Chapter 8 – SUMMARY AND RECOMMENDATIONS

by

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8.1 SUMMARY

Intelligent Propulsion Systems can potentially meet future challenges related to capability, affordability, safety, and environmental compatibility. The key enabling technologies for an intelligent GTE are:

1) Increased efficiencies of components through active control;
2) Increased overall engine gas-path performance and extended "on wing" life of the engine through model-based control and health monitoring; and
3) Reduced weight ratio of control system to engine through distributed control with smart sensors.

For these future capabilities sensor and actuator requirements were identified, current status and emerging sensing and actuation technologies were discussed, and roadmaps for developing the new technologies were developed. Chapter 1 provided an introduction of the report. A summary of the rest of the chapters including the major findings is given in the following.

Chapter 2 describes the various concepts of *Active Component Control* that can help to meet future engine requirements by an active improvement of the component characteristics. The concept is based on an intelligent control logic, which senses actual operating conditions and reacts with adequate actuator action. This approach can directly improve engine characteristics as performance, operability, durability and emissions on the one hand. On the other hand active control addresses the design constrains imposed by unsteady phenomena like inlet distortion, compressor surge, combustion instability, flow separations, vibration and noise, which only occur during exceptional operating conditions. The feasibility and effectiveness of active control technologies have been demonstrated in lab-scale tests. The report describes the following promising applications in detail:

Inlet:	Active Inlet Control, Active Noise Suppression, Active Noise Cancellation
Compressor:	Active Surge Control, Active Flow Control, Active Clearance Control, Active Vibration Control
Combustor:	Active Combustion, Instability Control
Turbine:	Active Clearance Control, Cooling Air Control, Active Flow Control
Nozzle:	Active Noise Control, Adaptive Nozzles, Thrust Vectoring, Active Core Exhaust Control, Afterburner Stability Control

Significant efforts in research and development remain to implement these technologies in engine rig and finally production engines and to demonstrate today's engine generation airworthiness, safety, reliability, and durability requirements. Active control applications are in particular limited by the gap between available and advanced sensors and actuators, which allow an operation in the harsh environment in an aero engine.

The operating and performance requirements for actuators and sensors were outlined for each of the gas turbine sections from inlet to nozzle.

Chapter 3 discusses *Intelligent Control and Health Monitoring* concepts using advanced model-based Multi Input Multi Output (MIMO) control architecture, where all available control actuators are manipulated in a coordinated manner. This overcomes the limitations of state-of-the-art engine control and can also provide outputs for which sensors are not available, i.e. virtual sensors. These virtual sensors provide the capability to directly control unmeasured variables such as thrust and stall margin. For implementation it is necessary to demonstrate that the control model reflects the actual condition of the engine by using a "tracking filter" (which estimates model parameters related to deterioration) and that the model parameters adapt to the individual engines. The MIMO controller can be designed to meet the desired performance objectives and also lends itself to automated fault accommodation.

With increased performance of the on-board computer there is a recent trend to have a stand-alone, engine mounted Engine Monitoring Unit (EMU). Such an EMU has access to continuous data, powerful computing capability that provides on-board analysis, can process large volume of data which are impractical to transfer to the ground, and can look also for transient effect and accomplish this throughout the duration of the whole flight. On-board condition monitoring determines the general health of the engine (level of degradation or effective age) and detects and isolates sudden faults (related to sensor fault, actuator fault or component fault).

Adaptive models open up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or accommodating any faults in a way such as to maintain optimal performance or trade-off performance with remaining useful on-wing life of the engine. The Model Predictive Control (MPC) is an emerging approach, which solves a constrained optimization problem online to obtain the "best" control action, based on a tracked engine model, constraints, and the desired optimization objective.

Requirements for improved and new sensors have been identified:

1) To improve model accuracy, reliability and enhance observability of virtual sensors;
2) To allow sensors at stations within the engine gas path that are currently not instrumented due in part to the harsh conditions including high temperatures; and
3) To allow additional monitoring of vibration, mass flows, fuel properties, exhaust gas composition, and gas-path debris.

The environmental and performance requirements for these sensors are summarized.

Chapter 4 discusses *Distributed Engine Control* using high temperature electronics and open systems communications will reverse the trend of increasing weight ratio of control system to total engine and also be a major factor in decreasing overall cost of ownership for aero propulsion systems. The implementation of distributed engine control is not without significant challenges, including needs for high temperature electronics, development of simple, robust communications, and power supply for the on-board electronics. Although no new sensors or actuators are needed to enable distributed engine control, there is a need for on-board electronics located on or close to the sensing element or the actuator, such that network communications can be enabled and the wiring harness required for communications between sensors and actuators and the engine controller can be substantially reduced. The location of the node will dictate the operating temperature requirement, which in some cases could be as high as 500°C. With the limitation of standard silicon technology to less than 125°C, newer material technologies are required. In the absence of sufficient temperature capability distributed architecture could still be implemented, but with a weight penalty for additional structure to minimize heat soak

from the engine. Another challenge for enabling distributed engine control is to supply the power needed for the on-board electronics – innovative power supply architectures and technologies will need to be developed to exploit the full potential benefits of distributed engine control.

Chapter 5 outlines *Universal Sensor and Actuator Requirements*. Even if the sensor and actuator technology meets performance requirements, there are still various hurdles to be overcome for the technology to transition into a real engine. Three broad areas for these "universal" requirements are discussed:

1) When a technology is being considered for incorporation onto/into the engine, the impact on revenue and cost and the ease of integration has to be evaluated.
2) Requirements (other than performance) are summarized that need to be met to consider a technology to be at a prototype level and ready for potential insertion.
3) The process of moving a product, process or component towards maturity is discussed.

It typically follows the development route as described in the Technology Readiness Level (TRL) definitions. Business, manufacturing, legislative, etc., issues must be covered at an appropriate level at all stages.

Chapter 6 discusses *Sensor Requirements and Roadmaps.* The standard GTE Gas Path Sensors are designed and packaged according to the specifications driven by the certification requirements to the aircraft and GTE and were mostly written by the GTE manufacturers following guidelines of MIL-STD 810F for tailoring sensors's environmental design and test limits to the conditions that the specific sensor will experience throughout its service life, and for establishing laboratory test methods that replicate the effects of environments on sensors. Specifications of the most of present sensors with integrated electronics are limited to environment conditions within –65°C to +115°C. Sometimes the temperature limitations can be overcome with integrally attached electronics that is installed in the GTE location with acceptable temperature. By changing the packaging and/or design features of the system some of the current sensors can be modified to meet higher then present operating temperature ranges. Operation environments of 750°C may be possible, which would meet requirements for sensors located towards the engine intake, compressor and in some cases low pressure turbine. For sensor locations closer to the engine combustion chamber or afterburner, sensors withstanding even higher temperatures (up to 1700°C) are required. Sensors for these temperature requirements do not exist. There is also a need for "smart" sensors, which would enable future distributed control architecture. In addition, a number of sensors, which are of interest for more intelligent gas turbine engines, are being explored or do not yet exist, for example the turbine emission species sensors, burning pattern factor sensors, fuel property sensors, and exhaust gas composition sensors. Meanwhile, rapid emerging technologies were made available during the three years duration of the Task Group, including tip clearance measurement technologies such as eddy current and microwave methods. Implementation of available sensors is an additional major issue. Sensors should be small, light, low cost, and reliable. Also embedding of the sensors within the structure of the engine is an issue that has been investigated by researchers, but has not been implemented in prototypes or even on military engines.

To meet the future sensor requirements, new fabrication and material technologies, advanced sensing principles, and their potential applications to new sensor technologies are being explored. Micro-Electro Mechanical Systems (MEMS) is a good candidate to address the need for high-temperature operation and for new types of sensors, including smart sensor capabilities. Silicon-on-Insulator (SOI) provides some advantages (with potential operational temperatures of 300ºC); the semiconductor SiC (up to 500°C) and the ceramic material SiCN (up to 1700°C) are explored for even higher temperatures.

Several advanced sensing technologies are explored in combination with MEMS, including gas chromatography, spectroscopy and metal-oxide elements (electronic noses). Also wavelength Tunable Diode Laser (TDL) technology, which is based on telecommunication-type devices operating in the visible and near-IR portion of the spectrum, is being explored for real-time measurements of important propulsion parameters, such as temperature, species concentration, pressure and velocity.

The status of current RandD for new sensors (current TRL level) and future expectations (years to achieve TRL 6 (prototype demonstration in a relevant environment)) are summarized in a comprehensive table. Some examples on sensor requirements and the possible timetable for implementing advanced technologies for the various sensing variables are discussed in the following.

For temperature sensors approaching 1700°C operational environment SiC and SiCN technologies are considered to have the highest potential. Various other techniques are being explored, but may not provide the required performance at high temperatures. The TDL technique has been demonstrated on full-scale gas-turbine combustor sector test stands, but challenges have to be addresses before implementation can be considered.

Pressure sensors that operate in an environment with temperatures below 250°C are largely available. Pressure sensors capable to operate in environment with temperatures from 250°C to 750°C are commercially available, however these sensors are used mostly on the test stands or for “rumble” or “screech” monitoring of GTE with augmentor, because they cannot measure static pressure and aerospace GTE, compared with industrial aeroderivative GTE, does not allow yet for controlling fuel delivery to each individual fuel nozzle. Pressure sensors that have to operate in temperature environment exceeding 750°C are not existent and are foreseen to be based on SiC and SiCN. Smart sensors based on SiC technologies are foreseen to be largely available by 2015. SiCN technology for pressure sensors and integrated electronics is not foreseen to be available earlier than 2020. Both SiC and SiCN technologies come with a great potential however, because of potentially embedding such high temperature sensors within the structure.

Vibration sensors located remotely from the fan and turbine could face significantly high temperatures (up to 750°C); therefore standard MEMS piezoelectric accelerometers cannot be used. Extension of the MEMS principles from Si or piezoelectric technology to SiC and SiCN technologies might significantly extend the capability of such systems to operate at high temperatures. The timeline for SiC and SiCN technologies applied to micro-accelerometers follows the same time frame as presented above. Non-contact sensing based on Doppler Velocity Interferometer is available for measurements at a temperature range from –65°C to + 125°C.

Emission species and exhaust gas composition sensors are largely available for test rig measurements. Sensors based on spectroscopy are far from a commercial product. TDL technology appears to be the most promising technology. However, challenges include “optical engineering” (dealing with heat transfer effects on fibers and windows and developing robust hardware designs for these components, and also for lasers, electronics and data processing) and “optical science” (optimizing the selection of wavelengths and sensing strategy). Spectroscopy technology is currently at TRL 2 and could be at TRL 6 in 2020.

Tip clearance and position/arrival time sensors have been demonstrated using capacitive sensors (now at TRL1 and TRL 6 expected in 2020) and microwave sensors (now at TRL 5 and TRL 6 in 2010). These sensors can operate at temperatures as high as 600°C. For higher temperature ranges up to 1700°C, SiCN based sensors are required; the timeline for the development for such sensors is 2020 or later.

Torque sensors to evaluate the real-time trust of the engine are largely available and are implemented in few classes of engines (helicopter turbine engines). Such sensors are in an advanced development state and implementation is expected within the next three years. The existent technology needs to be integrated in specific designs, the size of the sensors has to be reduced, reliability has to be improved, and drift from the calibrated point has to be minimized. The timeline for such type of sensors is 2010.

The need for sensors for determining air mass flow (without interference with flow), fuel mass flow (for high temperature operation at burners' nozzles), and fuel properties (on-board during or after re-fueling) has been identified for thrust and energy estimations. No sensors are available. The challenges to accomplish such type of sensors are significant, and it estimated that they are not available before 2020.

Chapter 7 outlines *Actuator Requirements and Roadmaps*. Generic **actuator** requirements for three common actuation functions were addressed, including:

1) Flow manipulation (of the boundary layer by either mechanical effects or aerodynamic means with blowing or sucking air);
2) Large scale flow switching (valves with applications to stall/surge control, bleed flows, cooling flows, other); and
3) Mechanical manipulation (intakes, variable guide vanes and nozzles).

Generic requirements for these three common functions have been summarized in terms of operational environment and performance/capabilities depending on component applications. In addition generic actuator requirements for fuel flow control, geometry control, and requirements for specific compressor/turbine applications (tip clearance and vibration) were added. Although generic requirements can be identified, developments towards these environmental requirements must be intimately coupled to the specific application requirements in order to satisfy the overall constraints.

Current actuation within a gas turbine has largely been limited to the five main variables, namely fuel input, variable guide vanes, bleed valves and variable geometry intakes and nozzles. First generation tip clearance control using casing temperature has also recently been added. Specific capabilities for various components were described.

Actuation within a gas turbine requires consideration of the interaction with the engine cycle. For example effects on air flows, combustion temperatures, etc., must consider integration into the engine components. Technology evaluation has to identify the current capabilities and likely future developments including full system requirements, costs, maintenance, failure modes, etc.

Established actuators such as hydraulics, electrical and even fluidics still offer considerable opportunities for future developments. Emerging technologies include:

1) Electroactive materials, including piezoelectric ceramics and Electro Active Polymers (EAPs);
2) Shape memory materials;
3) Magnetic strained materials (providing magnetostrictive effects);
4) Magnetic Shape Memory (MSM) or Ferromagnetic Shape Memory (FSM) materials; and
5) Microsystems, micromachines and MEMS.

Approaches of extending standard technologies and applying new technologies are discussed for the various components.

Actuator applications to the various components together with specifications, candidate technologies, current TRL, time to achieve TRL 6, and the challenges have been summarized in a comprehensive table. Current actuator TRL levels of 2 (for electro-magnetic and hydraulic actuation and high-temperature shape memory alloys both for tip clearance control) to 5 (for pneumatic actuation for tip clearance control) have been identified. The majority of the actuator technologies are considered currently at TRL 3. The years to achieve TRL level 6 range from 2010 (for electro-magnetic, miniaturized valves for fuel flow control and large-scale flow switching for compressor stator vanes and pneumatic tip clearance control) to 2020 (for high temperature shape alloys for turbine tip clearance control). Devices for micro-scale flow manipulation are considered to be at TRL 6 in between 2013 and 2018 mainly depending on operational temperatures and for geometric control in 2012 (standard action principles) to 2018 (shape memory alloys).

8.2 ROADMAP

The benefits of enabling technologies for the "More Intelligent Gas Turbine Engines" in terms of improved Performance, Safety, Affordability and Reliability, and reduced Environmental Impact are summarized in Table 8.1. These benefits are listed as High (H), Medium (M), and Low (L) to provide a qualitative assessment, and are summarized by the technologies discussed in the three main areas: Actively Controlled Components; Intelligent Control and Health Monitoring; and Distributed Engine Control. The anticipated timeframe for the technologies to reach TRL 6 is also provided along with some notes to give additional information such as the actuation/sensing technologies required to reach TRL 6.

Table 8.1: Component Roadmaps

		Year to Achieve TRL 6 Goal			Benefits (H, M, L)					Notes
Applications	Technology Areas	2010	2015	2020	Performance	Safety	Affordability	Reliability	Environmental Impact	
Actively Controlled Components	Inlet									
	Active inlet control		x		H					Inlet geometry control for supersonic speed
	Active inlet flow control		x		M	M				Pulsed microjets
	Active noise control		x		L				H	Fan noise control; pulsed microjets
	Compressor (AC of)									
	Surge	x			H					Using pulsating jets
	Flow			x	M					Pulsed microjets; elevated temperature
	Clearance		x		H					Pneumatic actuation
	Vibration		x					H		Piezo-electric actuation
	Combustor (AC of)									
	Combustion instability	x			H					Pulsed fuel injection; electro-magnetic valves
			x							Magneto-strictive
	Emission		x						H	Magneto-strictive
	Pattern factor	x			H					Electro-magnetic
	Turbine (AC of)									
	Clearance	x			H					Pneumatic actuation
				x						SMA
	Cooling air				H					Flow control valve at elevated temperature
	Nozzle									
	AC of noise			x					H	SMA actuation at elevated temperatures
	Thrust vectoring			x	H					Flow control valve for cross injection
Intelligent Control and Health Monitoring	Model based control		x		H	H				Current sensors with enhanced capabilities; SiC sensors
				x						New types of sensors with SiCN and TDL technologies
	On-board condition monitoring		x		H	H		H		Current sensors with enhanced capabilities; SiC sensors
				x						New types of sensors with SiCN and TDL technologies
	Adaptive control		x		H	H				Current sensors with enhanced capabilities; SiC sensors
										New types of sensors with SiCN and TDL technologies
Distributed Engine Control	Partially decentralized control		x		L		M			Component level control implemented locally
										and integrated with FADEC
	Fully distributed control			x	L		M			Performance - although low direct performance improvement, .
										this is critical for improved capability in terms of
										enabling active component control
										Affordability - improvement is in reduced operational costs
										through better diagnostics and "easier" upgrade capability

8.3 RECOMMENDATIONS

The concept of more intelligent gas turbine engines should be approached by incremental changes, both by improving existing technology and components and implementing new technologies. Although numerous newly built propulsion systems are already using intelligent components, it is expected that a sustained effort in the implementation of the distributed active control will be attempted, once the technologies targeted in this report are developed and demonstrated. A close interaction between the "Customers" and "Researchers" and "Technology Developers" is needed to optimize investment for meeting challenging for performance and implementation-related requirements. Recommendations for sensors and actuators activities are summarized in the following to achieve a goal of TRL 6 (fully demonstrate engineering feasibility) in the near-term (3-5 years), mid-term (7 to 10 years), and long-term (12 to 15 years).

8.3.1 Sensors

8.3.1.1 Near-Term Goals (about 2012)

For sensors, which are available now or have proven concepts (TRL 3), work should focus on prototyping and implementation for the target environment and interfaces. Examples are sensors for tip clearance (microwave sensing), position and arrival, and torque. Also sensing capability for health monitoring should be improved by adding vibration sensors for the fan and adding conventional gas path pressure and temperature measurements at locations that are presently not instrumented due to the harsh environments, including high temperatures.

Implementation of pressure sensors to determine inlet distortion and stall margin should be considered. The need for non-interference with the flow and exposure to ice, rain, sand, and dust has to be addressed.

Insertion of sensors for turbine emission species and exhaust gas composition should be considered. Such sensors are now available for low temperature operation. Improvements in the performance of electronic noses through nanotechnologies should be further pursued.

8.3.1.2 Mid-Term Goals (about 2016)

SiC (Silicon Carbide) technology should be further explored and transitioned, as soon as possible, to technical feasibility demonstrations. This includes technologies for specific sensor types and entire electronic circuits, which would allow development of smart sensors.

Sensors based on spectroscopy should be further explored. Tunable Diode Laser (TDL) technology appears to be the most promising technology. Challenges dealing with heat transfer effects on fibers and windows, robust hardware designs, and optimization of sensing strategy should be addressed.

8.3.1.3 Long-Term Goals (beyond 2020)

SiCN (Silicon Carbide Nitride) technology should be further explored and proof of concept validation should be provided, both for specific sensors and integrated electronics.

Other promising technologies should be pursued, including embedding of high temperature SiC and SiCN sensors, the application of spectroscopy, and advanced sensing principles for sensors (for example capacitive sensing for tip clearance).

In addition basic research should be initiated to identify sensing principles and define concepts for sensors to determine mass flows and fuel energy properties for thrust estimation.

8.3.2 Actuators

8.3.2.1 Near-Term Goals (about 2012)

Established actuator principles such as hydraulics, electrical and fluidics should be further considered to address future actuator requirements. New opportunities to develop higher temperature and miniaturization capabilities should be pursued, while considering full system requirements, costs, maintenance, failure modes, etc.

Prototyping of several actuators now at TRL3 should be considered. These include micro-jets and micro-flaps for inlet flow control, low-temperature piezo-electric and electromagnetic devices for geometry control (inlet),

electro-magnetic valves for large-scale flow switching for compressor stator vanes, electro-magnetic and magneto-strictive valves for fuel flow control, and pneumatic and electromagnetic actuators for tip clearance control.

8.3.2.2 Mid-Term Goals (2016)

Work should address micro-jets with increased mass flow and higher temperature capabilities and flow control valves with further increased flow capabilities. Applications for low-temperature SMA (Shape Memory Alloy) for geometric control should be considered, as well as hydraulic and piezo-electric actuators for tip clearance control. High-temperature applications of the piezo-electric, hydraulic, and electro-magnetic actuation principles should be explored.

8.3.2.3 Long-Term Goals (beyond 2020)

High-temperature applications for SMA and electromagnetic principle should be addressed (for example for tip clearance control). Also other emerging technologies such as Electro Active Polymers (EAPs) and Magnetic Shape Memory (MSM) or Ferromagnetic Shape Memory (FSM) materials should be explored for potential actuators.

8.3.3 Other Technologies

In addition to addressing sensor and actuator needs the following technologies should be addressed: power supply for distributed on-board electronics, Wi-Fi transmission with 99.999% fidelity, energy harvesting for sensors, and spintronics as novel sensing principle.

8.3.4 Follow-on Activity

It is recommended that the AVT Panel establish a new Task Group to demonstrate feasibility and reliability of new technologies in sensors and actuators [8.1]. The approach will be that the researchers will provide sensor and actuator prototypes along with the expected specifications to the sensor and actuator manufacturers, who will package and prepare the devices for the testing. The units will be shared by propulsion systems manufactures and incorporated in the engine tests to determine achievable specifications.

8.4 REFERENCE

[8.1] Appendix 7 – TAP for Proposed Task Group for Demonstration of Advanced Sensors and Actuators Capabilities for Future Propulsion Systems.