A Need-focused Approach to Air Force Engine Health Management Research

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Abstract—This paper outlines the work that the author has done to develop a structure to help direct Engine Health Management (EHM) research. It discusses the definitions of the relevant EHM terms, outlines the essential elements of an EHM system, deduces the aims of an EHM system through the contributions it can make to the top-level Air Force goals, and uses this to create an EHM vision. It then proposes a method of grouping EHM research programs in terms of their scope and offers a first order method of rating their likely impact. Finally, it raises a number of important issues that need to be considered when developing an EHM system.

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1. INTRODUCTION

Engine health management (EHM) research covers an extensive range of technologies, techniques and sciences, ranging from performance analysis to structural integrity, from traditional sensors to virtual sensors and from simple trending of raw data to sophisticated techniques based on artificial intelligence. However, the record of successful transition of the results of this research into fielded aero-engine systems is not as good as one would like. What is the reason for this and what should be done to improve the situation? Are the management mechanisms for transition inadequate, do engine managers lack vision, is the research not correctly focused, is it simply a question of insufficient funding, or is it a combination these?

While there are certainly difficulties in all these areas that prevent transition of EHM technologies to fielded systems, the author contends that the principal reason is that the needs and priorities for EHM are unclear. Conversely, many bold claims are made for EHM technologies, in terms of financial savings, improved operational readiness and enhanced safety, while less attention is paid to the difficulty and cost of implementation, particularly on a legacy fleet where the cost of fielding a completely new system could well be prohibitive. Furthermore, tangible benefits for EHM technologies are difficult to prove (and achieve) because the interactions between the EHM and support systems are complex.

Figure 1 — A Need-focused Approach

To help rectify this, the author believes that a structured, need-focused, top-down approach to EHM research should be taken, and the aim of this paper is to propose such a framework (Figure 1). The paper therefore first outlines important definitions that relate to EHM system coverage and operation, in order to start to provide a firm foundation. It then discusses the elements that constitute an EHM system, since this is essential when trying to determine the scope of an individual EHM system’s potential capabilities. The Air Force support needs lead to the prime goals of

1 U.S. Government work not protected by U.S. copyright.
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safety/airworthiness, mission success, availability/mission readiness, and low support cost. These are then broken down to their constituent objectives so that the contributions that can be made by EHM may be examined, and a broad EHM vision is then briefly drawn to provide a long-term target. The paper then proposes a structure for organizing EHM technology research programs, along with a simple method of rating program expectations. Finally, important EHM system development considerations are discussed. Although this approach is aimed at EHM, it could be extrapolated to health management of other aircraft systems and subsystems.

Much of the content of this paper is based on ongoing work with the US Air Force Research Laboratory, the SAE Aerospace Propulsion Division E-32 Engine Condition Monitoring Committee, and NATO RTO AVT-121 (Gas Turbine Engine High Cycle Fatigue) and AVT-126 (Military Turbine Engine Reliability) task groups.

2. EHM DEFINITIONS

Engine health management has moved a long way in the past few years and continues to evolve. Definitions that were appropriate ten years ago are no longer satisfactory and must be updated so that they are again representative. From an air force perspective EHM is about the pre-emption, postponement and accommodation of gas turbine engine degradation, faults and failures. Degradation, faults and failures are changes in an engine’s condition that compromise its ability to perform as required. For a military aerospace gas turbine, they thereby affect its ability to work safely, to allow the air vehicle to accomplish its mission or be available to do so, and increase its support costs. EHM should therefore be targeted to meet these challenges. EHM should be considered in a broad context, from the sensing of properties on the engine to the taking of any necessary action, since this encourages clear thinking about application and implementation of an EHM system. Traditionally, the term ‘EHM’ refers to the automated elements of a system and ends with the provision of information about an engine’s state. That said, the ultimate aim would be to automate as much as possible of an EHM system, ideally including any corrective or palliative action in order to speed up and simplify engine support and ensure a consistent approach.

The relevant SAE guide [1], which was published in 1993, refers to EHM as Engine Health Monitoring and focuses on the Engine Monitoring System (EMS), but the document is currently being updated to redefine EHM as Engine Health Management with its greater implied breadth. NATO reliability and maintainability standards, as reflected in [2], do not currently recognize EHM, although it is an important issue in a number of NATO task groups. Many other terms that cover capabilities that have been absorbed into EHM include Engine Health and Usage Monitoring System (EHUMS); Engine Usage, Condition and Maintenance Management System (EUCAMS); Engine Usage Monitoring System (EUMS); and Engine Condition Monitoring (ECM).

In the same way that EHM has absorbed other terms, it forms an important part of health management for the whole aircraft system. Two terms championed by the US Air Force Research Laboratory (AFRL) are Integrated Vehicle Health Management (IVHM) and more recently Integrated Systems Health Management (ISHM). ISHM was defined by AFRL’s Chief Technologist [3] as ‘efficient asset management through advanced design, monitoring, prognostics and maintenance practices’.

A further current term that has been coined by the F-35 Joint Strike Fighter (JSF) program office is Prognostics and Health Management (PHM). While we see prognostics as a part of health management, the term PHM clearly places the focus on the need to develop the prognostic elements of EHM technologies, something further evidenced by the Defense Advanced Projects Research Agency (DARPA)’s Engine System Prognosis (ESP) program (Figure 2).

Figure 2 – DARPA Prognosis Program

Degradation, Faults and Failures

It is also important to consider in a little more detail what an EHM system is intended to combat, since degradation, faults and failures are different in nature. A technical definition of degradation is difficult to find, but the word implies a gradual change between the period when the item is performing its function satisfactorily and the period when it is not. A good example is the loss of efficiency of an engine component over time (e.g., the compressor, through wear, leading to an increase in blade tip clearance) until the engine is unable to provide sufficient take-off thrust. Although a minimum thrust value will be specified in the aircraft’s release so that the aircraft can take off in all specified conditions, in practice it may not be obvious when the degradation has reached this level. Furthermore, a lower thrust level will be satisfactory with a lower payload and lower ambient temperature. Another example, again linked to the compressor, is surge, where operational factors will influence the engine’s susceptibility. Degradation is a form of ‘compromise (of) ability to perform as required’ that is traditionally pre-empted and managed by EHM systems by using some form of trending or periodic performance checking.
A fault is defined by UK MOD/NATO [2] as ‘the state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources’. This would tend to imply a clear delineation between the period when the item is performing its function and the period when it is not (ie, when it breaks). A failure is defined by UK MOD/NATO [2] as ‘the inability of an item to perform within previously specified limits’, and is again usually related to a sudden change of condition. These two definitions do not suggest a clear difference between the fault and failure. However, EHM specialists tend to refer to ‘fault to failure progression’, using the term fault to refer to an incipient condition reached on the route to failure. Indeed, the term ‘failure’ frequently refers to a sudden change such as a blade, bearing or disk failure.

Although these two regions of system ‘misbehaviour’ are different on the surface, they are not so dissimilar underneath. The ‘sudden’ changes of faults and failures are at source merely the result of a mechanical change and at a micro-structural level will have precursors. If these can be detected, then they can be managed. In the past, most EHM has been focused on macroscopic properties; although there is still much information available here, we also need to place an increasing focus on the microscopic.

Life

A standard definition for the term ‘life’ is difficult to find. UK MOD/NATO [2] defines a ‘Life Limited Item’ as ‘an item that has a limited and predictable useful life and could be considered for replacement on a pre-planned basis for reliability, safety or economic reasons’. The DoD Engine Structural Integrity Program (ENSIP) handbook [4] on the other hand refers to a ‘Design Service Life’ that an engine must exceed when subjected to particular usage. Although similar, one is framed as a limit and the other a target. From an EHM perspective it is useful and consistent to think of a ‘life’ as being a finite value of usage or ‘life consumption’ (whether measured in hours, cycles or some other damage accrual factor) at which a component would be deemed no longer serviceable. A ‘lifed’ item is one where this value has been specified.

Reliability/Mission Reliability

UK MOD/NATO [2] defines reliability as ‘the ability of an item to perform a required function under stated conditions for a specified period of time’. This is usually specified as a probability of failure within a given timescale or a ‘mean time between failure’. In this sense, EHM can affect reliability if it can modify an item’s environment, for example by smoothing throttle demand. It cannot affect the intrinsic material behaviour of a component. However, mission reliability is defined [2] as ‘the probability that an item will perform its required functions for the duration of a specified mission profile’. In this context, an EHM system’s ability to predict degradation, faults and failures comes to the fore, because a component that would have caused a mission failure may be replaced beforehand, thus having a direct impact on mission reliability (although still not affecting the component’s intrinsic reliability).

3. **The Elements of an EHM System**

Several complementary outlines for the elements of an EHM system exist, three examples being those from the Open Systems Architecture - Condition Based Maintenance (OSA-CBM) Overview [5], SMI [6], and Byington and Nickerson [7]. From an Air Force perspective, a medical analogy has been found useful in defining four essential elements of an EHM system (Figure 3); these are ‘symptomatics’, diagnostics, prognostics and prescriptive action. The use of these terms is explained below but they may vary a little from other published definitions [1], [2] and [7].

![Figure 3 – The Elements of EHM](image)

‘Symptomatics’

The term ‘symptomatics’ addresses the first step of the EHM process and is the ‘awareness of current condition and identification of a symptom or anomaly’. The medical parallel is an individual’s awareness of how they feel, which may or may not prompt them to take the next step to diagnostics. Other terms that have been used to describe ‘symptomatics’, or that form a part of it, include ‘state awareness’, ‘symptom identification’, ‘abnormality or anomaly detection’, and ‘condition monitoring’. They involve analysis of data from sensors, and/or periodic inspections, to determine an item’s state of degradation, or progression along a path towards failure, or the sensing of a symptom of abnormal condition. On occasion this EHM element has been included in ‘diagnostics’ [2] but, again following the medical analogy, there is often a distinct diagnostic step that is required to complete the picture so it is useful to treat it separately. For instance, an anomaly detection technique may be used to identify when an engine is performing abnormally, but without making an attempt to identify the cause or origin of the abnormality.
The need for diagnostics implies understanding its cause. The second EHM element is diagnostics, which is the inspection limits, for instance in the allowable damage on turbine or compressor blades, where the projection is that the blade will last at least up until the next programmed borescope inspection. The intention for the future is that more accurate predictions should be made, reducing the reliance on regular time-consuming manual checks and inspections.

It is useful to consider more than one prognostic ‘horizon’ (Figure 4). Short-term or ‘near-horizon prognostics’ gives a view of the near future and answers questions like ‘will the engine complete the sortie?’ or ‘will I need to change the engine in the next two weeks?’. These timescales are particularly useful to the pilot or a local commander; and high accuracy for individual engines is important. ‘Mid-horizon’ prognostics (between perhaps two weeks and two months) is of greatest use to the logistic chain so that spares may be moved into place, and for engineers to plan maintenance or prepare engines to avoid unnecessary failures and component changes early in deployments. ‘Far-horizon’ prognostics gives a longer-term view that is of greater value to the wing or headquarters for planning and provisioning purposes; high accuracy for individual engines is of less importance, the collective view being paramount here.

Diagnostics

The second EHM element is diagnostics, which is the ‘active process to undertake analysis of a symptom to understand its cause’. The need for diagnostics implies that there is some uncertainty about the current condition. Thus it is likely to involve some fault tracing or fault isolation to determine the underlying cause if relatively straightforward, or more involved root cause analysis if complex. Active diagnostics would not be required if the ‘symptomatics’ were targeted at a specific, known ‘pre-diagnosed’ fault. Moreover, if a symptom calls for non-trivial diagnostics, the implication is that the fault is complex and this would suggest that prognosis would also be difficult. Diagnostics invariably requires a sound knowledge of the system in question, and much of this knowledge is built into an engine’s Failure Modes, Effects and Criticality Analysis (FMECA), which is a powerful diagnostic tool.

Prognostics

This is the third foundation of EHM and is the ‘determination of where the cause or condition is leading and in what time frame’. In essence it is about predicting where degradation is leading, or what fault or failure will occur and when. This also implies a need to determine what effect this degradation, fault or failure will have on engine operation, or more specifically whether it will be critical or impact the aircraft’s ability to carry out its mission. It is essential that the prognostic output provide meaningful information in the time domain, and it must also be based on some understanding or assumption of how the engine will be used. Historically, prognostics has been built into inspection limits, for instance in the allowable damage on

Figure 4 – Prognostic Horizons

Prescriptive Action

This is the final, and key, EHM strand and is the ‘process to decide what to do about the symptom and doing it’. Again, if the ‘symptomatics’ is targeted at a specific known fault, the action will be pre-determined. Similarly to prognostics, prescriptive action can be taken at different levels. For an individual engine, the output could be an individual maintenance decision and action to replace a component (or indeed the engine); ultimately, some form of action (probably not component replacement) could be integrated into the engine control system. At the fleet (or sub-fleet) level the prescriptive action could be for a fleet-wide technical order, policy change or modification campaign. The decision support process would probably involve data mining and reasoning techniques although it would be some time before artificial intelligence could be
relied upon to make the decision itself, the final link in the chain remaining human for the foreseeable future.

4. AIR FORCE NEEDS

VAATE

From a US Air Force perspective, the current over-arching gas turbine engine research program is the Versatile Affordable Advanced Turbine Engines (VAATE) program (Figure 5). VAATE has the twin objectives of increasing performance and reducing life-cycle costs.

Figure 5 – The US VAATE Program

The wide range of technologies being pursued under VAATE is grouped into three focus areas: Versatile Core, Durability and Intelligent Engine (Figure 6). It is in the third of these that EHM falls. While VAATE provides the high-level focus for all engine technologies, it is useful to home in on the prime goals for EHM and build a more detailed structure from that.

Figure 6 – The Intelligent Engine Focus Area

Military Goals

The requirements of an EHM system for a military aero gas turbine engine are ultimately driven by the air vehicle’s overarching task of providing air power in a cost-effective manner. To achieve this, the air vehicle, or aircraft platform, must meet the four goals shown in Figure 7, which should be addressed in the following order:

Figure 7 – Air Vehicle Goals

Airworthiness or Safety—First, the air vehicle must be airworthy, or safe. In other words, the risk of a catastrophic failure, where the air vehicle might be lost, or its crew or the general public would be put at risk, must be within prescribed limits.

Mission Success—Accepting that the air vehicle is airworthy, the next priority is to ensure that, once launched, it is able to complete its mission.

Availability or Mission Readiness—In addition to being able to complete its mission, an air vehicle should be highly available, or at a high state of readiness, on the ground. In other words, the maximum number of air vehicles on inventory should be mission capable for the maximum amount of time. Furthermore, if a particular aircraft is suitable for a mission and is selected for it, there should be a high likelihood that it will launch successfully on that mission.

Low Support Cost—In addition to all three of the previous goals’ being met to the specified degree, the final goal is that the support cost of the air vehicle must be minimized. These costs cover a wide scope of maintenance and management tasks, with spare parts and maintenance work being high on the list.

Military EHM

EHM should therefore be targeted to meet these goals. In general, most measures that are focused on one particular goal will also have a beneficial effect on meeting the other goals. For example, a measure taken to enhance airworthiness is also likely to contribute to mission success, availability and mission readiness, and low support cost (if for no other reason than loss of an aircraft also has a detrimental effect on these other goals).
**Figure 8** — Airworthiness/Safety

*EHM Contribution to Airworthiness or Safety (Figure 8)*—
The engine’s contribution to air vehicle airworthiness or safety is principally through the prevention or management of failures that would lead to loss of the air vehicle. For multi-engine aircraft these are essentially those engine failures that would be uncontained and therefore threaten to damage the aircraft critically. This would typically include failures of critical rotating LCF-life-limited components (such as disks and shafts), loss of high energy blades, bearing failures, and failures that might lead to serious fires. To counter this threat, an EHM system needs to pre-empt each of these types of critical failure or, if the failure is manageable, mitigate it by initiating appropriate action or alerting the pilot to do so. If the failure is unmanageable, then by definition some form of prognostic capability is required; indeed most fielded prognostic-capable EHM technologies gained their place through airworthiness/safety needs. Such pre-emptive EHM includes LCF cycle usage monitoring, periodic blade inspections, engine vibration monitoring systems and oil debris analysis. EHM to allow mitigation of failures generally comprises warning systems. Future EHM techniques might include engine performance anomaly detection, advanced vibration analysis, non-intrusive blade health monitoring and on-line oil condition analysis. For single-engine aircraft the list of failures to consider is more extensive and, if the aircraft is unable to land safely without engine power, includes anything that would lead to non-recoverable in-flight shut-down (NRIFSD). An EHM system to counter this, such as on JSF, will need to be extensive.

**Figure 9** — Mission Success

*EHM Contribution to Mission Success (Figure 9)*—In addition to preventing those failures that would lead to loss of the air vehicle, mission success requires that those failures that would lead to mission failure be either prevented or managed. These might include failures of elements of the control system, including sensors or actuators. If such a failure can be mitigated in flight in such a way that the mission can still be completed, perhaps through system redundancy or reversionary modes, then the EHM system should assist with or manage the process. If not, then the EHM system needs to pre-empt such failures in a similar manner as with critical failures. Most of the EHM systems that contribute to airworthiness or safety (such as blade health monitoring) may also be directed at non-critical failures (eg, of compressor and turbine blades in multi-engine applications) and will thus contribute to mission success. Basic fault mitigation or accommodation has been with us for some time, in reversionary electronic controls for example, but in the future this will need to be extended, particularly for unmanned air vehicles, which will need to employ advanced logic and artificial intelligence for extended active control.

3 A simpler control mode that affords limited functionality sufficient for basic engine handling.
The foregoing is summarized in Table 1.

**Figure 10** — Availability/Mission Readiness

**EHM Contribution to Availability or Mission Readiness**
(Figure 10)—Again, all the measures employed to achieve airworthiness or safety and mission success will contribute to availability or mission readiness. Improved engine mission reliability and durability can also provide significant improvements to air vehicle availability or mission readiness. EHM can play a major role in increasing mission reliability through improved prognostic capabilities. EHM combined with engine control can contribute to greater durability by managing how the engine is used while still meeting the air vehicle’s demands. It can do this for example by minimizing the fatigue or thermal damage imparted to components, or by monitoring more accurately what damage is actually being imparted (eg, through advanced damage algorithms). EHM can also contribute to better availability or mission readiness by improving engine maintainability. Advanced EHM can help reduce preventive maintenance (including manual periodic inspections - a major burden for many legacy engines), speed up those inspections that need to be carried out, reduce false alarms, or speed up and improve diagnostic techniques. A powerful example of this would be where an engine performance monitoring system could reduce or remove the need to carry out both diagnostic and periodic performance ground runs. All these reduce the time that the engine is undergoing maintenance and speed up turn-round times. Finally, EHM with good long-term prognostic capabilities will allow provision of replacement parts to be accurately scheduled and maintenance to be more effectively planned.

**Figure 11** — Low Support Cost

**EHM Contribution to Low Support Cost** (Figure 11)—Finally, EHM can make a significant contribution towards reduction of support costs, through the reduction of maintenance man-hours and materiel costs. The reduction of maintenance man-hours will fall directly out of all those EHM measures that improve air vehicle availability or mission readiness, since these are making better use of resources. EHM reduces materiel costs in a number of ways. First, all EHM measures that improve durability directly reduce materiel costs. Second, many of the EHM techniques that pre-empt failures may also prevent collateral engine damage (eg, preventing an upstream blade failure will prevent extensive downstream blade damage). Third, EHM that improves knowledge of the state of components allows engines to be optimally rebuilt on overhaul, consequently extracting the optimum use from the parts. Finally, if EHM can provide good prognostic knowledge of engine health then a commander can forecast maintenance and tailor requirements for the spares and support equipment needed to support the engines (ie, reduce the logistic footprint). This has a particularly important impact for deployed operations, reducing the cost of deployment transport requirements.
Table 1 – Military EHM

<table>
<thead>
<tr>
<th>Goals</th>
<th>Principal Objectives</th>
<th>EHM Technical Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airworthiness/Safety</td>
<td>Prevent Engine Failures that would lead to Loss of Weapon System</td>
<td>Pre-empt Critical Failures</td>
</tr>
<tr>
<td></td>
<td>Manage Engine Failures that would otherwise lead to Loss of Weapon System</td>
<td>Mitigate Potentially Critical Failures</td>
</tr>
<tr>
<td></td>
<td>Prevent Engine Failures that would lead to Mission Failure</td>
<td>Pre-empt Non-Critical Failures</td>
</tr>
<tr>
<td></td>
<td>Manage Engine Failures that would otherwise lead to Mission Failure</td>
<td>Mitigate Non-Critical Failures</td>
</tr>
<tr>
<td>Mission Success</td>
<td>Improve Engine Mission Reliability</td>
<td>Direct Consequence of Failure Pre-emption/Mitigation</td>
</tr>
<tr>
<td></td>
<td>Improve Engine Durability</td>
<td>Minimize HCF Damage</td>
</tr>
<tr>
<td></td>
<td>Improve Engine Maintainability</td>
<td>Minimize LCF Damage</td>
</tr>
<tr>
<td></td>
<td>Improve Engine Part Availability</td>
<td>Extract Maximum LCF Life Potential</td>
</tr>
<tr>
<td></td>
<td>Reduce Engine Maintenance Manhours</td>
<td>Minimize Thermal Damage</td>
</tr>
<tr>
<td>Availability/Mission Readiness</td>
<td>Reduce Engine Materiel Cost</td>
<td>Direct Consequence of ‘Availability/Mission Readiness’ Goal</td>
</tr>
<tr>
<td>Low Support Cost</td>
<td>Reduce Engine Materiel Cost</td>
<td>Direct Consequence of ‘Improve Engine Durability’</td>
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<tr>
<td></td>
<td></td>
<td>Prevent Collateral Engine Damage</td>
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<tr>
<td></td>
<td></td>
<td>Build Optimum Engines with Available Parts</td>
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<tr>
<td></td>
<td></td>
<td>Reduce Logistic Footprint</td>
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5. AN AIR FORCE EHM VISION

An EHM vision derives from these goals and objectives. Through highly intelligent processing of data obtained from strategically placed advanced sensors, every engine in the fleet will be aware of its overall current condition in the necessary detail. Each engine will be able to accommodate operating requirements to minimize damage accrual and mitigate those failures with too short a prognostic horizon. They will assess whether they are ‘fit’ to perform their assigned missions, and when any system shows sign of impending malfunction (whether critical or not) will highlight the expected timescale for failure early. False alarms will be infrequent, and maximum life will be extracted from each part. Each engine will ensure that the local engineering organization is aware of its health assessment, where necessary highlighting the need for deeper investigation or impending failure in the appropriate timescales, and allowing any preventive or corrective actions to be conveniently scheduled, with spares and equipment ready, in good time. These actions will be efficiently planned, and rapidly and accurately executed, through advanced EHM-assisted techniques and requiring the minimum of ground support equipment. Enhanced engine condition awareness provided to engine overhaul facilities will allow optimum engines to be built. All the required information will be intelligently and rapidly deduced from the data collected and made available to the right person at the right time with a recommended prescriptive action. Each data element will be input into the seamlessly integrated infrastructure once only, at the node nearest its creation, automatically and requiring minimum of operator intervention.

The intention of the vision is to provide a broad perspective of the direction in which EHM should head. Many of the elements are farther downstream than others, and in the near future some will demand a higher priority than others. However, the elements that make up the vision need to be broken down into program requirements and fed into the structure drawn up in Section 6.

6. SCOPE AND RATING OF EHM RESEARCH PROGRAMS

Having established the EHM goals and vision it is then useful to organize research topics and programs into a structure because this allows the research manager to build up a picture of how the various technologies will fit together to form and organized whole. The organization will also help identify priorities, gaps and opportunities in the research portfolio and whether any inconsistencies exist. It is quite possible that research programs may not clearly fit into one category or another, and may migrate as they evolve or grow in scope. However, discipline and structure are essential to ensure that the research portfolio is balanced and has appropriate depth and breadth. The author suggests that it is useful to think of four scopes of EHM research:

a. EHM Foundation Technology Programs
b. Narrow-focus EHM System Programs
c. Broad-focus EHM System Programs
d. EHM Implementation Technology Programs

* Criticality of a particular failure will be influenced by whether an aircraft has one engine only or more than one engine.
These scopes are illustrated in Figure 12, discussed in the paragraphs below.

**A - EHM Foundation Technology Programs**

The first category of ‘EHM foundation technology’ programs covers research into the wide range of elements that will underpin and feed into the ‘narrow-focus’ and ‘broad-focus’ systems programs. These elements can be further sub-divided into ‘sensors’ and ‘techniques’. Sensor programs might range from improvement of environmental capabilities for an existing sensor to development of a novel sensor to detect a new health parameter. ‘Technique’ programs might cover component life usage/damage accumulation determination, anomaly detection, vibration analysis, the use of artificial intelligence or data management.

**B - Narrow-focus EHM System Programs**

A ‘narrow-focus EHM system’ program is one being developed to manage the health of a specific engine system, sub-system or component. It is therefore useful to sub-divide this group further into areas by the module or engine component type being managed to help clarify the relative focus being placed on different areas on the engine. Examples of programs within this scope include those aimed at disk, blade or bearing health management. Ultimately, one would expect a ‘narrow-focus’ program to mature and form part of a ‘broad-focus’ system program.

**C - Broad-focus EHM System Programs**

Research programs under the category ‘broad-focus EHM systems’ are those that manage the overall health of an engine or fleet. At the engine level, they would probably involve the integration of health management techniques into a whole-engine architecture covering multiple engine subsystems and feed off a range of EHM technologies. They might be specific, applicable to a particular engine program (eg, a comprehensive EHM system for an unmanned combat air vehicle) or generic, having wider applicability. Generic programs might cover a whole-engine on-wing diagnostic system, an advanced engine-level system for use in uninstalled engine test cells, or a system for fleet data reasoning.

**D - EHM Implementation Technology Programs**

The final category of ‘EHM implementation technology’ programs covers research whose end product may not be a specific EHM capability or system, but which is needed to pave the way for the development and transition of those programs into real systems. They might cover methodologies for the development of EHM strategies, cost benefit analysis techniques, EHM system simulation, fleet data management technologies, and information technology (IT) infrastructure or on-board-aircraft integration issues. These technologies are peripheral to core EHM in a functional sense, and are essential to enable them.

**Rating**

Having built the above structure it can then be populated with prospective and existing research programs in order to provide a complete picture of what needs to be done. An example of such a structure is shown in Table 2. To then assist with prioritizing EHM research programs, it is useful to look critically at each program and make a subjective judgement of what contribution it makes towards the goals identified in Section 4 using the following scoring system:

1. **No/minimal** benefit over baseline systems
2. **Some** benefit over baseline systems
3. **Worthwhile** benefit over baseline systems
4. **Significant** benefit over baseline systems
5. **Major** benefit over baseline systems

Clearly a more rigorous cost benefit analysis would be needed to form a decision about investing major funds into an EHM research program or implementing an EHM system across a fleet, but this exercise is useful in making a first order judgement and injecting a little rigour into determining what impact a particular technology might have. In order to do this it is important to be critical about likely capabilities.

It must also be remembered that a technology that is aimed principally at one goal may find its justification under another. For instance, a technology intended to give an airworthiness benefit may need to be justified on grounds of mission success or cost because the current level of airworthiness risk has been deemed acceptable.

**Other Benefits of the Approach**

Sorting research programs out in this way will often help identify where each type of organization will be able to provide the best benefit. For instance, small businesses and academia will tend to provide most input at the A and B Group level, whereas engine manufacturers will tend to aim...
more at the B and C levels. Airframe manufacturers and IT companies are likely to provide much of the input at Group D. Realising this will help build up the technology roadmap and realize the long-term vision.

Using this approach also ensures that the correct perspective is taken of a research program from the start. For example, it is unlikely that a Group A technology program could be implemented directly onto an engine; it would almost certainly need to be integrated into a Group B or Group C technology program, and might eventually be transitioned through a Group D technology program.

**Table 2**  
EHM Program Scopes and Rating

<table>
<thead>
<tr>
<th>Group</th>
<th>Research Program Scope</th>
<th>Area</th>
<th>Examples of Sub-Area/Objective</th>
<th>Probable Benefit to Achieving</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Airworthiness/Safety</td>
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7. **Other Important EHM Development Considerations**

There are a number of other important issues that must be considered when developing EHM technologies with a view to implementing and transitioning them, and in ensuring they have a long lifespan.

**EHM System Transition**

The end aim with all EHM research and development is to feed the results into an air vehicle so that they may be fielded. Generally, the target platforms fit into one of three categories: legacy (in-service), pipeline (being introduced) and future systems. Each have their differing transition opportunities for new EHM technology based on where they are in their life-cycle.

Legacy systems would appear to provide the strongest draw for an effective EHM solution, since unforeseen technical problems frequently provide a significant challenge to the operators and managers. However, the legacy fleet is where EHM transition may well be the most difficult and demanding. First, the fleet managers have real problems that need real solutions, and they need unequivocal evidence that a recommended EHM system will provide a solution. Second, this solution must be cost-effective and demonstrate real savings, since the managers will have to fund its implementation out of money that would be solving other problems or paying for spares and maintenance [10]. Furthermore, the costs should not be underestimated. From the hard EHM savings need to be subtracted the costs for integration, testing, purchase and embodiment of the new EHM system, both hardware and software; the EHM system’s own life-cycle support costs (including additional staff, operator training, etc); and any other infrastructure costs, including integration into an existing IT system, data movement/processing/storage, and possibly purchase of a new IT platform, together with its support. Finally, the savings and costs will be bounded by any production lead time, time required to embody the system across the fleet, and infrastructure lead time (eg, for IT). The embodiment time will be strongly influenced by how easily the EHM system can be fitted to the aircraft, and whether it requires the engines to be cycled through depot-level maintenance (for instance for a new sensor that requires a casing modification) and this may take a number of years. The bottom line is that, if the engine manager purchases a new EHM system, he or she will be the one who has to achieve savings.

Managers of pipeline systems again need to consider all those issues that apply to legacy systems although they may be balanced more in favour of the EHM system. Depending on precisely where the pipeline system is in its development or production cycle, it may be possible to introduce a new EHM technology into the baseline design and initial production, or into later production runs so the fleet fit is available early. Second, a pipeline system, being early in its life-cycle, will generally offer a greater payback timescale. Clearly, timing for maturity of the applicable EHM technology is critical to meet the required production deadlines.

Future systems offer the greatest opportunity for the implementation of EHM technologies, although again the timing for technology feed-in to the design is important. A major advantage is that the available EHM portfolio can be considered in breadth and depth and the engine and IT architecture can be arranged around those technologies that are or will be available. A technology must still ‘buy’ its way onto the engine and platform, but the major currencies may well be weight and maturity rather than implementation cost. The challenge is to align technology capabilities with ill-defined future requirements.

**Expect the Unexpected**

The aim of the Failure Modes, Effects and Criticality Analysis (FMECA) carried out during the design of an engine is to identify engine fault and failure problem areas and attempt to address them from the start. However, the natural corollary of this is that it is those issues that the FMECA did not fully identify that end up causing the major engineering management challenges. In other words, the many major airworthiness problems are unforeseen. Although it may not be possible to foresee the unforeseeable, it is worth bearing this truth in mind when designing EHM systems. For a start, technologies like anomaly detection may be able to play a part here if they can identify early symptoms of engine misbehaviour that can be tracked down to new failure modes or problems. However, much time could be expended investigating many anomalies that are of no consequence. A second possibility would be to allow some form of adaptable EHM architecture where new algorithms or even sensors could be integrated at a later date as new problems arise. Although this would not catch the first occurrence of a new problem, it might allow rapid control of it from then on.

**Confidence in the System**

Whatever the EHM technology, it must meet the twin challenges of being reliable in not highlighting unimportant issues (ie, have a low false alarm rate) while highlighting real problems with high confidence. If an EHM system is not able to achieve these twin aims then the few important problems will be missed, clouded by the many unimportant ones, and users will lose confidence in it and all the research, development and implementation effort may have been wasted. Clearly the EHM system also needs to have a higher order of magnitude of reliability than the problems it is trying to manage or the same fate will befall it. The SAE provides a sound quantitative methodology for assessing an EHM system’s capability [11]. Ultimately, the practicality and operational suitability of each proposed EHM system needs to be taken into account.
The need to store, manage, access and combine on-board performance and usage data with fault, asset, maintenance and supply data to both assist with health management of individual engines and build squadron, wing and fleet engineering pictures using data-fusion and mining technologies presents complex integration issues. Experience has shown that IT infrastructure is the Achilles’ heel of EHM implementation. The problem is clear with legacy systems where data is held on disparate systems, is difficult to manage and cannot be used to its best advantage. Data is not easily accessible for problem investigation, or research and development of future technologies. Elements of the solutions to these problems apparently exist (e.g., XML, middleware, open systems architecture and data warehousing) but differing requirements on the data systems pull in different directions and solutions are extremely difficult to identify and expensive to implement. Does a solution that may satisfy today’s requirements have the longevity and upgradeability to last far into the future? And how future-proof is it possible to make these solutions? Furthermore, data management philosophies evolve over time so that the best apparent solution changes. Invariably, new EHM solutions end up introducing their own new IT systems, which serve to exacerbate the integration problem.

When engine data is shared over multiple IT systems, a core data management issue is that of transfer of primacy/executive authority of different elements of data at different times. Using a legacy example, when an engine is installed in an aircraft and being operated, the data that defines accrual of usage of all the engine’s components is generated on the aircraft. This will probably then be transferred to a line-based IT system to form the prime, authoritative usage record. In addition, all the aircraft usage data that relates to an engine’s installation will probably be on that system. However, the authority to change overhaul or removal lives for different part-numbered components will cascade down from the engine management office, probably on a different IT system, and will need to drive the changes to the relevant records on the line-based system. When an engine is removed and dispatched for overhaul, the authoritative system must then become the overhaul IT system since components and assemblies will be removed, repaired and perhaps re-built into other engines. When the engine is returned to be installed in an aircraft, the previous regime will again apply. The integrity of the data must be retained across the transfers between these disparate systems throughout the life of the engine while still allowing the required flexibility and ease of maintenance. With future systems, it will be necessary to maintain the integrity of this asset backbone data with the flexibility to link detailed aircraft flight data with individual component histories. For instance, it may be desirable to relate a newly discovered fault with the history of particular flight regimes that may have stressed a part severely. It must be remembered that while many research technologies are designed to gather data from disparate systems and process them to produce information, they are not generally intended to address the issues of transfer of data primacy/executive authority. Although these technologies are extremely valuable, the primacy issue must still be addressed in the eventual solution, and these technologies must work with it.

In summary, data integration is a major technical and political challenge, involving many agencies, and these issues need to be considered when developing EHM technologies.

Retention of Raw Data

The majority of EHM systems ultimately depend on the timely availability of accurate data. On-board systems need to process performance and usage data rapidly and store the results, store the raw data, or do both. Each of these 3 options has its advantages and disadvantages. Experience has shown that we frequently wish we had access to engine data that we do not have, in order to process (or re-process) it and analyze it in different ways to learn more about engine health, re-evaluate usage calculations or test new techniques. It is true that data storage quickly becomes cheaper as time passes, but you can also be sure that our demand for information will grow more quickly than data storage capabilities, so striking the balance for a given program is not easy. Alternatively, it may be possible to devise some technique to save an analogue of the original data in a far more efficient manner, similarly to what has been achieved by MPEG for video information.

8. Conclusions & Recommendations

This paper provides a basis for managing an EHM research portfolio. It does this by building a framework that provides a clear understanding of what problems EHM can be expected to address and what an EHM system comprises; an explanation of the goals that EHM should be striving to achieve and the vision this creates; a structure for arranging, selecting and prioritizing the range of EHM research programs that will be required; and a discussion of a number of other important issues that must be considered when pursuing these research avenues. While aimed at gas turbine engine EHM research, the ideas outlined here could equally be extended to any other health management arena. The overall intention is to provide a structured approach that encourages the important issues to be taken into account with some rigour so that the program outcomes are more likely to be successful. For the US Air Force, the ideas have been used as a foundation for the ‘ApPRoVal’ process developed by Beachkofski for AFRL [12].

It is recommended that military EHM research portfolio managers consider setting up a structure that mirrors the one described here. This will help ensure that the correct programs are being pursued and that they are focused on providing worthwhile benefits to the end users. As a minimum, it is recommended that the paper’s content be
used as a yardstick against which to compare any existing EHM portfolio management system. Others who are involved in military EHM research, development, procurement or support should also find that the principles described in this paper are applicable to their work, and they are encouraged to adopt whichever elements may be of use. The benefits may well extend beyond that, to those who work in other, non-military, health management disciplines who may draw some inspiration from the ideas discussed.

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10. REFERENCES


11. BIOGRAPHY

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is a Royal Air Force officer serving on an exchange program in the Propulsion Directorate at the United States Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio. He is a program manager for USAF EHM applied research projects underway in industry. Squadron Leader Wade joined the Royal Air Force Engineer Branch in 1981 as a University Cadet prior to completing his MA degree in engineering at Cambridge University. Following officer and engineering training at RAF College Cranwell he has served in a variety of posts on flying stations and in staff appointments. He completed his MSc degree at Cranfield University from 1992-93 prior to serving as the Engineering Authority for the Tornado’s RB199 powerplant. He was then posted to Royal Air Force Bruggen in Germany to be Officer Commanding Mechanical Engineering (Air) Squadron where he was responsible for Tornado intermediate maintenance and operational preparation, and RB199 and aircraft component overhaul, during the Kuwait and Kosovo crises. More recently he was the engineer responsible for developing the support strategy for the EJ200 engine that will power Eurofighter Typhoon. He was posted to Wright-Patterson Air Force Base in August 2002.