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INTEGRATED MODEL-BASED CONTROLS AND PHM FOR IMPROVING TURBINE ENGINE PERFORMANCE, RELIABILITY, AND COST (POSTPRINT)

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GE Aviation

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14. ABSTRACT
Control of high performance military aircraft propulsion systems continues to become more complex in response to increasingly demanding operational and multiple mission needs. Propulsion systems of the future will require adaptive engine control to enable precise and repeatable performance within stringent reliability, safety and cost constraints. In order to achieve performance that meets these requirements, propulsion control systems must evolve towards advanced designs with multivariable control systems and integrate numerous systems, including inlet, exhaust, power and bleed extraction, electrical power, thermal and environmental management, fuel, starting, accessories, aircraft flight control, and often propellers, open rotors, or lift fans. Due to the significant growth in complexity and number of control variables coupled with the demands of multivariable implementation, software development and verification tools must support model-based development and cost effective validation and verification strategies.

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Integrated Model-Based Controls and PHM for Improving Turbine Engine Performance, Reliability, and Cost

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Control of high performance military aircraft propulsion systems continues to become more complex in response to increasingly demanding operational and multiple mission needs. Propulsion systems of the future will require adaptive engine control to enable precise and repeatable performance within stringent reliability, safety and cost constraints. In order to achieve performance that meets these requirements, propulsion control systems must evolve towards advanced designs with multivariable control systems and integrate numerous systems, including inlet, exhaust, power and bleed extraction, electrical power, thermal and environmental management, fuel, starting, accessories, aircraft flight control, and often propellers, open rotors, or lift fans. Due to the significant growth in complexity and number of control variables coupled with the demands of multivariable implementation, software development and verification tools must support model-based development and cost effective validation and verification strategies. The enabling technologies for the future advanced controls can be categorized as model-based control, multivariable and model-predictive control systems, condition-based prognostics and diagnostics, distributed fault tolerant controls, active controls, and efficient model based design software tools for software development, validation and verification. This paper will provide an overview of these technologies and propose a direction for future research.

I. Introduction

Future turbine engines will require the capability to adapt to multiple mission profiles. These adaptive turbine engines will require improved performance, safety, and reliability at reduced life cycle costs. To meet these requirements, control systems will become increasingly complex. Variable turbine engine cycles can be characterized by the number of control variables necessary to influence the behavior of the gas turbine while still meeting performance and safety specifications. This paper describes key control technologies that must be developed in order to deliver the needed adaptability and other key requirements. A model-based, multi-input multi-output (MIMO) control system integrated with an advanced Prognostic and Heath Management (PHM) system is a key to realizing the benefits of adaptive turbine engines. Figure 1 illustrates a typical engine framework with model-based control and PHM systems.

A turbine engine controller has many complex functions. The primary function of the controller is providing thrust in response to throttle position set by the pilot or flight control system. These functions are embedded into the FADEC ("Full Authority Digital Engine Control"). The FADEC must achieve the requested thrust with the lowest Specific Fuel Consumption (SFC) and ensure that the engine limits are not exceeded. These limits include: maximum fan and compressor speeds, turbine and exhaust temperatures, compressor discharge pressure, and rich burner blowout; minimum fan and compressor stall margins, compressor discharge pressure, and lean burner blowout. To achieve minimum SFC, the cycle must be able to operate at peak efficiency without violating component mechanical and thermal limits. Figure 2 shows the operating regions where the major engine

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operating limits exist. Engine operation at required thrust often leads to operation at one or more of engine operating limits and at the lowest SFC, noise, and emissions.

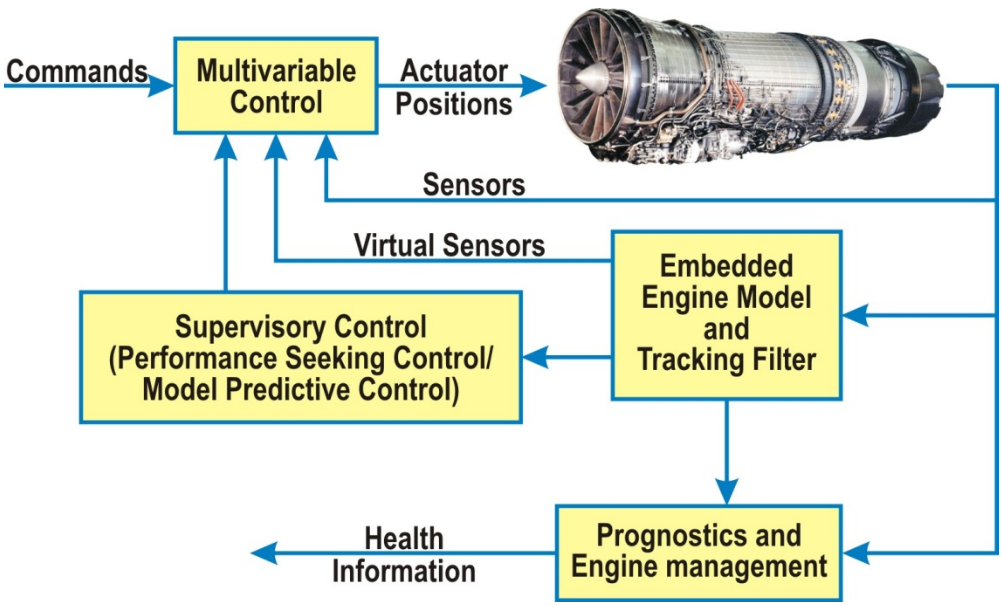

Figure 1: Model-Based, Multi-Variable Engine Controller with Integrated PHM

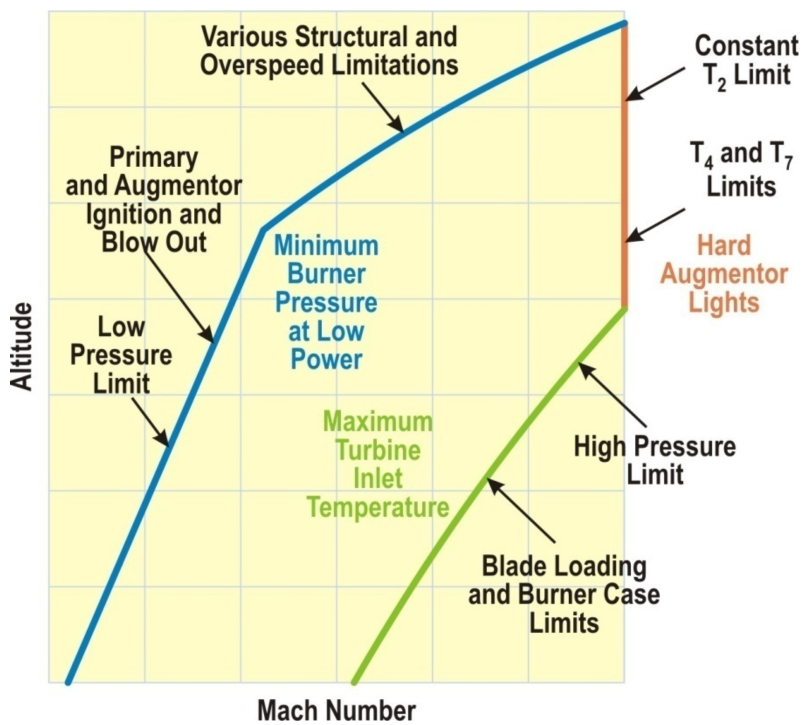

Figure 2: Example of Turbine Engine Control Limits (Ref. 1)

Past research has revealed numerous technical challenges. Newer turbine engines and associated components are operating at increasingly elevated temperatures. Components such as fuel pumps, fuel metering systems, and actuators must be optimized for weight and reliability to meet engine efficiency. The Air Force has funded many projects in the past to develop lightweight, high-temperature components that offer payoffs of up to 50% weight reduction, increased high temperature capability to 400ºF, and potential improvements in ballistic tolerance. These achievements have been mainly accomplished through innovative design techniques, and advanced materials such as composites and lightweight alloys. The transition of these technologies into production engines has been slow, however, due to lack of maturity as well the lack of an integrated approach to realize the benefits. The technologies described below provide means to address these issues.

II. MODEL-BASED CONTROL

Most product engines, both commercial and military, use sensor-based control. That is, since key engine characteristics such as thrust and stall margins cannot be measured, current control systems infer these parameters from sensed values. Thus, corrected fan rotor speed or engine pressure ratio are sensed and used as feedback parameters in closed-loop control systems. The relationship between the sensed variables (e.g., rotor speed) and parameters of interest (e.g., thrust) is not exact and subject to variation due to manufacturing tolerances, sensor errors, and engine deterioration. Therefore, steady-state performance design margins must be fairly large. The same is true of transient design margins such as those associated with a burst from idle to full power, during which compressor stall margin is consumed.

Model-based control (references 2-6) uses a model of the plant in the controller (engine model in the FADEC) to compute and directly control thrusts and stall margins. Another key feature of model-based control is a "tracking filter", which is essentially a parameter estimation algorithm. The tracking filter uses available sensors to update the model to match actual engine characteristics. Tracking filter techniques include classical observers, Kalman and extended Kalman filters, and PI controllers. The use of model-based controls allows steady state and transient margins to be reduced. Thus, although controls do not set performance capabilities (the turbo machinery does), they enable more of the available performance to be realized by enabling smaller margins while maintaining engine safety and operability.

Engine models are used in the development as well as operation of gas turbine engines. Traditional design methods for aircraft turbine engine control systems have relied on the use of linear models and linear control theory. While these controllers can provide satisfactory results, they do not exploit all the available knowledge regarding nonlinear engine behavior to optimize performance.

In the development phase, a thermodynamic model is used to optimize the engine and the controller design. In this phase the performance, operability, systems, and control engineers collaboratively design the engine for both transient as well as steady state operation. Thermodynamic models are based on knowledge of the engine physics and component characteristics, and provide information about the turbine engine behavior and operation. Such models are nonlinear and can be highly complex. For control design, it is often common practice to linearize the thermodynamics models around series of operating points and carry out model-order reductions to arrive at design models. These models must be validated against the detailed nonlinear model and actual engine data to verify their performance.

Model-based control system design methodologies are now increasingly being employed as a new methodology for control system development in order to support new adaptive cycle engines. Recent advances in electronic engine controls in terms of through put and memory have made it feasible to design control systems that use a detailed model of the engine embedded in the control logic. This technique offers significant improvement in the ability to model engine dynamics over the full flight envelope and evaluate multiple operational requirements.

Turbine engine performance depends on the control of a desired output in the presence of constraints using a large number of input variables to achieve the desired performance and safety limits. The interactions between various inputs and outputs, stringent accuracy, and response requirements, system cost, reliability, and maintainability demand a highly stable and robust control system. However, less attention has been paid to overall system efficiency and integration of the propulsion system with the entire aircraft. For example, thermal management issues, integrated flight and propulsion control, and more complicated maintenance procedures have led to increased control complexity. Model-based control systems offer the promise to streamline the implementation of multiple interactions and system constraints.

MULTIVARIABLE CONTROL AND MODEL PREDICTIVE CONTROL

Most current engines use Single-Input Single-Output (SISO) controllers, and interactions between control loops are ignored. If each controller has been individually tuned to provide maximum performance, then (depending on the severity of the interactions) loss of the system's performance and stability may occur when all the loops are closed. Therefore, SISO controllers are inadequate for modern military engines. Such engines have variable cycle features, increased bandwidth, and tighter decoupling requirements. Multiple-Input, Multiple-Output (MIMO) control is fundamental to achieving the desired system characteristics (reference 7).

The use of parallel processing and multi-core processors can offer new opportunities in control system design and can provide enhanced performance with built-in model based controls to incorporate more complex logic and improve fault tolerance while meeting processor throughput constraints. The development of supervisory control systems such as an on-board optimization system, an adaptive control system, or the use of artificial intelligence such a rule-based expert system allows the control system to adapt to changing mission requirements or plant characteristics due to damage or deterioration.

An example of supervisory optimizing control is Performance Seeking Control (PSC), funded by the USAF and the Navy over the last two decades (references 8, 9, and 10). In PSC, a constrained optimization algorithm is added to the model and tracking filter described earlier. The on-line optimization is typically activated once a steady-state condition such as cruise is detected. PSC can therefore be used to minimize SFC at constant thrust, subject to the same constraints that the control system must maintain. PSC is therefore a means for *point* optimization. The next logical step is research in to *path* optimization, wherein the path the controller takes from idle to takeoff power is optimized. Model-Predictive Control (MPC) is widely adopted in the process industry as an effective means to deal with large multivariable constrained control problems (reference 11 and 12). MPC has not been fully adapted to the aerospace industry primarily due to insufficient embedded computational power. However, processor throughput improvements and faster executing models and control algorithms make MPC feasible.

The main idea behind MPC is to choose the control action by repeatedly solving an optimal control problem on line. This technique aims at minimizing a performance criterion over a future horizon, subject to constraints on the manipulated inputs/outputs, and on specified outputs where the future behavior is computed according to a model of the plant. Most commercially available MPC technologies are based on a linear model of the process. For processes that are highly nonlinear such as the turbine engine, the performance of an MPC based on a linear model can be poor. This has motivated the development of Nonlinear Model Predictive Control (NMPC), where a more accurate, nonlinear, model of the plant is used for prediction and optimization.

MPC has established itself as the most advanced multivariable control in many industries. However, the benefits of MPC cannot be realized unless the controller can be operated with desirable performance for an extended period of time to collect data. The main issue regarding MPC is its feasibility for FADEC implementation. In many cases the benefits of MPC are not achieved due to its traditionally complex nature and narrow application. Reference 13 describes a new approach that simplifies Model Predictive Control's implementation and usability. MPC implementation is represented as a function block, and by using state-of-the-art techniques, the commissioning process becomes fast and easy, and the entire process of collecting and pre-processing data, creating a model, generating MPC definition, verifying the model and downloading the generated model and MPC definition to run in a FADEC, are fully automated. The authors also detail features of convenience such as graphical presentation of the MPC block inputs and outputs, model visualization, model editing capabilities, model verification and simulation before putting the control online.

Junxia Mu and David Rees (Reference 14) have described an MPC strategy using instantaneous linearization of nonlinear models incorporating the Generalized Predictive Control (GPC) called Approximate Model Predictive Control (AMPC), which is used to control a shaft speed of a gas turbine engine. This method has advantages over the Nonlinear Model Predictive Control (NMPC), which is computationally demanding and has local minima. The performance of the model based control schemes is dependent on the accuracy of the process model, so the paper examines the estimation of global nonlinear gas turbine models using NARMAX and neural network representations. The results illustrate the improvements in control performance that can be achieved relative to gain-scheduling PID controllers. Recent work on “Fast MPC” at Stanford (Reference 15) is also aimed at real-time implementation of MPC in today’s processors. However, these systems require substantial effort to validate models and to gain confidence that the models will not lead to undesirable behavior by the control system.

III. ACTIVE CONTROL

The bandwidth of most engine control loops is in the 1 Hz range, with actuator loops typically in the 2-6 Hz range. These bandwidths are adequate for providing the thrust control bandwidth required for flight control. However, there is renewed interest in active control systems, which we define to mean systems that require much higher bandwidth sensing and actuation, typically in the 1 KHz range. The idea is not new – for instance, active stall control was studied extensively in the 1970s and 1980s (references 17-20) as a way of running compressors at much higher pressure ratios. However, the systems were never implemented in products due to a lack of availability of high-bandwidth sensors and actuators capable of surviving the high-temperature, high-vibration environment of a jet engine. Active control spans active surge/stall control and three other closely related areas, viz., active combustion control (references 21-22), active noise control, and active vibration control. All of these are aimed at pushing more performance from the turbomachinery and allowing exploration of the design space beyond today’s hardware capabilities. As the need for improving thrust, SFC, and other performance measures while reducing weight and cost extend beyond the capabilities of conventional low-bandwidth control systems, additional research into active control will be required. This research will need to address hardware (sensors and actuators) as well as control logic and new architectures. Also, control engineers will have to work closely with hardware designers to take advantage of the newer capabilities, and with systems engineers to implement and test the active control systems in rigs and demonstrator engines.

IV. DISTRIBUTED CONTROL

A distributed control system (reference 23-26) on an aircraft engine offers numerous advantages including weight reduction through simplified wiring and elimination of a centralized controller, a faster and cheaper certification process, and use of active and smart control components. Although distributed or partially distributed systems will eventually be implemented in the aviation industry, it will require collaborative efforts to standardize interfaces and to develop high-temperature electronics and distributed control modules. See reference 27 for the description of a collaborative effort on the development of distributed control systems for aircraft engine applications. Broadly speaking, there are four phases in the progression from centralized to fully distributed control. In the first phase, current sensors are replaced with smart sensors, which include electronics for signal conversion. With a smart pressure transducer, long lengths of tubing are eliminated, leading to a lower-cost, faster responding system that is less prone to leaks. In the second phase, smart actuators that are capable of receiving a commanded position and include control laws to provide loop closure replace the current actuators. In the third phase, wireless sensors replace wired sensors. In the final phase, wireless self-powered sensors that harvest energy from engine heat or vibrations replace sensors that require power. The long-term vision is one of a distributed system communicating over an engine area network. The key enabler for this vision is high-temperature electronics that can withstand engine vibrations. Hence, the near-term implementation is to use smart sensors and actuators in the cooler front end of the engine. Also, diagnostic sensors used in PHM are more amenable to be replaced with wireless sensors than control sensors required for safe operation of the engine.

V. PROGNOSTICS and HEALTH MANAGEMENT (PHM)

Future control systems will include a real-time prognostics and health monitoring (PHM) system for detecting and isolating faults, for generating pilot alerts, for trending and estimating gas-path and subsystem health, and for performing life and damage calculations. The goal of future systems is away from scheduled maintenance towards condition-based maintenance. The PHM system for modern jet engines (Figure 3) will also include fusion algorithms and reasoners to integrate results from various diagnostic algorithms into unambiguous recommendations, thereby improving mission readiness, and reducing operating and line-maintenance costs. Engine health assessment can also enable an intelligent control system capable of control reconfiguration to react to battle damage. Although controls and diagnostics functions were essentially separate in the past, there is a trend towards a more integrated control and PHM system that is model-based, state-aware, and capable of multi-objective optimization in real time.

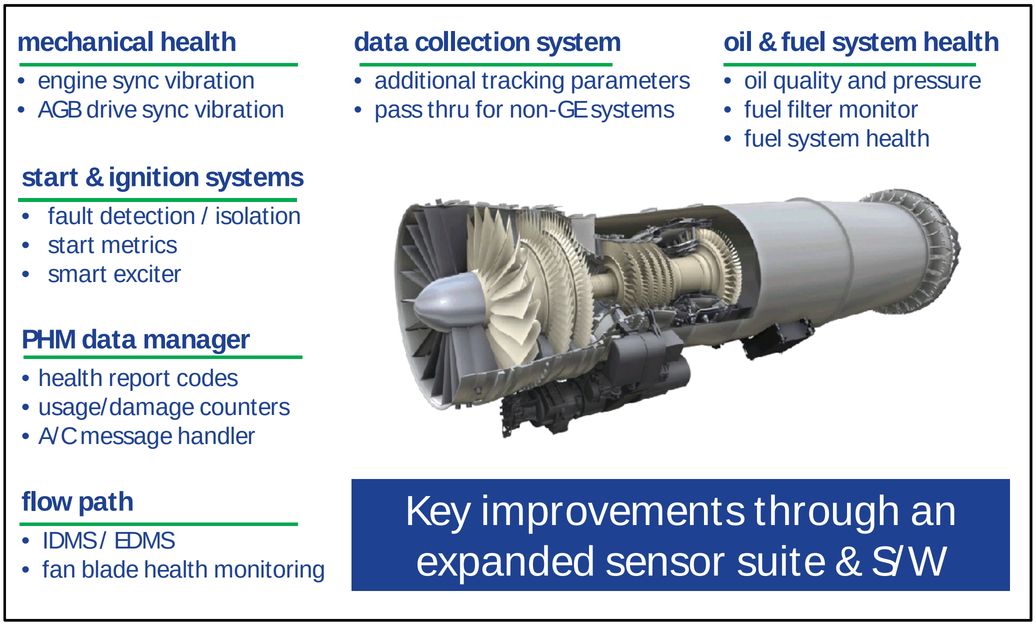

Figure 3: Modern Fighter Jet PHM Systems

VI. MODEL BASED SOFTWARE DEVELOPMENT, VALIDATION, AND VERIFICATION TOOLS

Model Based Design (MBD) is a graphical modeling methodology employed in the design of complex control systems. It provides a framework for four key elements in the software development process. MBD methods serve to 1) Model the plant; 2) Analyze the controller integrated with the plant; 3) Simulate the plant and the controller; and 4) Deploy and communicate the controller. MBD has several efficiency advantages over traditional methods. Design errors can be identified and fixed earlier thus reducing costs. MBD provides a common design environment that facilitates communication and co-development activities thus reducing cycle time. Finally, MBD facilitates software reuse, reducing both cost and cycle time.

Software tools can facilitate the development, validation and verification processes associated with the production control system. As advanced controls require more complex computations relative to traditional SISO systems, and software complexity as measured by source lines of code (SLOC) is generally higher, development costs significantly increase as does time required to introduce changes during the product lifecycle. Two model based tools used by GE Aviation are the Mathworks Suite (MATLAB and Simulink environment) and Esterel's Safety Critical Application Development Environment (SCADE). The Mathworks product's strength is the ability to simulate dynamic systems while SCADE delivers a qualifiable development environment. Certified code generation technology virtually eliminates low-level testing, therefore saving significant time and money in the verification process. Both products automate the full life cycle of development including requirements traceability, simulation, design documentation, configuration management, verification, and automatic code generation from graphical models. Model based design tools enable design flaws and inconsistencies to be caught early in the development process when they are less costly to fix.

VII. CONCLUSIONS AND FURTHER RESEARCH

There are a number of important technological trends developing in the aerospace industry, which have implications for future control system capabilities. Among these, the fastest emerging trends are within the embedded control system development area and include:

- ***More complex aircraft propulsion philosophies***. The STOVL operation is an example of an application that is imposing more stringent performance and operability requirements on engine systems. These requirements are necessitating the use of more complex control laws (e.g. multivariable model-based control), and more sophisticated dynamic verification and validation procedures. Other impacts can be seen in the increasing use of variable geometry for performance modulation and/or fault accommodation over the flight trajectory.

- ***More stringent reliability and maintenance requirements***. These requirements underlie the increased demand for sophisticated diagnostics and fault-tolerant control algorithms to enable fault accommodation and survivability. The resulting increase in sensing needs for prognostic health management (e.g. Blade Health Monitoring, Inlet Debris and Exhaust Debris Monitoring on the modern jet engines) is also driving the need for low weight, high bandwidth sensing capabilities in next generation FADEC technology.

- ***Increased use of distributed control and networked aircraft systems***. As airframers continue to upgrade to newer communication protocols, engine systems are being forced to incorporate support for these new protocols in order to retain the ability to collaborate with aircraft flight management systems. Similarly, within engine systems themselves, it is becoming necessary to shift toward distributed control architectures to enable weight-neutral expansion of FADEC sensory and actuation capacity. This can, in part, be achieved using any one of a number of wireless protocols, possibly implemented using software-defined radio in order to minimize the number of physical interfaces in the system.

- ***Growing customer requirements.*** Changing funding environments, along with increased real-time visibility into aircraft/fleet operation, are encouraging an increase in the frequency with which engine users request control software modifications. Increasingly customers submit late-stage requirements changes while simultaneously expecting a fast turnaround and no schedule impact. Minimizing cost and schedule impacts can be achieved by utilizing state-of-the-art development tools and processes.

These trends are having a dramatic effect on current jet engine control development efforts, and are forcing a *de facto* change in the control system development paradigm. Research in the advanced control system enabling technologies is required to address the needs of the highly integrated military jet engine of the future.

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PRESENTATION OUTLINE

- INTRODUCTION
- EXAMPLE OF TURBINE ENGINE CONTROL LIMITS
- TURBINE ENGINE CONTROL LIMITS
- MBC, MV CONTROL / MPC, ACS, DCS, ICPHM,
- CONCLUSIONS AND FURTHER RESEARCH

2

INTRODUCTION

- Future Turbine Engine Control
  - Control of high performance military aircraft propulsion systems continues to become more complex
  - Will require the capability to adapt to multiple mission profiles
  - Adaptive turbine engines will require improved performance, safety, and reliability at reduced life cycle costs.
  - A model-based, MIMO control system integrated with an advanced PHM system is a key to realizing the benefits of adaptive turbine engines
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  - FADEC must achieve the requested thrust with the lowest SFC and ensure that the engine limits are not exceeded
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INTRODUCTION (CONTINUED)

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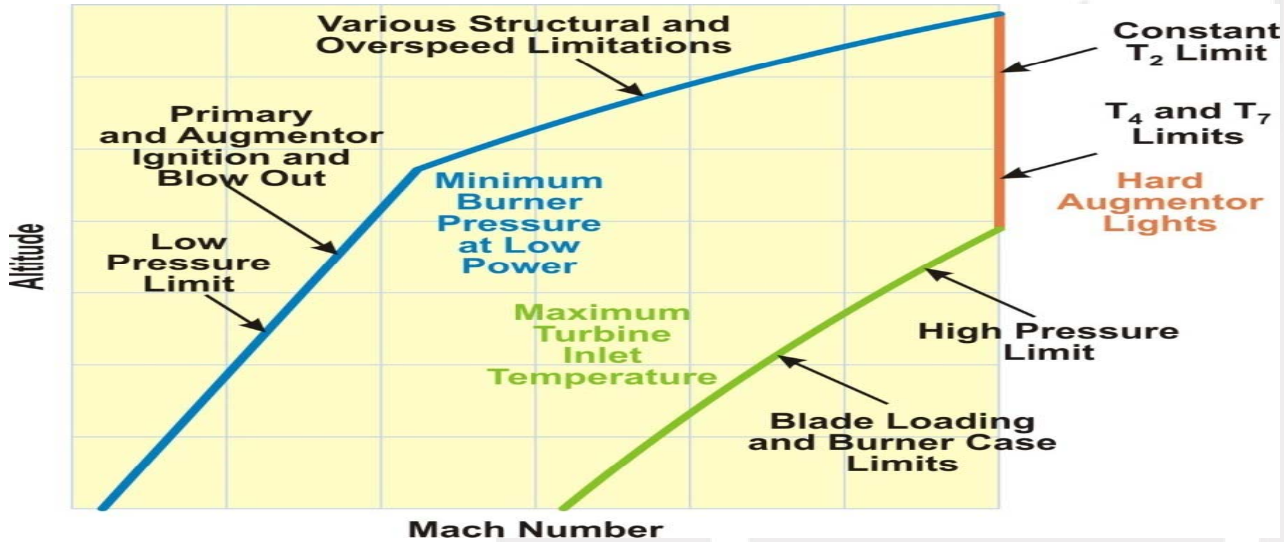
  - Newer turbine engines and associated components are operating at increasingly elevated temperatures
  - Engine gas-path components as well as control components such as fuel pumps, fuel metering systems, and actuators must be optimized for weight and reliability to meet engine efficiency
  - The future challenges for turbine engine controls are implementation of specific technologies for distributed control, active control, and prognostics and health management.
- System Design Issues
  - High temperature components technology must interface with existing and planned engine interface and communication architectures and survive high vibration environment
  - FADEC throughput and memory required for advanced control laws

EXAMPLE OF TURBINE ENGINE CONTROL LIMITS



Above shows the operating regions where the major engine operating limits exist. Engine operation at required thrust often leads to operation at one or more of engine operating limits and at the lowest SFC, noise, and emissions.

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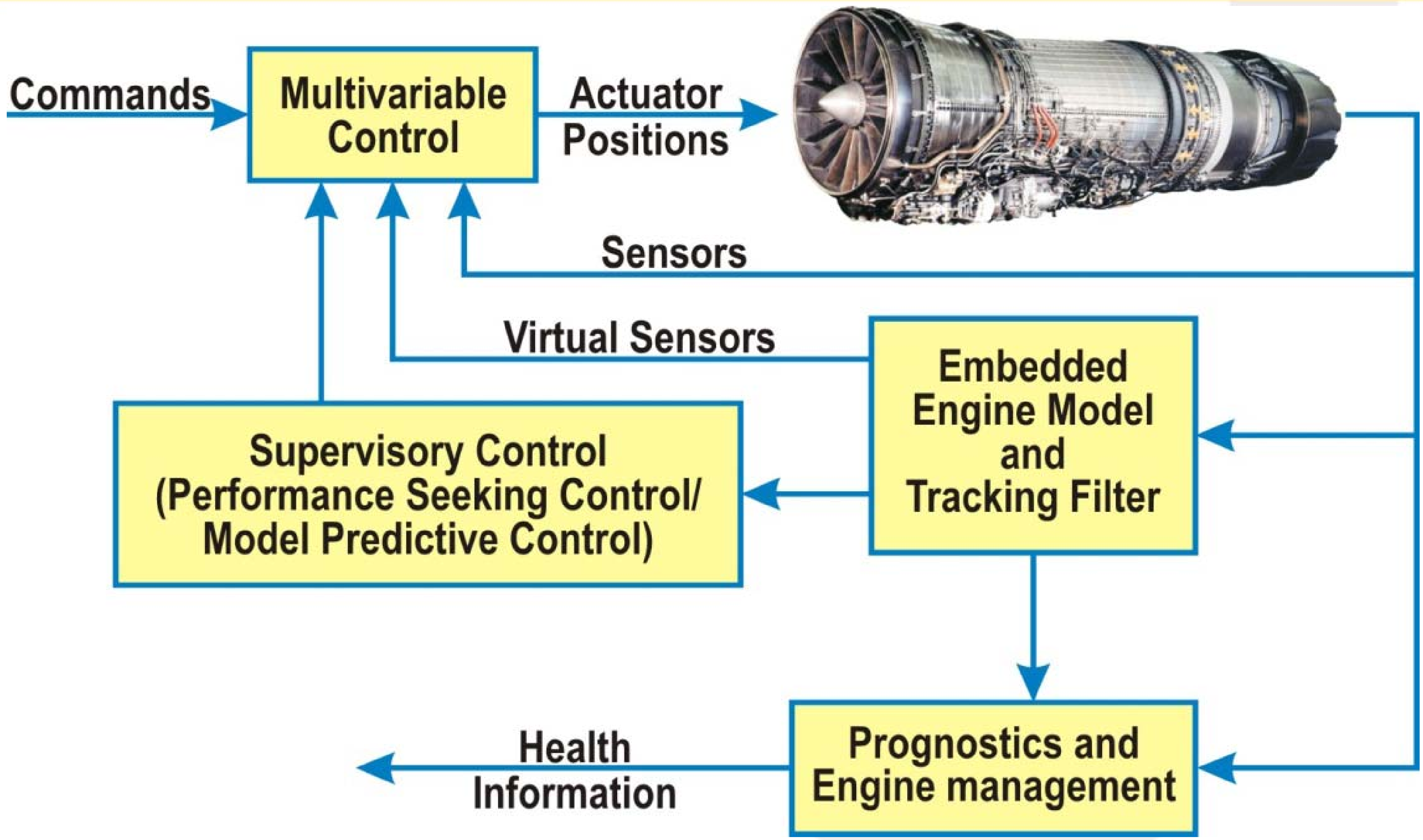
MARKET DRIVEN CHALLENGES

- To meet increasing demand for capability to reduce maintenance cost and increase life of turbine components, use of increased diagnostics and material stress or damage measurements will be required
- Cost of high temperature sensor technology for aerospace applications will be higher than the current SOA
  - Potential use in emerging commercial applications can mitigate the expected high cost of advanced materials and new designs
- Controls contribute up to 20% of engine cost
- Control systems may impose 40% maintenance burden (life cycle cost) on the engine
- Need for PHM measurements is increasing to enhance maintenance, fault isolation, and prognostics

MODEL-BASED CONTROL (MBC)

- MBC system design methodologies are now increasingly being employed as a new methodology for control system development in order to support new adaptive cycle engines
- Performance depends on the control of a desired output in the presence of constraints using a large number of input variables to achieve the desired performance and safety limits
- Current commercial and military engines use sensor-based control
- Key engine characteristics such as thrust, turbine temperatures, and stall margins cannot be measured, current control systems infer these parameters from sensed values
- Corrected fan rotor speed or engine pressure ratio are sensed and used as feedback parameters in closed-loop control systems
- MBC uses a model of the plant in the controller (engine model in the FADEC) to compute and directly control thrusts and other unmeasurable parameters

MB, MV ENGINE CONTROLLER WITH INTEGRATED PHM



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MBC

- Key feature of model-based control is a "tracking filter", which is essentially a *parameter estimation algorithm*
- Tracking filter uses available sensors to update the model to match actual engine characteristics
- Tracking filter techniques include classical observers, Kalman and extended Kalman filters, and PI controllers
- use of MBC allows steady state and transient margins to be reduced
- Controls do not set performance capabilities, they enable more of the available performance to be realized by enabling smaller margins while maintaining engine safety and operability

MV CONTROL AND MPC

- The use of parallel processing and multi-core processors can offer new opportunities in control system design
- Most current engines use SISO controllers, and interactions between control loops are ignored
- SISO controllers are inadequate for modern military engines; Such engines have variable cycle features, increased bandwidth, and tighter decoupling requirements. This leads to use of multivariable, i.e., multi-input, multi-output (MIMO), controls
- The main idea behind MPC is to choose the control action by repeatedly solving an optimal control problem on line
- MPC has established itself as the most advanced multivariable control in many industries. However, the benefits of MPC cannot be realized unless the controller can be operated with desirable performance for an extended period of time to collect data
- “Fast MPC” techniques are aimed at real-time implementation of MPC in today’s processors
- These systems require substantial effort to validate models and to gain confidence that the models will not lead to undesirable behavior by the control system

ACTIVE CONTROL SYSTEMS (ACS)

- Active control spans active surge/stall control and three other closely related areas, viz., active combustion control, active noise control, and active vibration control
- All of these are aimed at pushing more performance from the turbomachinery and allowing exploration of the design space beyond today's hardware capabilities
- As the need for improving thrust, SFC, and other performance measures while reducing weight and cost extend beyond the capabilities of conventional low-bandwidth control systems, additional research into active control will be required
- ACS will need to address hardware (sensors and actuators) as well as control logic and new architectures

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DISTRIBUTED CONTROL SYSTEM (DCS)

- Offers numerous advantages including weight reduction through simplified wiring and elimination of a centralized controller, a faster and cheaper certification process, and use of active and smart control components.
- Require collaborative efforts to standardize interfaces and to develop high-temperature electronics and distributed control modules
- Broadly speaking, there are four phases in the progression from centralized to fully distributed control: smart sensors, smart actuators, wireless sensors, wireless self-powered sensors. All of these require a smart, fail-safe data bus
- The long-term vision is one of a distributed system communicating over an engine area network.
- The key enabler is high-temperature electronics.
- Also, diagnostic sensors used in PHM are more amenable to be replaced with wireless sensors than control sensors required for safe operation of the engine.

INTEGRATED CONTROL/PHM TECHNOLOGIES (ICPHM)

- Future control systems will include a real-time PHM system for detecting and isolating faults, for generating pilot alerts, for trending and estimating gas-path and subsystem health, and for performing life and damage calculations
- The PHM system for modern jet engines will also include fusion algorithms and reasoners to integrate results from various diagnostic algorithms into unambiguous recommendations, thereby improving mission readiness, and reducing operating and line-maintenance costs
- Through integrated ground-based and on-board control, diagnostic, and prognostic systems, the goal is to maximize engine time-on wing while minimizing support cost without compromising performance and survivability
- PHM technologies are key enablers of CBM+ and autonomous logistics. CBM enabled by PHM allows operational performance and availability to be balanced with total operating cost

PHM SYSTEMS

mechanical health
- engine sync vibration
- AGB drive sync vibration

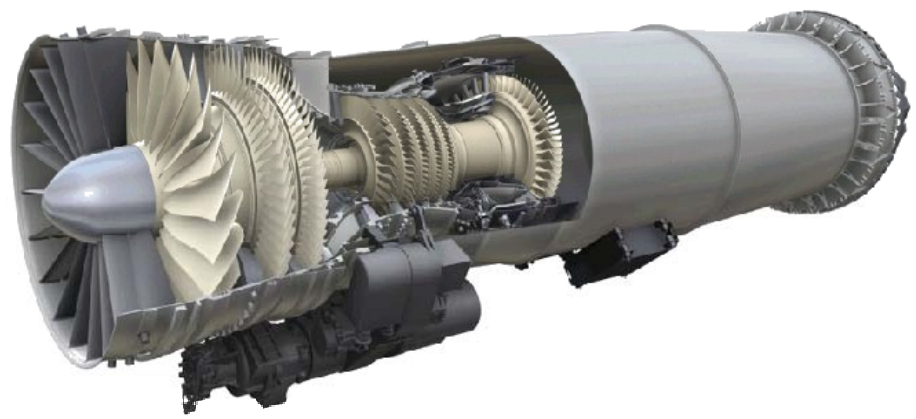
start & ignition systems
- fault detection / isolation
- start metrics
- smart exciter

PHM data manager
- health report codes
- usage/damage counters
- A/C message handler

flow path
- IDMS / EDMS
- fan blade health monitoring

data collection system
- additional tracking parameters
- pass thru for non-GE systems

oil & fuel system health
- oil quality and pressure
- fuel filter monitor
- fuel system health



Key improvements through an expanded sensor suite & S/W

CONCLUSIONS AND FURTHER RESEARCH

There are a number of important technologies developing:

- More complex A/C propulsion philosophies (e.g. STOVL operation); more complex control laws (e.g. MV and MBC); active control systems; more sophisticated dynamic verification and validation procedures; more variable geometry; and, fault accommodation over the full flight trajectory.
- More stringent reliability and maintenance requirements. Sophisticated PHM and fault-tolerant control algorithms (e.g. Blade Health Monitoring, Inlet Debris and Exhaust Debris Monitoring) on modern jet engines.
- Increased use of DCS and integration and networked aircraft systems.
- Growing customer requirements. Changing funding environments, along with increased real-time visibility into aircraft/fleet operation.
- Minimizing cost and schedule impacts can be achieved by utilizing state-of-the-art development tools and processes.

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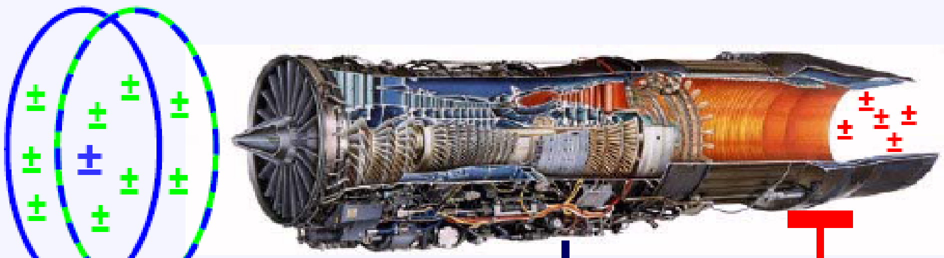
ENGINE GAS PATH MONITORING (IDMS & EDMS) SYSTEM

IDMS

EDMS

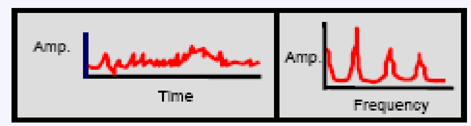


Engine Operating Data

EDMS: Button sensor installed in exhaust duct

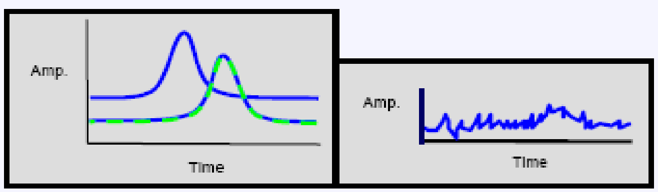
IDMS FOD: 2 ring sensors installed on the inlet

IDMS Dust: 1 sensor on the inlet (ring or button)



EDMS/IDMS Processing

Engine System Level Data Fusion



Data acquisition and processing:

Airborne or ground based system

Stand alone or integrated

EDMS/IDMS feature extraction

Correlation of EDMS / IDMS with engine operation / flight data

Output key features / diagnostic / prognostic data

Complexity depends on monitoring requirements

System Level Data Fusion:

EDMS/IDMS key features / diagnostic / prognostic data fused with higher level engine / aircraft and other PHM sensor information for system level health management