systems to provide complete and precise fault diagnosis of the entire aircraft system which will enable timely and effective maintenance action and repair with minimum effect on aircraft use. With more access to high fidelity models, and the ability to run them efficiently, prognostics and predictive algorithms are being implemented. Support of prognostic concepts (see 5.3.m) and predictive maintenance (as opposed to reactive maintenance) practices should be considered in an EHMS architecture design.

The underlying architecture should be structured to utilize all available data on the aircraft to provide decision support for effective maintenance of the aircraft and predictive trending for safe utilization and maintenance based on the actual condition of the operating propulsion system.

4.11 Growth

Care must be taken to ensure that the integration process does not compromise the hardware and software growth margins of the integrated systems.

5. PARAMETERS SELECTION AND REQUIREMENTS

5.1 Introduction

The number of parameters required for EHM may range from a few for limit exceedance and trending, to many for diagnostics, performance analysis and life usage. Some of the parameters may exist for other purposes (e.g., engine control or indication) and additional parameters may be needed solely for engine health management. Legacy aircraft may be limited by the fact that available parameters are those existing for engine control and update rates for available parameters are already established. Some parameters would be sensor outputs, appropriately filtered, while others may be synthesized values to accommodate sensor validation and/or redundancy.

As mentioned in 4.1 of this document, a cost benefit analysis should help determine what parameters are used. The analysis will include estimates of costs for development and implementation of parameter sources, and their corresponding benefits. The costs should include development, test and validation, production deployment, and service support for both the sensors themselves and the supporting analytical techniques.

5.2 Parameter Requirements

Each parameter will have requirements unique to monitoring. These requirements may be different than those required for the control and indication system. These general parameter requirement headings are meant to be generic. When a sensing system is being implemented, due consideration will be given to specific aircraft systems it interfaces with, the parameter being monitored, and the end user's requirements. Each requirement heading below can have an effect on the system overhead. An Engine Health Monitoring System's acceptability and success is directly influenced by the detail behind each parameter requirement. Consideration must be made for the certification level for both hardware and software, as well as continuing maintenance requirements. The requirements come under the following headings:

a. Accuracy (both static and dynamic): For EHM, parameter accuracy should not be limited to the general description of accuracy which is the ratio of parameter error to full scale output (FSO), often expressed as percent of FSO. For temperature and pressure parameters, the compensated temperature range, repeatability, hysteresis, output noise, measurement and quantization errors shall also be factored into the determination of parameter accuracy.

b. Resolution: The minimum change in the parameter that can be detected. For a digital parameter it is the magnitude of the least significant bit as expressed in the parameter units. For example, if a parameter ranges from 0 to 10 volts and is digitized to 12 bits, then its resolution is 10/(2^12) = 0.0024V.

c. Repeatability: The variability (measured by sample variance) in a measurement of a parameter in exactly the same condition over multiple instances.

d. Flight Phase or Mode Dependence: Capture/monitoring of some parameters may only be necessary during certain portions of a flight or in a portion of the flight envelope. This parameter characteristic may influence the storage requirements of the EHM system, e.g., parameter values may need to be captured during a specific part of the flight and stored for later processing.

e. Sampling Rate: The frequency at which the parameter is capable of changing, measured in samples/sec or Hz. Sample rate is the rate at which the A/D converter operates.

f. Update (processing) Rate: Update rate is the rate at which the computer or Digital Signal Processor (DSP) processes the signal (note that this rate can be much slower than the rate at which the computer is capable of executing an instruction because of other programming load on the computer).

g. Output Rate or Availability: Output rate is the rate at which the processed output is available to the downstream process; a cockpit display, a recording device, transmission circuit, etc.

h. Nonlinearity: The change in gain at various parts of the range of the parameter. The gain is defined as the change in the output parameter due to a smallest measurable change in the input parameter. If this is constant over the entire range of the parameter, then it is said to be a linear device. Otherwise, the parameter is said to be nonlinear.

More details on parameter/sensor requirements and their uses can be found in the documents listed in 2.1 (Applicable Documents).

5.3 Parameter Uses

Parameters may have multiple uses, each requiring different treatment. Figure 3 indicates parameters which are useful for the EHM functions identified below and helps the system designer to match the parameter selection with user needs. For some installations, other parameters may also be needed.

a. Limit/Exceedance Monitoring: Data that defines the exceedence (how much and how long) is used to determine appropriate maintenance action required because of the exceedence. Accuracy is consistent with noise levels to ensure sufficient signal to noise ratio that allows high probability of detecting true exceedances while ensuring low false alarm rates. Update rates can vary from several times per second to once per flight depending on the criticality of the parameter and the ability to download the occurrences of exceedances to the aircraft system.

b. Life Usage Monitoring: Life of a life limited part (LLP) must be tracked by serial number to ensure timely replacement and enhance system safety (AIR1872). Other critical components are inspected regularly to ensure that danger of failure is minimized. In the future, usage based lifing will become more common. Parameters different than the ones listed in Figure 3 will typically be needed to assist this function. Accuracy of the parameters should be relatively high to enable the tracking of peak stress points which are needed to calculate consumed life. Update rates for these parameters are generally low because of limited data processing and transmission capability. As technologies advance, it is anticipated that higher update rates in the 10 Hz range will be supported. Data compression techniques will allow transmission of this high sample-rate data for analysis remote from the data capture system (e.g., ground analysis).

c. Performance Trending and Diagnosis (Modular Analysis): Faults (and degradation) related to engine performance can be identified through modeling the gas path and monitoring deviations from estimated parameters. These deviations can be trended so that performance issues can be identified and isolated to particular engine modules. In addition to anticipating performance issues, this will help in maintenance workscope planning (see AIR1873 for more details of performance trending). For commercial engines gas path analysis is generally carried out on steady state cruise points. For military engines take-off points serve as the desired analysis regime. In some cases operators might add in a special ground test engine run on a periodic basis, possibly after a flight, just to collect steady state data for analysis. On-board analysis is becoming feasible with increased computer throughput and memory. Performance of these algorithms is crucially dependent on having high signal to noise ratios, and the accuracy of the reference models.

d. Mechanical Trending: Tracking the deterioration of the mechanical integrity of some component of the engine toward some threshold prior to failure. Data from sensors such as vibration, oil pressure, oil system chip detection are trended so that failure can be anticipated and preventive action taken. (More information on oil system and vibration parameters can be found in AIR1828 and AIR1839 respectively.) To eliminate noise, it is a best practice to capture sequential data used for Performance Trending at conditions that are as similar as possible from point to point, for example, while dwelling at some operating condition (e.g., max. continuous, take-off or climb power). In conflict with this practice is the recognition of valuable information for Mechanical Trending which is often found in data captured during a transient operation (e.g., thrust run-up for take off). For example, with the advent of electronic particle detection, it is possible to perform real-time trending of mechanical debris in an oil system and eliminate scheduled inspection of magnetic chip collectors. For accelerometer signals, sampling rates can be up to 50 kHz or even more for monitoring wear-induced vibration from bearings, gears, and other mechanical components.

e. Mechanical Diagnosis: As opposed to performance trending, mechanical diagnosis is the precursor event followed by monitoring of time-to-failure. Diagnosis is essentially identification of the responsible area of the engine. Having diagnosed mechanical deterioration, trending is used to define when corrective maintenance is required. Analysis techniques such as extracting tracked vibration orders, or using diagnostic chip detectors in scavenge lines from individual bearings may be used as described in 5.3.d above.

f. Fleet Averaging: Characterizes the service behavior of a group of engines, which may be operating in a particular environment, or of a specific build standard. Data from many sensors are used to identify any generic problems with the type of engine or operation. The information may also be used for commercial purposes in administering guarantees, such as performance retention. Parameters for fleet averaging are typically calculated at steady state conditions, except for specific parameters such as maximum thrust margins.

	EHM Function / Parameter	Limit/Exc. Monit.	Life Usage	Perf. Tending / Diag.	Mech. Trends	Mech Diag.	Fleet Ave.	Control System Diag.	Event Analysis	Start-Up Monit.	Shut-Down Monit.	Build-Up Systems
FLIGHT DATA	A/C Identification	X	X	X	X	X	X	X	X	X	X	X
	Date / GMT	X	X	X	X	X	X	X	X	X	X	X
	Flight Origin	X	X	X	X	X	X	X	X	X	X	X
	Planned Destination	X	X	X	X	X	X	X	X	X	X	X
	Actual Destination	X	X	X	X	X	X	X	X	X	X	X
	Flight Number	X	X	X	X	X	X	X	X	X	X	X
AIRCRAFT DATA	Flight Phase	X	X	X	X	X	X	X	X	X	X	X
	Auto-Throttle Status	X		X	X	X	X	X	X	X	X	X
	Total Air Temp.	X	X	X	X	X	X	X	X	X	X	X
	Mach Number	X	X	X	X	X	X	X	X	X	X	X
	Altitude	X	X	X	X	X	X	X	X	X	X	X
	A. of Attack / Side Slip	X		X		X		X	X	X	X	
	Calib. Air Speed	X	X	X	X	X	X	X	X	X	X	X
	Generator Load	X		X	X	X	X	X	X	X	X	X
	Gross Weight	X	X	X	X	X	X	X	X			
	Center of Gravity						X					
	Auto-Pilot Status			X		X		X	X			
	Air Bleed Selection	X	X	X	X	X	X	X	X	X	X	X
	Anti-Ice Selection	X		X	X	X	X	X	X	X	X	X
	Fwd/Lat./Vert. Accel.	X							X			
	A/C on Ground	X	X	X	X	X	X	X	X	X	X	X
ENGINE DATA	Thrust Lever Angle					X		X	X	X	X	
	Thrust Mode Selection	X	X	X	X	X	X	X	X	X	X	
	Inlet Temperature	X		X			X		X	X	X	X
	Inlet Pressure	X		X			X		X	X	X	X
	RPM (N1,N2, N3..)	X	X	X	X	X	X	X	X	X	X	X
	EGT (or ITT)	X	X	X	X	X	X	X	X	X	X	X
	EPR / N1 actual	X	X	X	X	X	X	X	X	X	X	X
	EPR / N1 command							X	X			
	HPC Press		X	X	X	X	X	X	X	X		
	HPC Temp.		X	X	X	X	X	X	X			
	Comp. Press 1 or 2			X			X		X			
	Turb. Press 1 or 2			X			X		X			
	Turb. Temp. 1 or 2			X			X		X			
	Fuel Flow			X	X	X	X	X	X	X	X	X
	Oil Press. / Temp.	X			X	X	X	X	X	X	X	X
	Oil Consumption				X	X	X		X		X	X
	Oil Particle Count	X			X	X	X		X			X
	Oil Filter Delta Press	X			X	X	X		X	X	X	X
	Nacelle Temp.	X			X	X	X	X	X		X	X
	CVG Angle			X	X	X	X	X	X	X		X
	T/R Selection		X	X			X	X	X	X	X	X
	Water Injection Sel.	X	X	X			X			X	X	
	Eng. Start Selection									X		X
	S/O Valve Position								X		X	X
	Starter Duct Press.									X		
	Torque	X	X	X			X	X	X			
	Tracked Vib. (all)	X		X	X	X	X		X		X	X
	Broad Band Vib.	X		X	X	X	X		X			X
	Vib. Channel			X	X	X	X		X			X
	Vib. Spectral Analysis				X	X		X				
	Fan Trim Bal. Amplitude	X			X	X	X		X			
	Fan Trim Bal. Angle				X	X	X					
	Fuel Temperature	X					X	X	X		X	X

FIGURE 3 - MATRIX OF PARAMETERS TYPICALLY USED FOR VARIOUS EHM MONITORING FUNCTIONS

g. Engine Control System Trend and Diagnosis: Identifies degradation in sensor signals and actuators used by the control system, aids in signal source selection and aids subsequent fault Isolation, typically to an LRU. Raw data is formatted, usually within a ground station for comparison to previous cycles and levels to aid in interpreting excursions and degradations. Typically, these aid in immediate line-maintenance actions during gate turn-around but can lead to more complex maintenance actions such as LRU replacements during overnight stops. Probabilistic concepts are being applied to enhance diagnostic capabilities for control system electronics (e.g., eliminating ambiguity). This concept utilizes the Failure Modes and Effects and Criticality Analysis (FMECA) model for the system to demonstrate compliance with fault detection and isolation requirements.

h. Event Detection, Analysis, and Tracking: Provides visibility to events outside the normal operation parameters or established limits to allow isolation of maintenance actions. Events can trigger the capture of a limited number of parameters on a transient basis, just as in the case of control system faults. These can be stored on the ground for subsequent analysis and tracking. The update rates can vary depending on the events being detected, and can be as high as that allowed by the control system minor-frame time.

i. Engine Start-up Monitoring: Captures key initial start-up parameters during ground and air starts to provide the EHM system the ability to trend these parameters and provide fore-warning about potential issues with the starting system. Update rates are consistent with the control system time frame.

j. Engine Shutdown Monitoring: Data captured during spool down can be used to identify deterioration of mechanical components such as bearings. Update rates are consistent with the control system time frame.

k. Engine Build-Up (EBU) Systems: Identifies degradation of engine accessories and how it may influence engine performance.

l. Engine-to-Engine Comparison: To compare data from all engines on a particular aircraft real-time, in-flight. This comparison can be done with the data collected for any of the functions listed above. Results of the comparison may, in some cases, provide corroborating evidence for a result for data analysis for an individual engine.

m. Prognostics: Generally, prognostics establishes the Remaining Useful Life (RUL) of a component once symptoms have been identified through one or more of the monitoring concepts above and a diagnosis established that the component is on a given path to failure.

6. SIGNAL SOURCES

6.1 Introduction

EHM Signal Sources are primarily engine-mounted sensors in conjunction with data and information from other aircraft (system) sensors and computers required to capture complementary information about the operating conditions.

A detailed business case is required prior to adding dedicated EHM-only sensors as the development, implementation and certification cost need to be off-set by reductions in engine maintenance costs.

Historically, this has resulted in the use of existing engine control and indication signal sources to provide the majority of the EHM data. Furthermore, sensors currently used for safety-related and cockpit indication functions (like vibration sensors, generator oil temperature etc.) are available signal sources at aircraft level that may be used for EHM purposes.

Additional EHM-only signal sources are also being added to the latest generation of aerospace propulsion systems (at the time of writing Revision B) in order to support high-fidelity on- and off-board models.

Section 4 describes the requirements for the EHM functions that need to be considered. Various sources, such as AIR1873, provide additional information for the Signal Source selection as well as the following paragraphs.

6.2 Selection

The selection of signal sources must include consideration of all error contributions, data format and characteristics, compatibility with signal conditioning and processing capability, as well as reliability and integrity. Some sensors require that the associated system provide electrical power or excitation. Other sensors may require heaters, special compensation, etc. Data interruptions during built-in test of the data source must be accommodated.

6.3 Signal Source Sharing

Given the economic restrictions mentioned in 6.1, signal sources may need to be shared with other systems, or are even primarily used for these other systems. Hence, there are various possibilities for source sharing:

- The desired signal already exists from a source, either the sensor itself or a conditioner that can easily be shared.
- The desired signal already exists but the sensor or signal conditioner must be replaced by a new one to allow signal sharing. This condition is often found on legacy systems with analog data buses while current design technology with (deterministic) digital data buses enable easier data exchange between many aircraft systems.
- The desired signal already exists but signal sharing is not practical or cost-effective, and a new source must be provided for the EHM.
- The desired signal does not exist and a new source must be provided.

6.4 Aircraft Parameters

The following parameters are examples of signals from aircraft systems, or from crew entry into an on-board system, that may be used for EHM:

TABLE 1 - EXAMPLE AIRCRAFT PARAMETER LIST USED FOR CORRELATION PURPOSES IN EHM SYSTEMS

a.	Air temperature (Static Air Temperature and/or Total Air Temperature)
b.	Altitude
c.	Airspeed (Mach Number, Indicated Air Speed and/or Calibrated Air Speed)
d.	Gross Weight
e.	Air/Ground logic
f.	Flight mode/phase
g.	Flight leg
h.	Aircraft identification/registration number
i.	Time (Coordinated Universal Time UTC)
j.	Center of Gravity
k.	Angle of Attack
l.	Normal flight path acceleration
m.	Auto-thrust/Auto-throttle/Auto-pilot mode
n.	Throttle lever angle
o.	Anti-ice on/off
p.	Cabin bleed flow rate, pressure, temperature
q.	Environmental control system pack status on/off
r.	ECS or Engine cross-bleed
s.	APU bleed status
t.	Control surface deflection
u.	Gun fire (military)
v.	Rotor speed (helicopter)
w.	…

This example list will need to be amended on a case-by-case basis with the available parameter list, whether as raw data or as computed parameter from any aircraft system source, if at all useful or used in the EHM models. In an extreme case, all available parameters (raw and computed) available on any aircraft data network might be used for EHM purposes; the synthesis of these might however occur on-ground rather than on-board.

7. SIGNAL TRANSMISSION, CONDITIONING, AND DATA PROCESSING

Signal transmission, conditioning, and data processing capabilities move hand-in-hand with the general miniaturization of the computer industry. Previously, the discrete functionalities of (1) signal conditioning (A/D conversion), (2) signal and data transmission and (3) data processing have been implemented as different sub-assemblies of the Engine Control Unit or the Engine Health Management Unit to which the raw signals from sensors are transmitted. Miniaturization is allowing these functions to be implemented in a distributed system where the signal conditioning may take place fully or partially at the sensor level (e.g., smart sensors). Similarly, the signal and data transmission, data processing and the following data storage (covered in Section 8) may be fully or partially carried out by one or several components at the most convenient level depending on the actual implementation.

7.1 Signal Transmission

Signal transmission, both prior to and after conditioning and/or processing, must be given sufficient attention to ensure that the integrity and accuracy of the data are not compromised. Once the sensor signal has been conditioned, the problem resolves into how the output of one system is introduced to the other. Various formats, such as the well known ARINC data transmission protocol, allow for multiple users to acquire broadcast data. Current technology includes full duplex and ethernet communications. Signal and data sharing will be further enabled by higher bandwidth transmission networks

Future technology could include wireless communication networks between sensors and health management hardware, as well as its current implementation for data retrieval. In cases where a supplementary output is provided, due consideration must be given to the design load capability. Use of incorrect loads may well incur an accuracy penalty and may also allow fault propagation across otherwise independent system boundaries.

Consideration must be given to:

- Source and load impedance
- Field strengths and types
- Lightning, EMI, and ERFE
- Load filtering and susceptibility
- Data timing
- Interconnects
- Cable movement

Wiring methods, designed to preclude signal corruption, include:

a. Twisted cables

b. Twisted-shielded cables

c. Single-shielded cables

d. Double-shielded cables

e. Single cables run as a pair

f. Random cable run

g. Grouping and separation for noninterference

h. Fiber optics

7.2 Signal Conditioning

Source data, in analog or digital form, needs to be conditioned before it can be used by the EHM system. Because of harsh environments, these systems are generally mounted at a distance from the signal source itself. Signal attenuation, noise generation, signal corruption, as well as susceptibility to electromagnetic interference must all be considered during the design of the signal conditioning system. Additionally, for reasons of cost, weight and space, the same signal may be transmitted to and shared by a number of independent systems and the outputs of independent systems may be combined. The following are some of the points to be considered when designing the signal conditioning system:

a. Isolation of source from unwanted signals during sensing, amplification and/or transmission

- Common mode rejection

- Coupling and crosstalk

b. Sensor absolute accuracy versus repeatability

c. Overall environment, including lightning, EMI, and HERF

d. Failure propagation

e. Analog to digital (A/D) and digital to analog (D/A) conversion

- Sampling Rate

- Resolution

7.3 Data Processing

Signal conditioning and data processing are essential elements of transforming sensor data into useful information by the EHM system. Signal conditioning is a low level process that conditions the raw sensor signal in a variety of ways, such as filtering, analog to digital (A/D) conversion, etc. Data processing consists of all higher level processing such as Fast Fourier Transformation (FFT), feature extraction, data fusion, etc.