Chapter 1 – INTRODUCTION

by

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With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircrafts, there are many new challenges being faced by the designers of aircraft propulsion systems. There is significant investment being made by various NATO countries in development of advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. The key enabling technologies for an Intelligent Propulsion System (see Figure 1.1) are the increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control to enhance operational reliability and component life, and distributed control with smart sensors and actuators in an adaptive fault tolerant architecture. Development of appropriate sensors and actuation systems is critical to affordable and reliable implementation of the technologies for a more intelligent gas turbine engine.

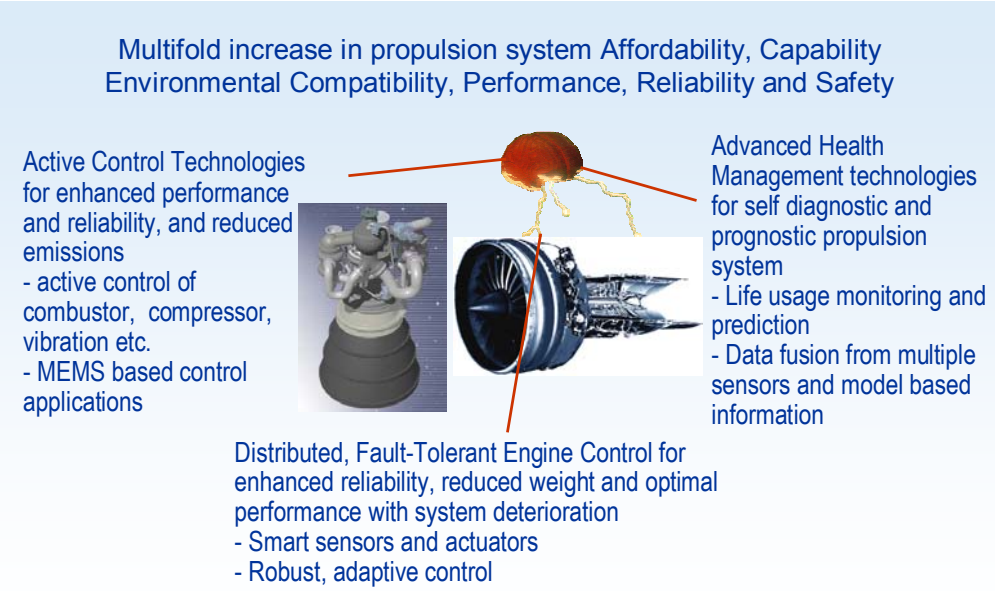

Figure 1.1: Advanced Control and Health Management Technologies for "More Intelligent Engines" [1.1], [1.2], [1.3].

The objective of this report is twofold:

1) Help the "Customers" (NATO defence acquisition and aerospace research agencies) understand the state-of-the-art of intelligent engine technologies, how these technologies can help them meet challenging performance and operational reliability requirements for aircraft engines, and what investments need to be made in sensor and actuator technologies to enable the various capabilities of "Intelligent Engines" so that limited resources are used in a most efficient manner; and

2) Help the "Researchers" and "Technology Developers" for sensors and actuators identify what sensor and actuator technologies need to be developed to enable the "Intelligent Engine" concepts so that their research efforts can be focused on closing the gap from current capability to that needed to meet identified requirements, and also increase their awareness of "requirements" that need to be met other than performance (such as cost, durability, etc.) to enable the transition of technology to a product. This latter emphasis helps ensure that the "non-performance" requirements are taken into consideration in developing solutions to meet performance requirements, and the limited resources are not "wasted" on technology paths which are not amenable to transition into a product.

The overall technology areas that fall under the umbrella of "intelligent engines" are too broad to be covered by this report. For example, just the component optimization will cover many areas as identified in Figure 1.2. Similarly, the area of diagnostics and prognostics will cover all the components shown in Figure 1.2 with a significant technology investment in vibration monitoring, diagnostics for accessories, etc., and including technologies for ground maintenance.

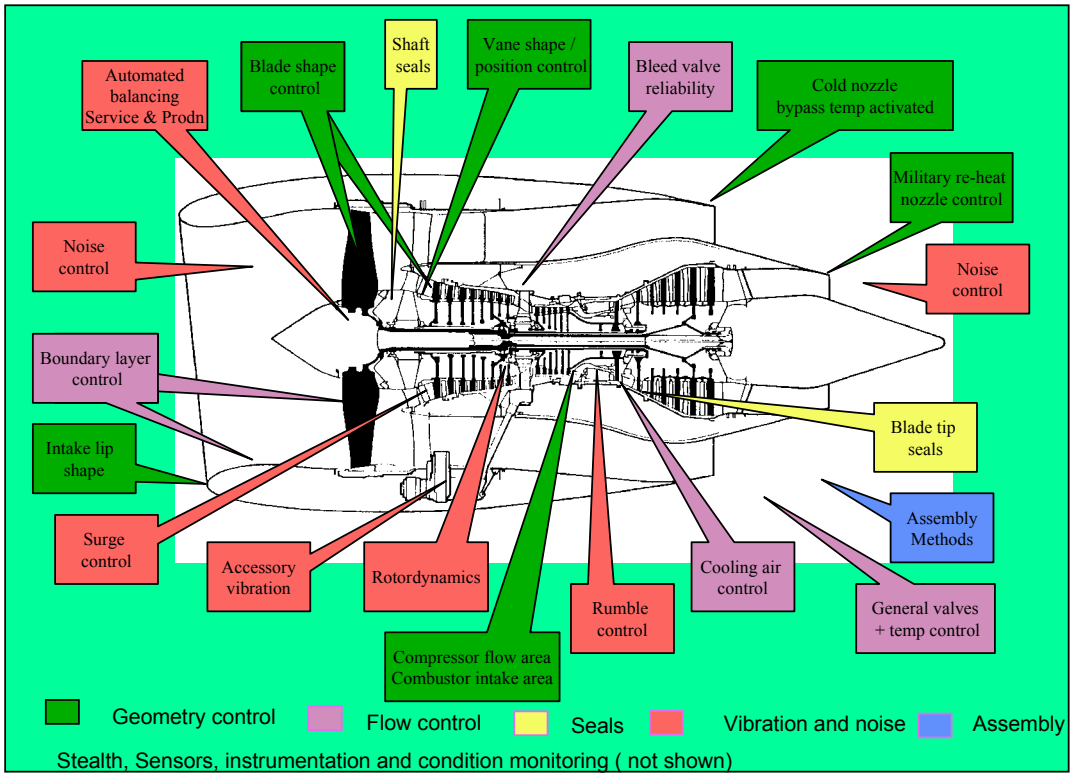

Figure 1.2: Identified Opportunities for Adaptive Optimization within a Gas Turbine Engine [1.4].

To keep the current effort manageable, the focus of this report is on "On-Board Intelligence" to enable safe and efficient operation of the engine over the life time, and adapt to changing internal and external environment to provide "optimum" achievable performance based on operation mode and current condition. The discussions in this report are limited to:

1) Technologies for active control of components in the gas path to enhance performance and reduce emission and noise;

2) Intelligent control and condition monitoring from the overall engine gas path performance perspective; and

3) Advanced control architecture concepts such as distributed engine control.

The emphasis throughout the report is on identifying the sensor and actuator needs to realize these intelligent engine concepts with the ultimate objective being to identify sensor and actuator technology development roadmaps. The organization of the report is briefly described in the following.

Chapter 2 discusses various concepts for active control of engine gas path components such as inlet, compressor, combustor, turbine and nozzle. Such components have been designed for optimum component performance within some overall system constraints and the control design problem has been to transition the operating point of the engine from one set point to another in a most expedient manner without compromising safety. With the advancements in information technologies, the component designers are beginning to realize the potential of including active control into their component designs to help them meet more stringent design requirements and more affordable and environment friendly propulsion systems. The following topics are discussed with respect to each gas path component:

1) Advantages and limitations of passive component design and benefits of active control to further increase operational flexibility and efficiency of each component;

2) Performance objectives for active component control and various high level approaches – what will be controlled and how. For some of the most promising approaches, the state of the art is discussed along with technical gaps and challenges; and

3) Performance and operating environment specifications for sensors and actuators to enable the active component control capability.

Chapter 3 describes the various aspects of intelligent engine control and condition monitoring from an overall gas path system perspective. The need to have more reliable and safe engine service, to quickly identify the cause of current or future performance problems and take corrective action, and to reduce the operating cost requires development of advanced diagnostic and prognostic algorithms. The objective for this health / condition monitoring technology is to maximize the "on wing" life of the engine and to move from a schedule based maintenance system to a condition based system. The chapter provides a brief description of state-of-art of engine control (system level) and inherent limitations in current architecture. Subsequently objectives for intelligent engine control are described including simplifying control design (such as direct or model based nonlinear approaches), adapting performance to engine degradation, extending on-wing life, and improving FDIA (Fault Detection, Isolation and Accommodation), prognostics and accommodation via corrective action. An overview of approaches to achieve these objectives is provided. For the various approaches, the technology development needs for modeling, control algorithm and hardware, and new sensors are described, with an emphasis on the latter. To keep the scope manageable, the discussion of diagnostics and prognostics technologies is limited to that required for achieving "closed-loop" control objectives. The focus of advanced control schemes is on developing algorithms that are implemented in the FADEC (Full Authority Digital Engine Control) in the form of software without any hardware changes on the engine in terms of any additional control effectors/actuators. The chapter is organized into five sections:

1) State-of-the-art of engine control;

2) Model based control;

3) On-board condition/health monitoring;

4) Adaptive control; and

5) Challenges and sensor needs to enable more intelligent control and health monitoring.

Chapter 4 discusses the technologies required to move from the current highly centralized engine control architecture to a more distributed control architecture to reduce the weight ratio of control system to engine and simplify the complexity of a centralized FADEC. The state of the art engine control architecture using a central FADEC is briefly described along with its limitations and the need for distributed control. Various options for distributed control architecture and the pros and cons of these options are discussed. Challenges due to the harsh environment of the engine, as summarized in Figure 1.3, and weight and volume limitations imply the need for developing high temperature electronics and data communication hardware to enable smart, self diagnostic sensors and actuators to fully utilize the benefits of distributed control architecture.

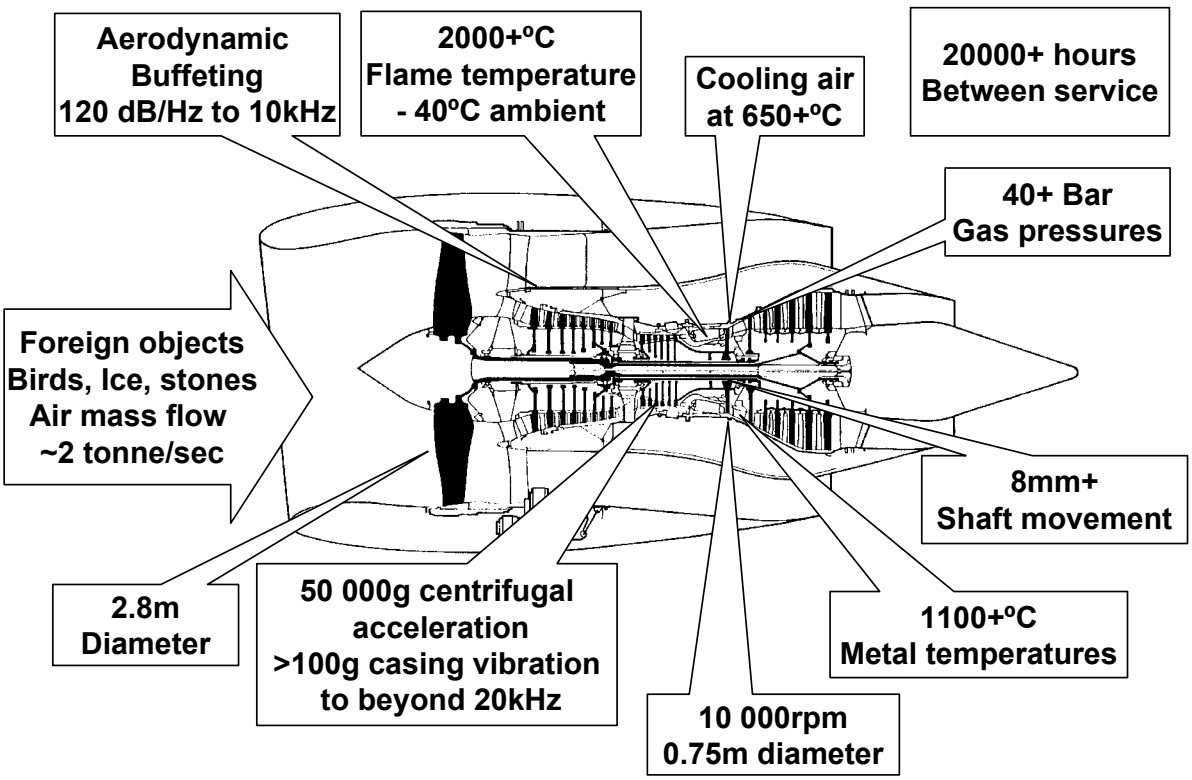

Figure 1.3: Environment within an Aircraft Gas Turbine Engine [1.4].

Chapter 5 summarizes the requirements, other than performance, that a sensor or actuator technology needs to meet in order to be considered for implementation on an engine. Such requirements relate to Technology Readiness Level (TRL) [1.5], durability, reliability, volume, weight, cost, etc. The objective is to help educate the researchers or technology developers on the extensive process that the technology has to go through beyond just meeting "performance" requirements before it can be implemented on a product. The discussion includes:

1) A summary of the value analysis that is done to make a "business case" to consider a new technology (sensor, actuator, etc.) for implementation on a production engine (new design or a variant); and

2) The evaluation steps that a prototype goes through for the technology to be considered to be mature enough for the engine company or customer to pay the development costs needed to insert the technology into product.

Chapter 6 focuses on sensor requirements with the objective to identify the status of current and future potential sensing technologies and a roadmap for sensor developments. The discussions are based on generic sensor requirements, which have been derived from performance requirements of Chapters 2 to 4. Generic requirements for all sensing variables are defined by measurement capability (range, bandwidth, resolution, and accuracy) and the capability to withstand certain operation environments (temperature and vibrations). Current sensing principles and sensor technologies which can meet these requirements are described. New sensing principles and their application to future potential sensors are summarized. The need for high-temperature operation capability and smart sensors is emphasized. RandD needs / gaps and roadmaps for these future sensor technologies are discussed. A preliminary assessment of various sensing approaches against the "non-performance" requirements discussed in Chapter 5 is also provided. The chapter concludes with a table which summarizes the following for each of the sensed variables: environmental and performance requirements; applications; potential technologies; current TRL and years to achieve TRL 6 (prototype demonstration in a relevant environment); and expected challenges.

Chapter 7 identifies generic actuators requirements based on the component specific actuator requirements of Chapter 2. For the main application areas, three generic actuation principles are defined and addressed. The issues and considerations which must be made in the choice of any actuator for a specific application are reviewed followed by an assessment of available actuators and their application to specific components. For future development needs a selection of the more promising emerging technologies are summarized, and the potential application to specific components is discussed. The chapter concludes with a table which summarizes the following for each of the actuator variables: the environmental and performance requirements; applications; potential technologies; current TRL and years to achieve TRL 6; and expected challenges.

Chapter 8 provides a summary of the chapters and summarizes in a table for the main "intelligent gas turbine" technology/component areas both the years to achieve TRL 6 and the potential benefits. The chapter concludes by providing some recommendations on priorities for sensor and actuator technologies development based on the potential for meeting the mid to long term needs of more intelligent engine capabilities.

The report is based on activities of the RTO Task Group AVT-128 "More Intelligent Gas Turbine Engines". Details regarding participants, Technical Activity Proposal (TAP) and Terms of Reference (TOR), and dates and places of meeting are described in [1.6] to [1.9]. AVT-128 is a follow-on activity of RTO Task Group AVT-078 "MEMS Applications to Air, Land, and Sea Vehicles". Applications of interest to the present report included active flow control and active control of gas turbine components [1.10]. A roadmap for potential gas turbine applications was developed [1.11].

1.1 REFERENCES

[1.1] Annex B1.2 – Sanjay Garg, *"Controls and Health Management Technologies for Intelligent Aerospace Propulsion Systems"*, AVT Task Group 128 Meeting, October 2004, Prague, CZE.

[1.2] Annex C.2 – S. Garg, *"Controls and Health Monitoring Technologies for Intelligent Propulsion Systems"*, NASA TM-2004-212915.

[1.3] Annex C.4 – S. Garg, *"NASA Glenn Research in Controls and Diagnostics for Intelligent Propulsion Systems"*, NASA TM-2005-214036.

[1.4] J. Webster, *"Are Shape Memory Alloys about to come to age for gas turbine applications?"*, ISABE Conference, Beijing, September 2007, Paper Number 1294.

[1.5] Appendix 1 – RTB Endorsed Proposed NATO Hardware TRL Definitions (24 September 2007).

[1.6] Appendix 2 – AVT-128 Task Group Participants.

[1.7] Appendix 3 – Technical Activity Proposal (TAP) for AVT-128.

[1.8] Appendix 4 – Terms of Reference (TOR) for AVT-128.

[1.9] Appendix 5 – Task Group Meetings (Dates and Places).

[1.10] Annex C.6 – TR-AVT-078-Chapter 4 MEMS Applications.

[1.11] Appendix 6 – Roadmap for MEMS Application to GTE Active Control (TR-AVT-078).