A Probabilistic, Diagnostic and Prognostic System for Engine Health and Usage Management

Squadron Leader Richard Friend
Air Force Research Laboratory/Propulsion Directorate, Turbine Engine Division, Components Branch
1950 Fifth Street, Building 18D
Wright Patterson Air Force Base, OH 45432-7251
937-255-2734
richard.friend@wpafb.af.mil

Abstract - The combination of high engine life-cycle costs, concerns for greater safety and changing operational demands create the need for improved engine diagnostics and prognostics. Engine maintenance represents perhaps the largest part of overall aircraft maintenance costs and, due to safety considerations tends to be performed conservatively. Better information on the actual engine condition, usage and life monitoring can significantly reduce maintenance costs. The United States Air Force (USAF) has invested in the concept of engine health monitoring with current systems such as Comprehensive Engine Maintenance System (CEMS) IV and Research and Development (R & D) programs in the early 1990s to investigate additional health and performance monitoring technologies. There is a need to develop these capabilities further and combine data from an array of sensors to enable engine health management using more advanced diagnostic and prognostic techniques, and the latest sensor technologies. The integration and correlation of data from multiple sensors is key to practical and affordable engine diagnostics and prognostics.

A Probabilistic, Diagnostic and Prognostic System (ProDaPS) for engine health management is the next major step forward towards this target. The long-term objectives of the ProDaPS program are to develop a flyable, real-time working system that can be used to enhance the management of current as well as future engine fleets. The proof of concept has been demonstrated and the current program is considered to be the first stage of the technology development and transition to the commercial market.

TABLE OF CONTENTS

1. INTRODUCTION [*]

The United States Air Force commenced R&D into engine condition monitoring several years ago as part of the drive towards the Integrated High Performance Turbine Engine Technology (IHPTET) program. Recognizing the spiraling costs of technology and the need to provide the maximum availability of aircraft and equipment, specific research into Engine Health Monitoring and Management (EHM) was borne. The key goals for EHM then were to make engines more available and more affordable, and these goals have not changed. However, within the Propulsion R&D community, and the Department of Defense (DoD), there is a growing shift in focus from performance to affordability, which increases the importance of EHM.

Scope

The purpose of this paper is to:

1. Provide details of the recent history of EHM applied research and development in the USAF.
2. Discuss the growth in sensors, from the halcyon days of monitoring the basic engine parameters to the profusion of new sensors following the growth in computer technology. This paper will highlight key sensing technologies that enable diagnostics and prognostics.
3. Highlight the development of new sensors that have been successful through the USAF Small Business Innovative Research (SBIR) Program and Dual Use Science and Technology (DUST) Program.
4. Discuss the DUST Program with Smiths Industries Aerospace to develop a ProDaPS for EHM.

To keep the paper short, it will be limited to brief descriptions.

Background

In the Eighties many innovative programs were implemented by the Engine Trending and Diagnostic

(ET&D) working group from the main USAF engine depots at Kelly and Tinker Air Force Bases. Perhaps the most notable implementation was CEMS that is now on its fourth iteration. CEMS IV provides an archive/store for basic engine performance data and some oil condition and particulate monitoring data, but relies mainly on the intelligence of expert users to trend engine performance and predict future problems. Maintenance personnel can use the System to help determine the condition of an engine, track parts, and life, and aid with maintenance; the main benefits have been to improve visibility and engine availability. Some of the units have been able to get better return from CEMS by retaining the people employed on CEMS. Indeed, there are recognized experts in the field and these personnel are highly sought after by engine managers. In addition, there are annual ET&D and CEMS conferences that highlight new advances and keep personnel and users up to date. CEMS IV is due to get a facelift with the incorporation of Artificial Intelligence in the form of an add-on module that will automate many of the procedures, improve the alarms for limit exceedances and close-to-limit trending, and help the user get more information from the data. Without doubt, CEMS is a tremendous tool that has great use and good potential to expand and be integrated with other systems. A future CEMS could offer autonomic logistics, the automatic provisioning of spares and call for certified maintenance personnel. The idea is to get the Right support at the Right time for the Right reason. The R^3 support methodology could include the call for tools, provision of electronic maintenance manuals/details and electronic equipment log card recording.

Expectations have mushroomed with the computer revolution as storage space for data has greatly reduced and the speed of processing can now realistically be done in real time. Consequently, engine component lifing can now be calculated in real time, on wing, instead of using a worse case scenario and applying this across an engine fleet. This old safe-life methodology maintains safety but wastes significant component life by requiring the rejection of components before their actual life limit has been met. This key area is seen as having the potential to save many millions, perhaps even billions of dollars in the USAF alone, and may help refine designs based on new, whole-of-life measurement and recording. Indeed, there are other technologies being applied in this area to help measure the life remaining in rotating disks, and other components, by measuring the residual surface stress in the discs both at manufacture and during depot repair. For example, Residual Surface Stress measurements could indicate the life remaining to Low Cycle Fatigue (LCF) surface crack initiation. Measuring this parameter on disks at new and at every overhaul opportunity would enable the compressive stress at new to be figured into the life prediction algorithms. Also, measurement during overhaul would back the LCF usage and allow for comparison of the calculated/measured life to the defined model. More work is being done in this area to define how residual stress relates to life and whether the reduction in compressive residual stress can accurately predict LCF crack initiation.

The USAF owns many engines, about 25,000 in 1999, and including spares and consumables is in excess of $32 billion. This massive inventory will double in cost with the recent commitment to acquire the F-22 RAPTOR aircraft and could exceed $70 billion by 2005, a year that will see the completion of the IHPTET program and the move to the Versatile Affordable Turbo Engine (VATE). VATE will begin a new series of research thrusts for the Propulsion Directorate of the Air Force Research Laboratory to further the development of the gas turbine engine. The achievements of the IHPTET program, a 2 X increase in thrust based on the YF119 engine, will be pushed again to realize a 2.5 X increase in thrust, but the main focus will change from performance to affordability. Affordability is the Number One concern for the DoD and is defined as:

$$\frac{\text{Capability}}{\text{Cost}} = \frac{(\text{thrust/weight})/\text{Total Specific Fuel Consumption}}{\text{Cost}}$$

Where cost is defined as the sum of engine Development, Production and Maintenance costs

The Joint Strike Fighter (JSF) Prognostic Health Management (PHM) program has been hungry for new technologies to get the maximum life from new equipment and improve availability. Moreover, it will provide the commander in the field with unequalled visibility of the performance of the aircraft to allow precise selection for operations and individual sorties. It seeks to provide predictive diagnostics of faults, performance and life, (prognostics) and transmit this information from the aircraft via a secure communications link to a ground system. This system, the Joint Distributive Information System (JDIS), will link the aircraft to a comprehensive maintenance network that includes equipment suppliers and the aircraft overall equipment manufacturer. PHM is being applied to many systems on the JSF including the engine, auxiliary power unit, and environmental control system, areas that are known to be a source of concern or have seen a high number of faults on aircraft like the F-15 EAGLE or F-16 FALCON.

2. Engine Health Monitoring and Management

EHM research was initiated with mainly SBIR programs, beginning applied research with small, specialized companies. The first round of EHM SBIRs identified new sensor technologies to revolutionize the data collected and provide the best information to the operator and maintainer. Today we monitor mainly temperatures and pressures but are beginning to explore vibration, oil and other health monitoring parameters. The subsequent SBIR rounds have been to provide artificially intelligent systems, neural network based, test them on uninstalled engines and fit them to engine test facilities. In the future, SBIRs will help to flight test advanced EHM systems, fit them to new aircraft and retrospectively fit them to older aircraft, as they become problematic and expensive to operate. The rationale is to ensure that the cost of modification is recovered in a short period of time, perhaps 5-10 years. Nonetheless, Rolls Royce is focused on fitting an artificially intelligent EHM system to its most reliable engine in service today, the RB211-535E4 powerplant fitted to the Boeing 757 aircraft fleet. The aim is to increase its despatch reliability from 99.91 percent to 99.95 percent and attain the elusive Six-Sigma standard for quality [Reference[1]]. Moreover, an aircraft diversion can cost an airline a significant amount owing to the costs of disruption, off-loading passengers onto a second aircraft, rescuing the original plane, hotel bills, guarantee payments and compensation to customers. These secondary costs of failure can be more expensive than the direct costs for the recovery of the engine.

Artificial Intelligence

There are many new and emerging technologies that are making engine monitoring more complete and informative. Many of the current single temperature or pressure sensors that are hard wired to control systems or the cockpit, will be replaced by sensors offering at least a dual capability, one sensor perhaps measuring both pressure and temperature. Furthermore, these new sensors may be without wiring sending digitized radio, frequency agile signals back to a central processor or control center where the data will be fused with data from other sensors to control or determine, with a high degree of accuracy, the health of the engine. Moreover, the use of artificial intelligence will allow the data to be processed, using neural networks to predict future faults well ahead of the occurrence. This will allow for preventative maintenance to be carried out to reverse the trend or allow for the engine to be operated without corrective maintenance until the next planned maintenance opportunity. This will provide the most cost-effective way to operate aircraft and maximize operational availability. Sensing technology is seen as being vital to new engines, under the IHPTET and VATE programs, and is already a key area within the Propulsion Directorate. An USAF technology leader, Kelly Navarra, heads the Propulsion Directorate sensor R&D efforts.

Affordability

It has been estimated that the USAF expends an average of $400/hr to operate its engines fitted to the fast jet fleet. As new technologies are introduced to enhance performance we cannot afford to let this operating cost surge to higher levels. We need to provide the same for less or more for the same. Consequently, VATE will address affordability as its main issue and will drive to provide 10X affordability based on the Pratt and Whitney F119 engine fitted in the F-22 RAPTOR aircraft.

Benefits

In response to the changing needs in the market place and requirements of their customers, all the engine manufacturers are now researching and developing EHM. Moreover, health monitoring is being applied to many inherently unreliable systems in order to improve visibility, reliability and maintainability. A system that monitors and provides predictive diagnostics is a major advantage to any management. Many transportation industries are realizing the benefits and locomotive operators are applying advanced EHM systems to their fleets.

Sensors

Diagnostics and Prognostics - To enable diagnostics and prognostics, sensors must provide a greater range of data than the typical base parameters of temperatures, pressures and speeds. However, basic parameter monitoring can and does provide valuable information on the performance of an engine. Through intelligent processing, and integration with other parameters, valuable information can be acquired including actual life consumed, life remaining, and the condition of the engine relating to its performance on the last mission or succession of missions. Whilst this can provide a good baseline for diagnostics and prognostics it will provide the best information if the data is fused with data from other sensors measuring health parameters like vibration, oil condition, and gas path electrostatics. There are many papers and workshops on each of these sensing technologies but it is clear that by using the data that each provide, and by fusing this in a data fusion center, a system can provide a high degree of confidence in the diagnostic and prognostic arena. Moreover, further fusion with electronic maintenance manuals and individual engine and fleet histories will heighten the confidence to a level where maintenance and operational decisions can be confidently made.

Oil - For several years' analyses of oil condition and particulate monitoring has told us much about engine health. However, in many cases the information from the oil analysis laboratories can take several hours or even days to reach the aircraft maintenance controllers. Consequently, aircraft have been released for flight based on the last record, before a clear indication of engine bearing health has been established. Consequently, if we wish to pursue a real on-condition based maintenance philosophy, and use components safely up to a point before failure, there is a pressing need to provide this information real time. To ensure the oil provides the acceptable level of lubrication, and cooling, its condition must be continually monitored and assessed. Moreover, the particulates from the oil-wetted components must be analyzed in real time to monitor the health of bearings and seals. When this data is fused with data from complimentary sources, like vibration, it will provide a high degree of confidence in the health of the engine and help make the right management decisions. Consequently, it can be seen that a prognostic and diagnostic system must have some degree of oil, vibration and gas path monitoring, and that this must be integrated to provide the best information.

Size, Environment and Reliability - In a fighter aircraft, space and weight are at a premium and equipment must win its way onto the aircraft by proving its operational value and cost effectiveness. Whilst a profusion of sensors might provide a means to providing highly confident monitoring systems for ground based gas turbine engines, like that fitted to the M1 Abrams main battle tank, it is not acceptable for an airborne application. Equally, whilst a sensor must be rugged and compact, it must not represent the "tip of the iceberg" and have a mass of circuitry and supporting hardware. Perhaps a better understanding of engine operations will lead to more use of virtually sensed parameters that will be combined with data from actual sensors to provide a comprehensive indication of health and life. Aircraft sensors must be able to survive in a harsh environment that has massive temperature extremes, vibration, fluid contamination, high aerodynamic forces, and sustain the rigors of poor handling. Many of the first piezo-electric vibration sensors suffered from countless errors and gave too many false alarms. This eventually led to vibration alarms being ignored and in some case the sensors being disconnected and tied back. Future sensors and systems must be highly reliable and provide ultimately 100% confidence in alarms and warnings to the operators and maintainers.

The future - A vision for sensors of the future is that one sensor will have the ability to read more than one parameter, perhaps even several, and be self powered by engine heat or vibration. Consequently, for a limit alarm, the sensor will turn itself on when a limit has been reached and alert the control center or pilot of an exceedance leading to a potential failure, long before that failure occurs. For VATE applications, this could be integrated into controlling systems that will be aware of mission criteria and adapt engine operation to maintain aircraft and system availability.

Systems

TEDANN - There are many EHM and diagnostic systems available today but one deserves a special mention because of its similarity to where the USAF is going and is on a similar path to what the JSF will achieve through PHM. The United States Army is installing an artificially intelligent EHM system into its M1 Abrams main battle tank using a system called the TEDANN, Turbine Diagnostics using Artificial Neural Networks. Artificial Neural Networks (ANN) represent a branch of the artificial intelligent techniques that have shown increasing acceptance for condition monitoring in a wide range of industrial applications. The ANN is a mathematical method modeled after biological brains. Its abilities to approximate features, recognize patterns, and to learn from samples have made it attractive for the control and monitoring of complex systems such as gas turbine engines [Reference[2]]. The Abrams AGT1500 turbine engine is equipped with 48 sensors, 32 that are factory installed and 16 that are retrofitted using a wiring harness. These 16 include 7 for pressure, 6 for temperature, 2 for oil chip/particulate sensing, and a vibration sensor. The sensor signals are conditioned using 2 printed circuit boards, multiplexed to a data acquisition card, and then analyzed by a Pentium microprocessor. Results of the analysis are presented in various forms. The tank crew may display only the most critical information, whereas the maintenance personnel can display graphs of temperatures, and pressures, and more detailed diagnostic output. TEDANN is being developed using model-based diagnostics and artificial neural networks. Consequently, this will allow the diagnostics and prognostics to model normal engine performance, learn to recognize deviations from normal behavior, and classify those deviations requiring maintenance attention. The longer-term vision for the TEDANN is to make higher-level status information available to command center decision-makers that will facilitate tactical and logistics planning. This vision will enable tactical commanders to assign vehicles to engagements based on expected operational readiness, and enable logistics/maintenance planners to schedule maintenance or order replacement parts. If fully deployed in the field, the TEDANN system would be integrated with other electronic systems on board the tank [Reference [3]].

Airborne - For airborne systems the judgment of what is processed and analyzed on board is a difficult one; computer speed, power, and size are critical to this decision. It is easier to store data and download this to a ground-based system and have that system carry out the analysis and integration with other systems and advisors. In helicopter HUMS much data is processed on-board and the results or indicators are stored. However, if processing is carried out on-board there is an additional certification cost and the software has to be certified to a higher level. In helicopter HUMS, if maintenance credits are to be gained from the system the ground-based software has to be to the same level as the airborne. Hence, there is no real advantage in either approach in terms of certification, and software costs and effort. The benefits of providing a health management capability in the air, real time, far outweigh the difficulty. Achieving the right balance for EHM technology is crucial at this time and dependent on current capabilities and customer requirements. By 2002 the first Rolls-Royce engine will be fitted with a high-tech Black Box that will examine its performance in minute detail. So sophisticated are the new monitoring systems – including lasers, radar, acoustic sensors and particle detectors – they will put engine health on a fully scientific basis for the first time.

3. PRODAPS

Using Dual Use Science and Technology (DUST) programs the USAF seeks to cost share with industry the R&D of technologies into useful tools that are mutually beneficial both militarily and commercially. The government funding is provided from DUST funds and from DARPA. ProDaPS was proposed by Smiths Industries Aerospace and the contract was awarded in September 1999. The competition was fierce but the potential benefits of ProDaPS, and the negligible technical risks, ensured it was ranked high. Smiths Industries is involved in the development and manufacture of avionics and related electrical systems for aircraft. They have experience in engine health and usage monitoring, engine sensor development and applied technology in the aerospace industry.

Concept

The concept for this program was to make a marked improvement in the development of EHM, using a ProDaPS demonstrator system. The System will utilize an open architecture to integrate known and emerging sensor technology now and provide the opportunity to add and expand later as better sensors become available. ProDaPS sensors were selected on their capability, and cost, and the program will integrate them to provide the best mix to obtain the best information. However, the concept can be applied even to a basic monitoring system that does not benefit from special sensors.

The technical objectives for the program are to demonstrate a ProDaPS reasoner that is real-time, accurate, timely, and provide both diagnostic and prognostic capabilities for events like faults, life, health, performance and condition. The Service needs are to provide a maintenance advisor to achieve reductions in logistic support and cost, whilst increasing operational capability, reliability and safety. These key issues have been highlighted on numerous occasions by many military leaders, and were recent concerns in Kosovo that were subsequently highlighted by Major General Haines, the Logistic commander of Air Combat Command. ProDaPS has related efforts with aging aircraft, the Integrated High Performance Turbine Engine Technology (IHPTET), its follow-on program the Versatile, Affordable Turbo Engine (VATE), and the JSF.

Requirement

ProDaPS will utilize commercial off the shelf (COTS) supply for computer hardware and software to reduce costs. The sensor set will include state-of-the-art inlet and exhaust electrostatic particulate sensors, combined with standard sensors providing performance data, vibration information, high cycle fatigue, low cycle fatigue and creep monitoring, and life usage monitoring. These data will be integrated and fused to enable complete engine diagnostics, prognostics and life management. It will produce a PC-based demonstrator prototype and identify how this can be migrated to future aircraft or retrofitted into the current aircraft fleets. The main subjects for research are identified

ProDaPS GOTChA Chart

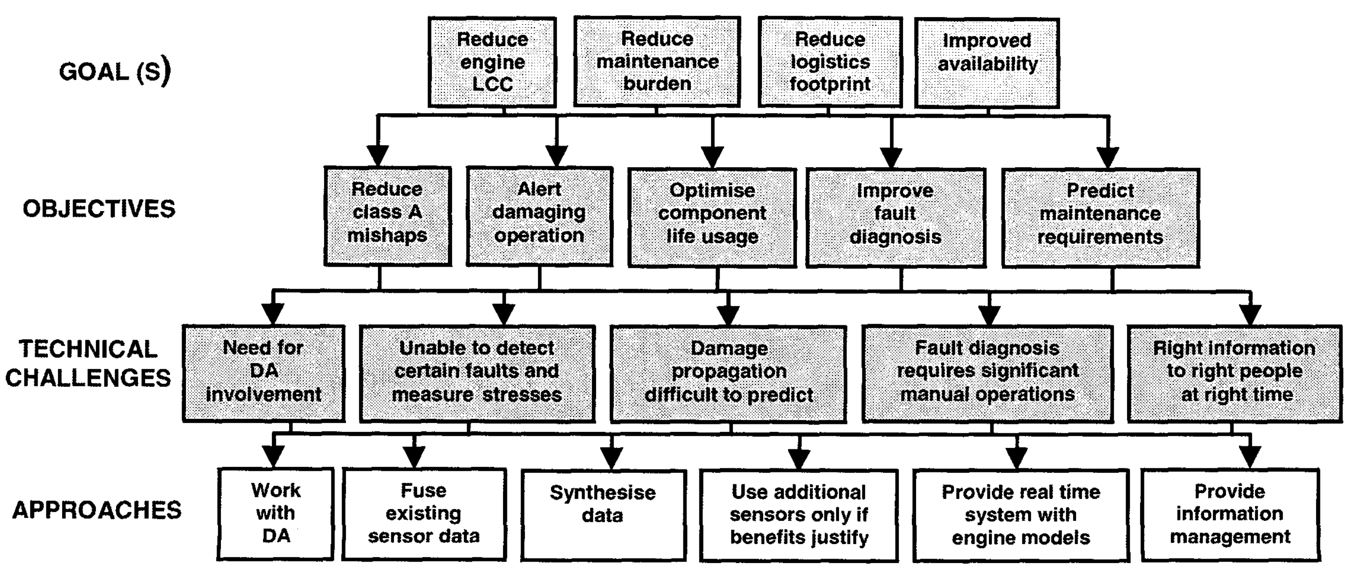

Figure 1 ProDaPS GOTChA Chart

in the ProDaPS GOTChA chart, Figure 1.

Tool Set

ProDaPS will be programmed in the commonly available C++ language and operate using the Windows® NT operating system. It will provide 4 operating modes: the Maintainer Mode, the Manager Mode, the Policy Maker Mode, and the Pilot-debriefing Mode. The Pilot-debriefing Mode is seen as a future capability and will not be progressed under the current program requirements. However, the Pilot debriefing mode will be progressed if more funds become available. Each of these 4 modes will provide a list of options to improve visibility and the management of aero-engines as follows:

1. The Maintainer Mode will:

a. Comply with the design/maintenance procedures in a strictly controlled way.
b. Process all transmitted data automatically.
c. Trigger audio and visual maintenance alarms when specific warning or maintenance actions are required.
d. Indicate required actions.

2. The Manager mode will:

a. Use controlled information only.
b. Provide clear management reports using a graphical interface where necessary.
c. Forecast engine component condition for each engine and across the fleet.
d. Trace the cause and source of degraded engine condition.
e. Evaluate the impact of roles or missions on the condition and availability of aircraft.

f. Select aircraft for missions based on the operational requirement, operational and maintenance histories, and projected availability.

3. The Policy Maker Mode will:

a. Evaluate the cost of missions in terms of fatigue life, crack growth and other predominant aspects.
b. Access all tasks available for Maintainers and fleet Managers under the 2 previous modes.
c. Access all data and information to perform statistical, regression and trend analyses.
d. Synthesize missions and roles.
e. Predict and analyze the impact of future operations on engine condition.
f. Assess the impact of new EHM sensor technologies across the engine fleet.

4. The Pilot-debriefing Mode (future mode) will:

a. View multiple FDR graphs and frequency charts.
b. Mark graphs with exceedances of the operating envelope.
c. Display progressive accumulative damage and condition indicators.
d. Animate aircraft cockpit dials with additional dials showing the impact of manoeuvres on component conditions.

ProDaPS will be developed so that it can be retrofitted to older aircraft like the F-16. ProDaPS is significant in the development of advanced EHM as it will provide the first opportunity to flight test new sensors and be the first to use and fuse the data in an integrated but open architecture.

ProDaPS Program Plan

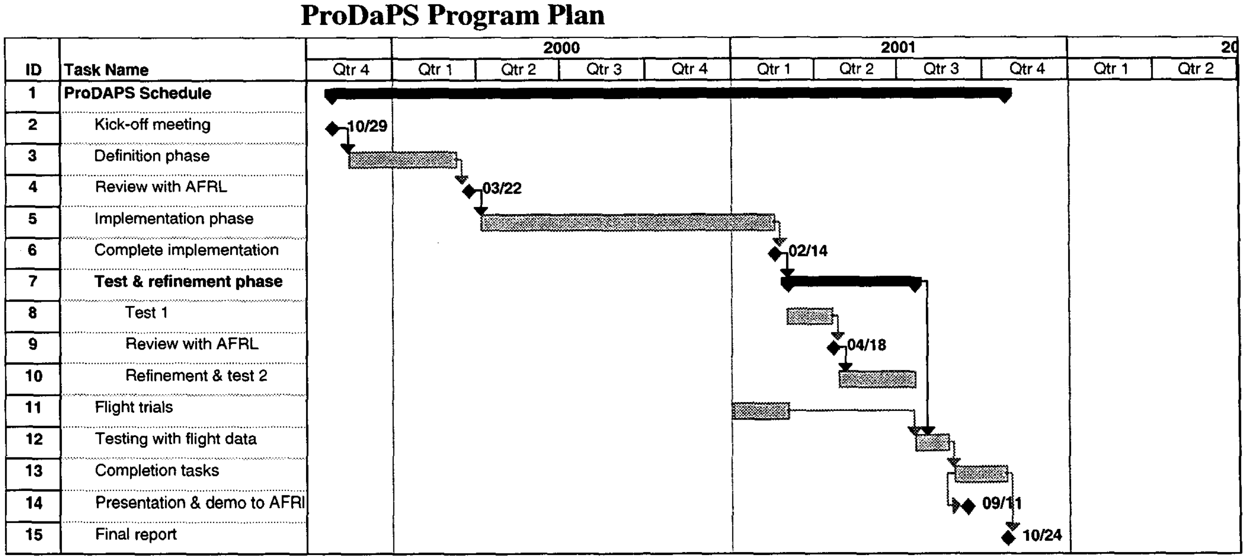

Figure 2 ProDaPS Program Plan

Program

ProDaPS will enable the application of true on-condition maintenance, eliminating scheduled and costly unscheduled/corrective maintenance. It can be seen as a logical spin off from failure prediction maintenance allowing the user to safely identify the remaining life of deteriorating components whilst they are in use and to capitalize on that knowledge for operational and/or cost reasons. The System provides a clear indication of when maintenance is due, and when linked to an Autonomic Logistic System will automatically schedule the parts list, tooling and certified labor required to restore the engine system that is deteriorating towards a health, performance or safety limit. ProDaPS is a short, medium and long-range maintenance and mission-planning tool, which will significantly reduce costs with enhanced operational capabilities at the same or improved safety margins. The program comprises 6 top-level tasks that form a 3 phase, 15-item program plan, Figure 2 above.

The Definition Phase will see the collection of USAF and Pratt and Whitney (P&W) experience on F100 engine operations to scope the main reasons for failures and engine rejection, and to provide a list of target faults to build and train ProDaPS. Engine fault signatures will be collected or assembled. The ProDaPS architecture and technology modules will be defined. Furthermore, during the Implementation Phase guidance from both the USAF and P&W will tailor the program to meet USAF target benefits and engine management requirements. The program will be routinely assessed to ensure these benefits are met. The Test & Refinement Phase will see real data used to show the diagnostic and prognostic potential of the System. Furthermore, the electrostatic sensors for the inlet and exhaust will be flight tested, coupled with other advanced sensors, and a mass of flight data will be used to test and demonstrate the System.

ProDaPS Model

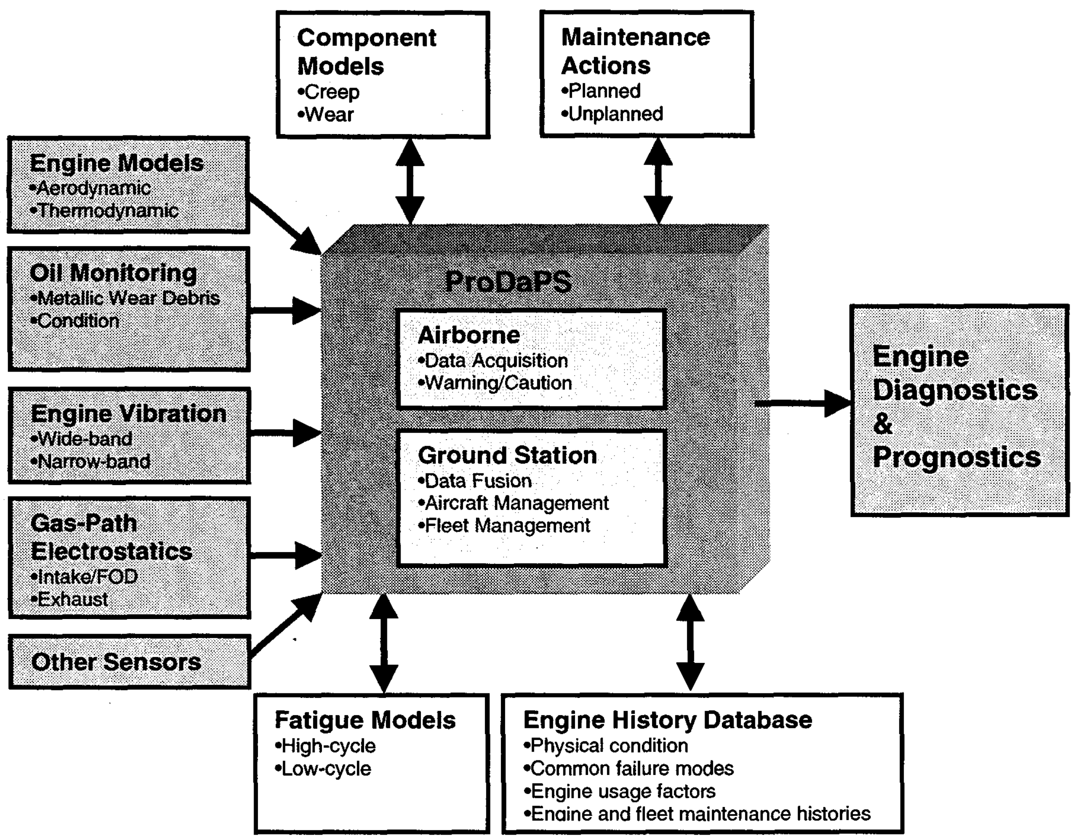

Figure 3 ProDaPS Model

4. SUMMARY

With spiraling engine support costs and the advent of new technology offering more complex and expensive equipment, the USAF is seeking reductions in life-cycle costs in the form of advanced EHM. Through advanced diagnostics and trending – prognostics - it will be possible to predict problems before failures occur and ensure preventative maintenance is scheduled at a time to suit the operator and maintainer, providing the right action at the right time for right reasons. Moreover, it will speed diagnostics, significantly reduce maintenance and improve availability. Continued success and confidence in health management will reduce failure, and expensive and disruptive corrective maintenance, and allow the aerospace industry to move towards condition-based maintenance, based purely on equipment condition and not worse case estimated life. Moreover, it will allow commanders in the field to select the best aircraft to provide the highest chance of operational success. Artificial intelligence embedded within monitoring systems will process fused data from smart sensors to provide accurate and timely information about equipment performance and condition. Only where absolutely necessary will the pilot be alerted but the information will be passed via secure data link to a ground distribution system that will feed information and data to a network of suppliers and maintainers. This true 'team' approach will increase visibility, improve availability and management. In the future, engine data could be further fused with aircraft data and be embedded in active control systems that will change engine operating conditions to minimize the effects of High Cycle Fatigue, extend life and reduce life-cycle costs. Advanced EHM will realize its potential; it will help to provide more reliable engines and make engines more affordable.

ProDaPS is a positive step in that direction; it will use state-of-art sensors and integrate sensor data in a data fusion center to provide the best information to the operator and maintainer. Moreover, it will allow new sensors to be fitted, as they become available. It will enable prognostics and provide sensor confidence for the initial PHM suite chosen for the Boeing Joint Strike Fighter and under consideration for the alternative aircraft from Lockheed Martin. ProDaPS will provide the avenue to assist in flight testing an advanced EHM system and has the potential to be tailored and fitted to suit any gas turbine engine, including the many in use with the airlines and power industries, and be adapted for use on machinery. It will provide confidence to move to on-condition based maintenance, reduce operating costs, and enable better business and management processes. ProDaPS will provide equipment intelligence, adaptability and affordability in a more competitive world.

REFERENCES

[1] Marcus Gibson, "The Forensic Approach to Engine Health," *Rolls Royce The Magazine, Issue 82.* September 1999.

[2] SAE E-32 Committee for Engine Condition Monitoring, "Neural Network Applications for Engine Condition Monitoring," *SAE Aerospace Resource Document ARD50069.* Revision May 15, 1999.

[3] Frank L. Greitzer, Lars J. Kangas, Kristen M. Terrones, Melody A. Maynard, Barry W. Wilson, Ronald A. Pawlowski, Daniel R. Sisk, and Newton B. Brown, "Gas Turbine Engine Health Monitoring and Prognostics", *International Society of Logistics 1999 Symposium,* August 30-September 2, 1999.

***Squadron Leader Richard Friend** is a Royal Air Force engineering officer serving on an exchange program in the Propulsion Directorate at the United States Air Force Research Laboratory, Wright Patterson Air Force Base. He is the senior project manager for the ProDaPS program and managers several USAF EHM research projects underway in industry. An aero-mechanical engineer, he is specialized in gas turbine engines and has accrued over 22 years experience in the maintenance and management of fighter aircraft, engines and engine test facilities. Formally a senior engineering officer on a Tornado F3 equipped squadron at Coningsby, England, he has served at the Defence Research Agency at Pyestock, Farnborough, England, where he researched Foreign Object Damage, the mechanisms of object ingestion, and aero-engine operating costs. As a Flight Lieutenant he was: an engineering authority responsible for the management of installed and uninstalled engine test facilities for the UK Armed Forces; was officer in charge of a Tornado RB199 engine overhaul facility, repairing engines and provided specially modified engines for the Royal Air Force Tornado aircraft that operated in Operation DESERT STORM. As a junior engineering officer he served on the Phantom Operation Conversion Unit that trained pilots for operational service. He served 9 years as an engine and airframe technician, saw active service in the Falklands Island conflict, and achieved the rank of sergeant. He was commissioned into the engineering branch in 1986.*