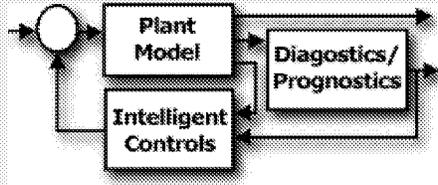


Propulsion Controls and Health Management Research at NASA GRC

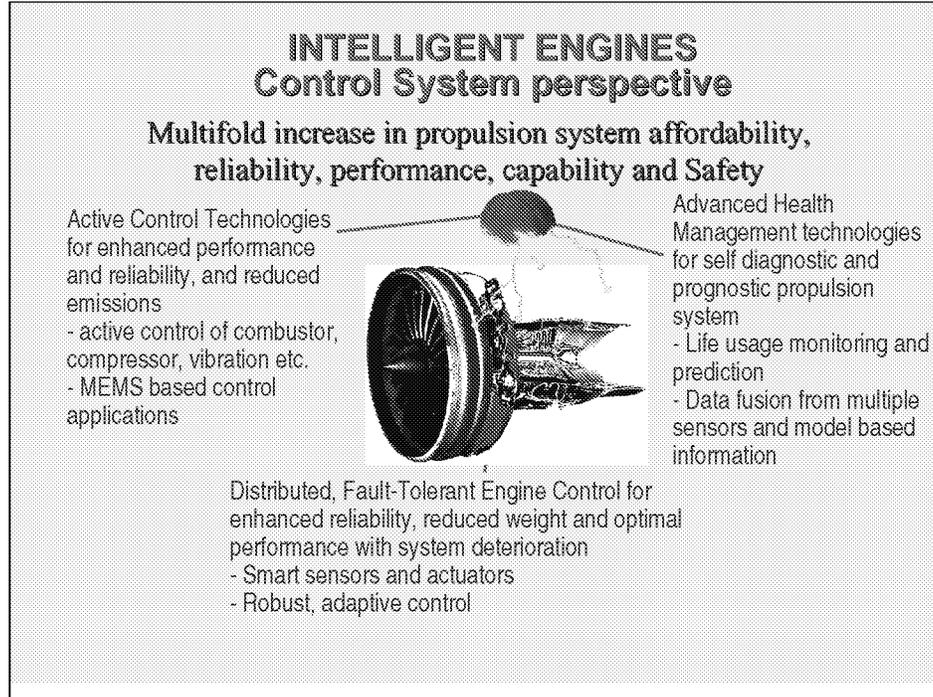


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Abstract

With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircraft, there are many new challenges being faced by the designers of aircraft propulsion systems. The Controls and Dynamics Technology Branch at NASA Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with the U.S. aerospace industry and academia to develop advanced controls and health management technologies that will help meet these challenges. These technologies are being developed with a view towards making the concept of “Intelligent Engines” a reality. The major research activities of the Controls and Dynamics Technology Branch are described in the following.

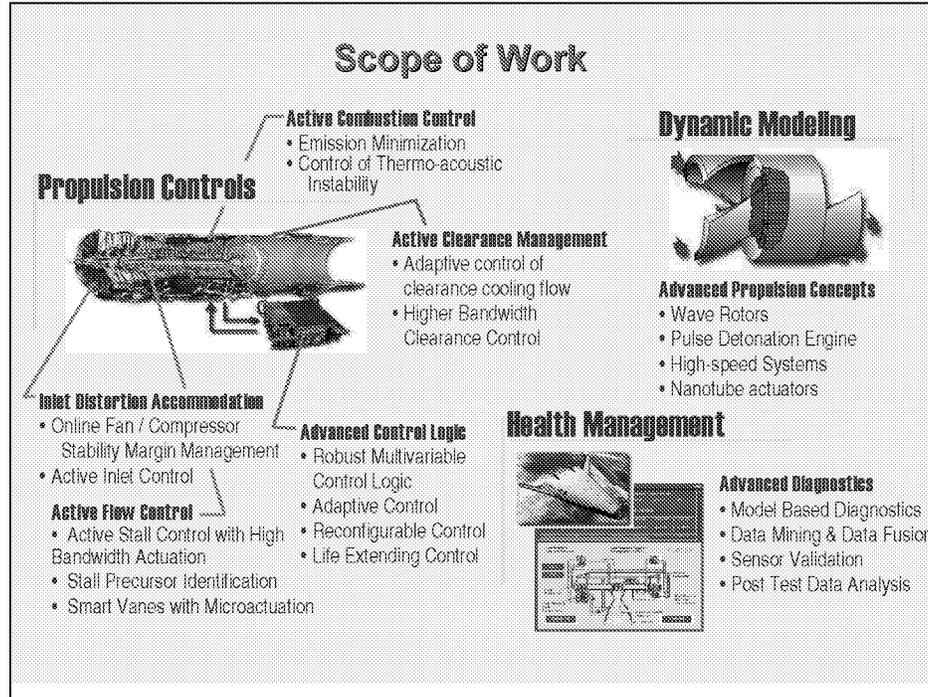


The control system enabling technologies for “Intelligent Engines” can be organized into three broad categories – active component control, advanced health management, and distributed fault tolerant control.

The traditional propulsion control system problem has been that of providing a desired thrust response to pilot PLA (power lever angle) commands while maintaining the safety of the engine. In the past engine components such as combustors, fans and compressors, inlet, nozzle etc. are 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 the need for affordable and environmental friendly propulsion systems.

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 technology development is to maximize the “on wing” life of the engine and to move from a schedule based maintenance system to a condition based system.

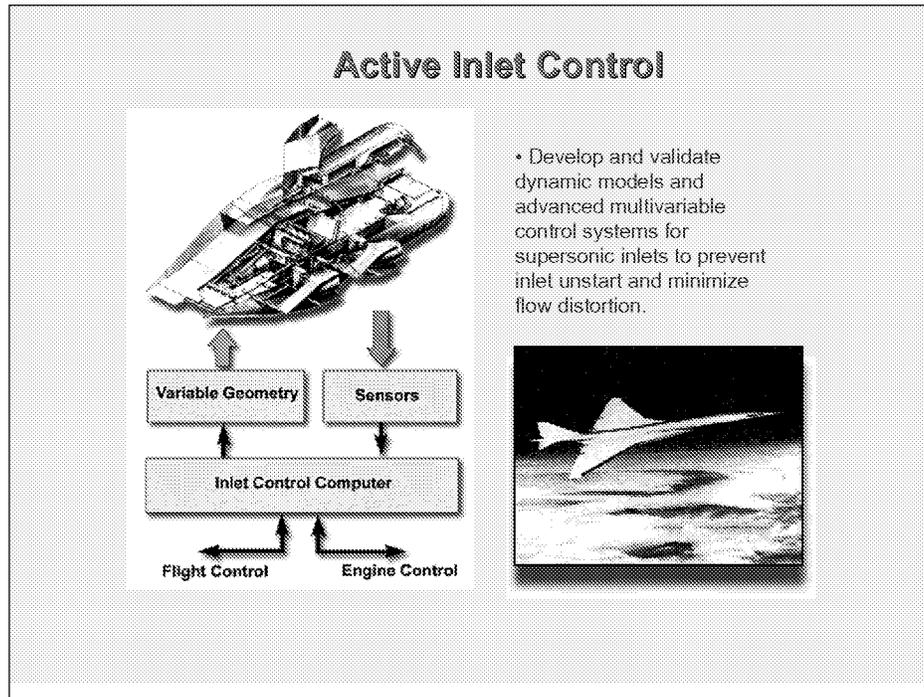
Implementation of these concepts requires advancements in the area of robust and adaptive control synthesis techniques, and development of new hardware such as smart sensors and actuators. Attention will also need to be paid to integration of the active component control and diagnostics technologies with the control of the overall engine system which will require moving from the current analog control systems to distributed control architectures.



The Controls and Dynamics Technology Branch at NASA GRC is actively involved in developing technologies that will help the aerospace industry make the concept of an “Intelligent Engine” into a reality. The main focus of the Branch is in development of technologies for propulsion control, dynamic modeling and health management. The various activities of the Branch in these three main areas are listed in the above figure. These are further described in the following sections. All the technology efforts are aligned with NASA’s goals for Aerospace Technology.

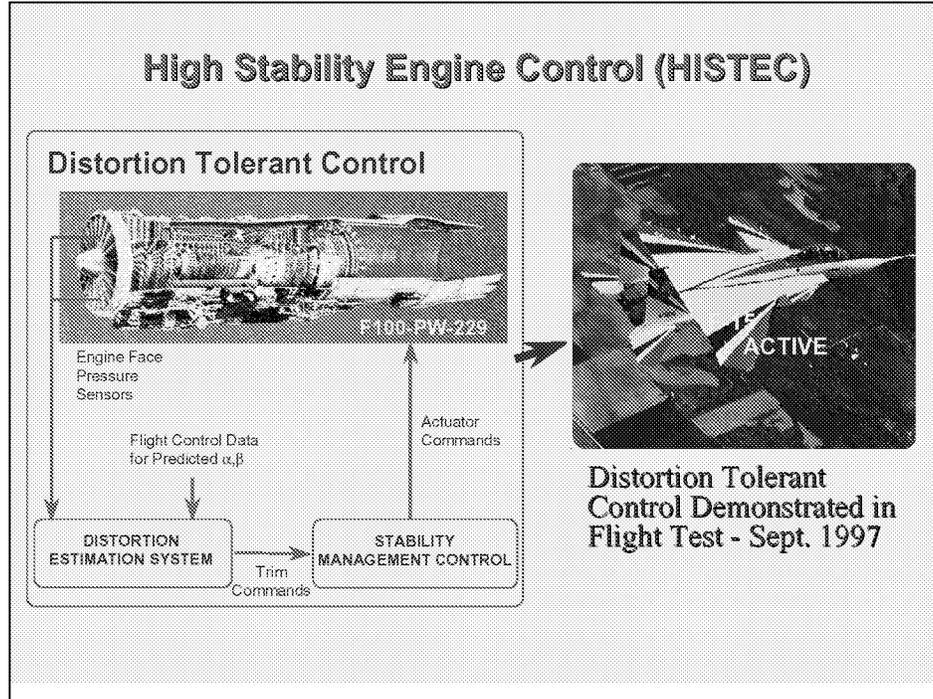
It is important to note that development of the controls and diagnostics technologies is a multi-disciplinary effort. The Controls and Dynamics Technology Branch works collaboratively with various internal organizations within NASA Glenn Research Center for development, implementation and validation of the technologies. Also, there is a strong collaboration with aerospace propulsion industry to ensure that the problems being addressed are relevant to the industry and that the technologies being developed will be suitable for transition into a product. Academic institutions are a strong contributor to the technology development efforts, specially in conducting fundamental research which has applicability towards long term goals.

The technology development efforts are coordinated with other NASA Centers, and the Department of Defense to ensure that the government resources are utilized in the most effective manner and there is no duplication of efforts.



For High Speed Civil Transport, the efficient and safe operation of the engine requires that the leading shock at the engine inlet be maintained within a narrow range of locations at the inlet face. If the shock moves too far out in front of the inlet, it results in a phenomenon called inlet “unstart” where there is no flow to the engine and the engine shuts down resulting in violent motions of the aircraft. The active inlet controls program was being conducted in direct support of the NASA High Speed Research (HSR) program which was developing technologies for a future commercially and environmentally viable supersonic civil transport aircraft.

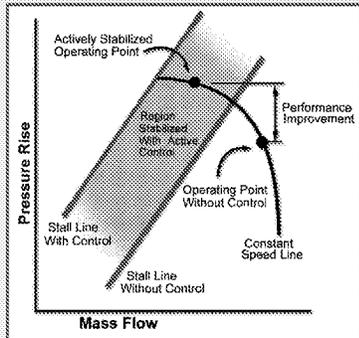
The objective of the active inlet control is to develop and validate dynamic models and advanced multivariable control systems for supersonic mixed-compression inlets. The control system will be designed to include inlet unstart prevention, automatic restart, distortion minimization and inlet/engine integrated control. The technologies are to be demonstrated through wind-tunnel tests on scaled versions of variable geometry inlet concepts developed by Boeing. Some of the challenges in implementing active inlet control are determining the best effectors for controlling the shock position and developing accurate models of inlet operation to be able to estimate shock position from pressure measurements.



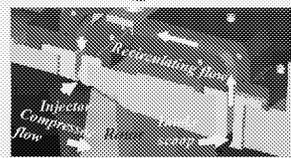
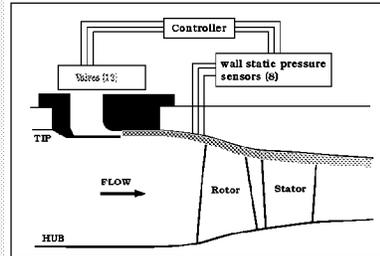
For aircraft engines a safety margin, called the stability margin, is built into the operation of the engine to prevent inception of fan/compressor stall due to inlet distortions caused by aircraft maneuvers or atmospheric disturbances. This stability margin results in a performance penalty being paid even at low distortion operating conditions such as cruise. Engine companies have estimated that being able to actively control the engine so as to safely maintain low stability margins under such low distortion operating conditions can result in reduction of 2% or more in Specific Fuel Consumption.

NASA GRC in partnership with Pratt & Whitney, Air Force, McDonnell Douglas Aerospace and NASA Dryden Flight Research Center developed and demonstrated technologies to allow for on-line active management of the engine stability margin. The technologies include development and validation of engine inlet distortion estimation algorithms, estimation of stability margin sensitivities to inlet distortion, and development and implementation of advanced control logic that will allow active control of engine operating point in a safe and time critical manner. Under the HISTEC (High Stability Engine Control) program, the critical technologies were demonstrated and evaluated in flight tests on a modified F-15 aircraft which is referred to as the ACTIVE (Advanced Control Technologies for Integrated Vehicles) aircraft.

Active Stall Control



- Detect stall precursive signals from pressure measurements.
- Develop high frequency actuators and injector designs.
- Actively stabilize rotating stall using high velocity air injection with robust control.

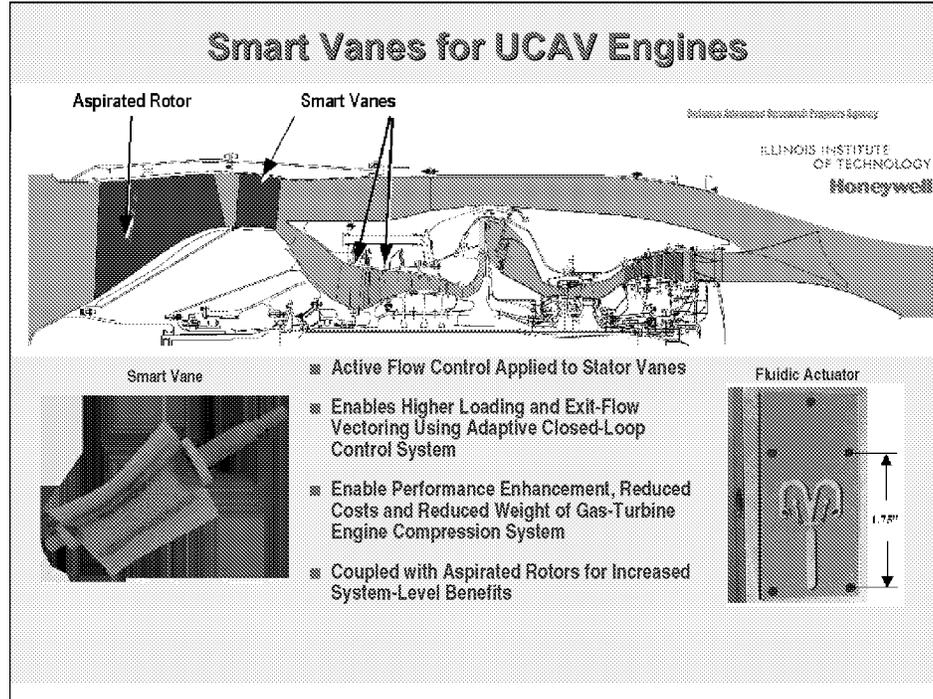


Compressor Stability Enhancement Using Recirculated Flow

The peak efficiency operating point of a turbine engine compressor is very near the compressor stall line as shown in the above figure. In order to prevent catastrophic stall from occurring during large transients, the engine is operated with a large safety margin. If the compressor can be safely operated closer to the designed compressor peak efficiency then it will result in increased engine efficiency and reduced engine cost leading to significant savings in aircraft fuel costs.

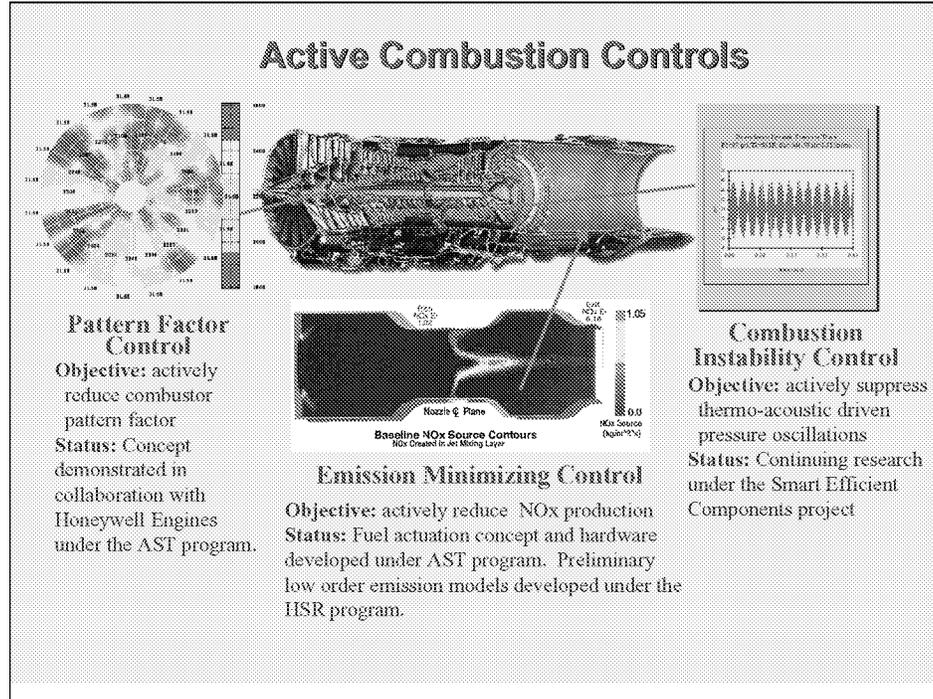
As shown in the above figure, the compressor stall line can be moved up through active control thus allowing safe operation at peak efficiencies. The active stall control is obtained by sensing pressure changes at the inlet face of the compressor which will indicate flow distortion that is the precursor to stall, and activating high bandwidth flow valves located around the circumference of the compressor that blow high pressure air to counter the flow distortion before it builds up to stall. The challenges for implementation of active stall control are developing accurate models of the stall phenomenon that can be used for control design, developing high bandwidth (of the order of 500Hz) actuators for controlling flow valves and understanding the effectiveness of different actuating schemes for stall control.

The active stall control program at NASA GRC is a cooperative program with industry and academia with strong participation from MIT (Massachusetts Institute of Technology). Active stall control has been demonstrated in the laboratory environment at NASA GRC for a single stage high speed compressor. Experimental investigations were recently completed in collaboration with industry to demonstrate the technology on a multiple stage compressor in the presence of inlet distortion, and simulating the effects of bleeding air from rear stages of the compressor for injection in the front stages. These results indicate that substantial extension in safe operating range of the compressor can be achieved by active stall control technology.



Another representative technology for intelligent engines is Smart Vanes research. This research is being conducted in collaboration with Honeywell, and Illinois Institute of Technology and is being partially funded by DARPA (Defense Advanced Research Projects Agency). The goal of Smart Stator Vanes is to provide enabling technology for intelligent engines by diagnosing and eliminating separation on the suction side of stator vanes. It is particularly beneficial in highly loaded compressors. Although work reported here is focused primarily on the compression system, smart vanes can have benefits in both the front and rear of the engine.

These vanes are proposed as a replacement for inlet guide vanes and adjustable stators and will eliminate the complexity and weight associated with these mechanical components. As part of this approach, air, injected through the trailing edge of a vane, is used to turn the flow rather than turning the flow by mechanical means. In addition, air blown through holes in the surface of the blade can reduce or eliminate blockage due to separation that can occur on the suction side of the blade. Both steady and unsteady approaches are being investigated. To date, the unsteady blowing shows the most benefit and it requires less flow than steady injection. In a current application, fluidic actuators (lower right) embedded in the vane are being used to oscillate the flow producing an unsteady boundary condition at the blade surface or trailing edge. Future efforts will focus on closed-loop control of separation by coupling a separation sensor with control laws and a valve.

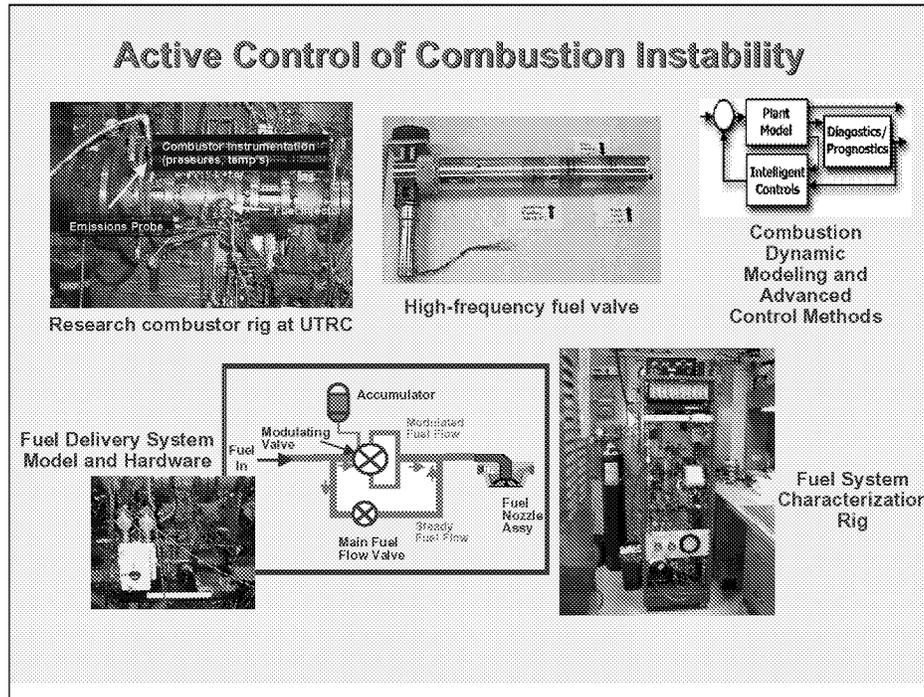


The three main areas of interest in the active control of aircraft engine combustion systems are: pattern factor control, emission minimizing control and combustion instability control.

The Burner Pattern Factor is defined as the ratio of the difference between the maximum and average temperature at the turbine inlet to the average temperature at the turbine inlet. Reducing the burner pattern factor through active control will allow for more efficient fuel burning, decreased emissions and increased life of turbine blades.

For a given combustor design, it is possible to reduce the NO_x (Nitrogen Oxide) emission through active control of the fuel/air mixture. The challenges for this technology are development of emission sensors for the harsh engine environment, development of simplified NO_x production models that can be used for control design, and in investigating the most suitable approach to actively control the fuel/air mixture ratio.

As the requirements for reducing emissions become more stringent, the combustor designs move towards a “lean” burning solution where the fuel/air mixture is richer in air to allow for complete combustion of the fuel. Such combustor designs are prone to instability due to thermo-acoustic driven pressure oscillations. Active control of such oscillations will allow for more efficient combustor designs. Very little research has been done in this area and most of it has been at the laboratory stage. The NASA GRC effort will lead to improved modeling of the thermal-acoustic instability for actual combustors in an engine environment, and will demonstrate the feasibility of active control of this instability through engine tests.

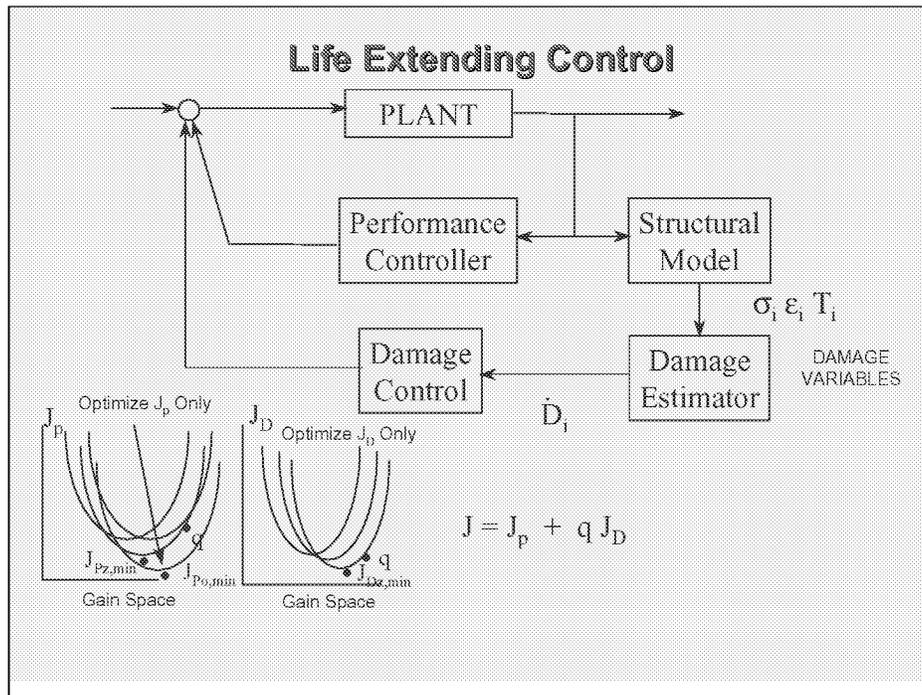


NASA GRC is working in collaboration with Pratt & Whitney (P&W) and United Technologies Research Center (UTRC) to develop and demonstrate technologies for the active suppression of thermo-acoustic instability. As part of this effort, a single nozzle combustor rig was developed at UTRC which has the capability to duplicate the thermo-acoustic instability that was observed in an actual engine test.

In order to suppress instabilities, it is necessary to modulate the fuel flow entering this representative combustor at roughly 600 Hz (function of combustor length). A valve was developed in conjunction with Georgia Tech which is capable of generating the required high frequency modulations in fuel flow. An actuator characterization rig was built up at GRC to be able to identify the dynamic characteristics of the valve so that the actuator models can be used for control design development.

Another critical component is the fuel delivery system. An improperly designed fuel delivery system can attenuate perturbations generated by the valve and render the control system ineffective. The fuel delivery system was modeled to better understand these attenuation effects, and open loop testing of the high frequency actuator in the combustion rig is currently being conducted to ensure adequate effectiveness of fuel modulation.

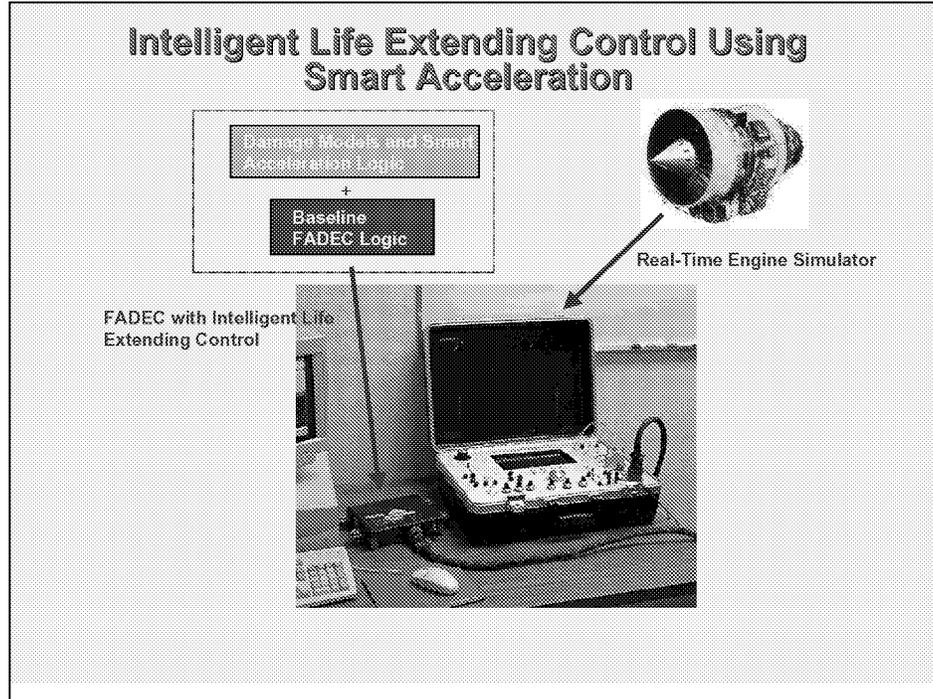
A 1-D CFD (Computational Fluid Dynamics) model of the combustor rig was developed which accurately simulates the thermo-acoustic instability characteristics of the rig. This model is being used to develop instability suppression control laws using advanced control methods. Experimental demonstration of high frequency instability suppression is planned for the near future.



With the recent emphasis on reducing engine operating cost, the industry is interested in developing technologies that will allow the engine and its component to operate longer thus increasing the time between engine overalls.

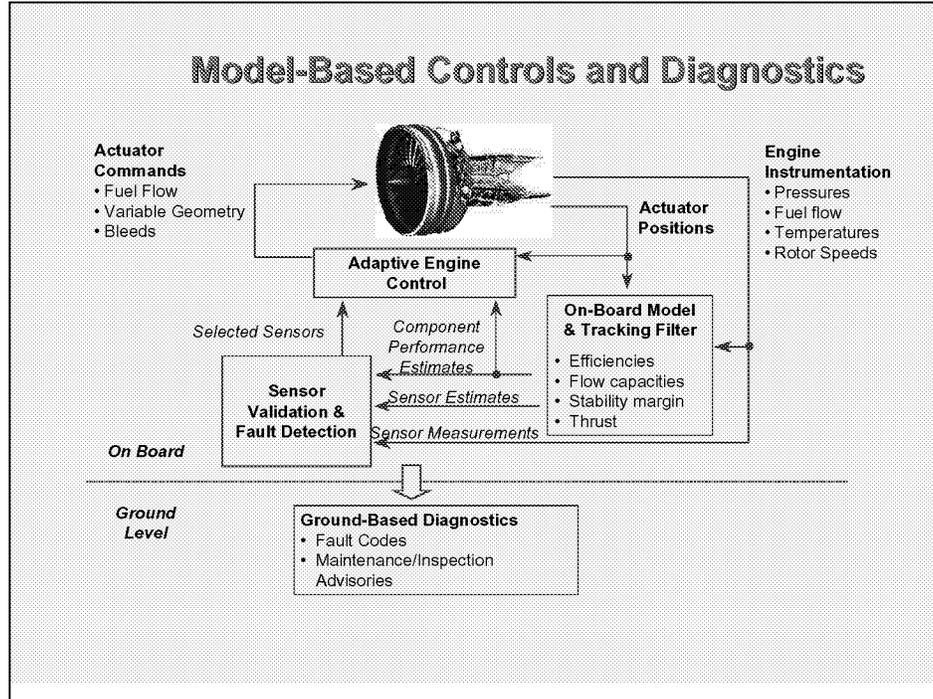
How the engine is controlled has a severe impact on the life of the components. Typically, the propulsion system control design engineer attempts to get the maximum performance out of the system while maintaining safe operation. Recent studies have shown that small changes on engine operating parameters, such as turbine inlet temperature, can have a significant impact on the damage accrued by engine components while having no noticeable change in engine performance.

NASA GRC has developed the concept of Life Extending Control where the engine control system is designed to achieve the desired performance while minimizing the damage accrued in engine components and hence maximizing the usable engine life. The feasibility of this concept was demonstrated for the Space Shuttle Main Engine through engine simulations. Efforts are currently ongoing to develop and validate this technology for airbreathing propulsion systems.



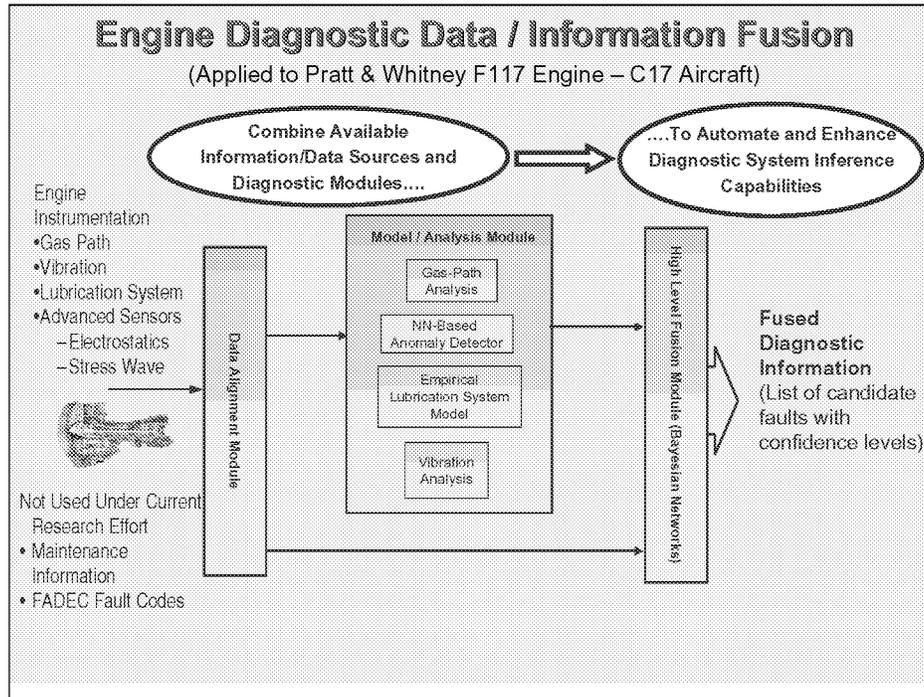
NASA GRC is pursuing development of both near term and long term technologies for extending the life of engine components through smart control. The near term approach to Life Extending Control is new control concept, called smart acceleration logic, that will include factors for engine damage as part of the control function. During take-off, when the pilot pushes the throttle to move the engine from idle to maximum thrust, the engine control generates a fuel flow command based on acceleration logic that ensures that the maximum thrust is achieved within a time limit based on FAA (Federal Aviation Authority) requirements. The engine components accumulate damage during this transient due to the quick and large changes in temperature and aerodynamic loads. By adjusting the acceleration logic such that the time to achieve maximum thrust is just within the FAA requirements, the temperature and load changes on the engine components can be kept to the minimum required to meet the performance. This will result in reduced damage accumulation for each take-off and hence increase the amount of time the engine can stay on the aircraft before a major overhaul is required.

The smart acceleration logic, developed by NASA, Scientific Monitoring Inc. and Honeywell, was successfully integrated in a flight-grade engine controller and demonstrated on Honeywell's full-envelope, real-time simulator for an advanced engine for short-haul aircraft. This hardware-in-the-loop demonstration is an important step in assuring that the Intelligent Life Extending Control logic will perform in real working environments.



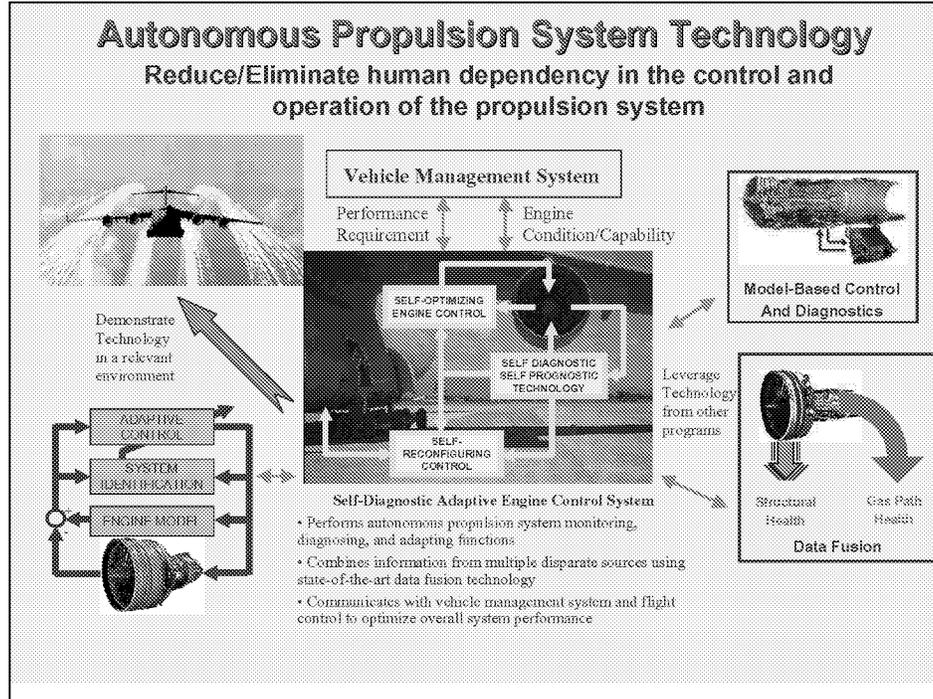
To be able to correctly and reliably identify engine system faults and take appropriate corrective action is critical for safe and efficient operation of the propulsion system. Aircraft operators have used model-based gas turbine engine condition monitoring systems in ground-based applications to trend engine performance from recorded engine measurements. Recent developments in adaptive on-board engine models have now made it possible to consider real-time engine condition monitoring and optimization of engine control to accommodate off-nominal engine behavior. Model-Based Controls and Diagnostics (MBCD) consists of a real-time on-board aerothermodynamic engine model incorporated into the engine control architecture as shown in the figure above. Such an architecture provides several benefits including continuous real-time trending of engine health, synthesized sensor values which can be used in sensor validation logic, and estimates of the unmeasurable engine parameters such as thrust and component stability margins which can be used in feedback control logic.

NASA GRC is working in collaboration with General Electric Aircraft Engines (GEAE) to extend MBCD technology to provide prognostic and diagnostic capability and fault accommodation in the propulsion system, thereby preventing or reducing the severity of potentially significant safety failures. The aviation safety concerns include the loss of control, controlled flight into terrain, or rejected takeoffs caused by the pilot's incorrect response to engine malfunctions. The emphasis of this activity is to prevent in-flight shutdowns and engine surge events in order to enhance propulsion safety. However, a continuous on-board monitoring system provides additional benefits. For example, early detection of incipient failures can prevent more costly failures from occurring, and can reduce the unplanned maintenance and engine removals.



A wealth of aircraft turbine engine data is available from a variety of sources including on-board sensor measurements, operating histories, and component models. Furthermore additional data will become available, as advanced prognostic sensors are incorporated into next generation gas turbine engine systems. The challenge is how to maximize the meaningful information extracted from these disparate data sources to obtain enhanced diagnostic and prognostic information regarding the health and condition of the engine. To address this challenge, NASA GRC and Pratt Whitney (P&W) are working collaboratively to plan and conduct research in the area of data/information fusion.

Data fusion is the integration of data from multiple sources to achieve improved accuracy and more specific inferences than can be obtained from the use of a single source of information. Techniques for data fusion are drawn from a wide range of areas including artificial intelligence, pattern recognition, and statistical estimation. Data fusion will enhance aircraft gas turbine engine Prognostic and Health Management system capabilities by reducing false alarms and missed detections, improving engine diagnostics for accurate isolation of faults, and improving engine prognostics for the accurate assessment of component life consumption and prediction of impending anomalies. These enhancements will directly support NASA and industry aeronautic strategic goals of reduced operating cost, increased safety and increased reliability.



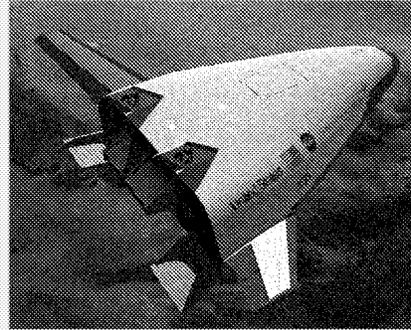
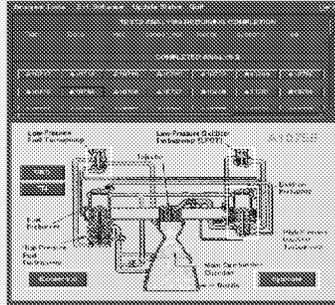
In the current aviation system airplanes, the pilot serves the critical function of integrating the propulsion system control with the flight control. The only exceptions to this are the “autothrottle” system which is deployed as part of the auto-pilot and is limited to operation at cruise under fair weather conditions, and the “autoland” system which is limited to landing under favorable conditions. Developing technologies for autonomous accomplishment of propulsion system control, diagnostics and prognostics functions is critical for enabling highly or fully autonomous operation of airplanes.

NASA GRC has initiated a new multi-year research effort for developing and demonstrating Autonomous Propulsion System Technology (APST). The APST project will develop and mature propulsion control, diagnostics and prognostics technologies that will enable autonomous operation of the propulsion system based on commands generated from an autonomous flight control. The technologies will be developed with a goal to demonstrate them on a flight test bed which is representative of a large UAV (Uninhabited Air Vehicle) for commercial application. This effort will leverage upon the various other technology development efforts within NASA and other government agencies in the area of propulsion control and diagnostics.

Post-Test/Post-Flight Diagnostic System

Objective: Develop and mature technologies that automate the analysis of rocket engine data to detect and isolate system and component failures

- Production version of system delivered to MSFC for integration into SSME data analysis process
- System developed for application to aerospike engine under the X-33/RLV program.



NASA GRC has been very active in the development of the health management technologies for space transportation propulsion systems. An important element of the health management program is the Post Test/Post-Flight diagnostic system. The objective of this system is to significantly reduce the cost and time associated with review and analysis of post-test and post-flight data. The system incorporates technologies for model based sensor validation, event detection to identify and isolate failures and expert based knowledge for early indication of component degradation. The NASA GRC developed system has a modular architecture that enables applicability of the system to propulsion systems other than the currently implemented Space Shuttle Main Engine.

A user-friendly post test diagnostic system (PTDS) for the Space Shuttle Main Engine has been developed and delivered to Marshall Space Flight Center. This PTDS system is now a part of the regular data processing and review stream for all shuttle flights and engines tests. The PTDS system was modified and augmented for application to the linear aerospike engine for the X-33 single stage to orbit technology demonstration vehicle. This system was to Rocketdyne in time for it to be used for all the test firings of the engine. Based on the PTDS performance during these tests, Rocketdyne estimated that a fully evolved PTDS would reduce test turnaround time from 13 days to one day and would improve engine flight turnaround time by an order of magnitude.

Conclusion

- **A multidisciplinary cross-organizational collaborative approach is critical for successful development and demonstration of “Intelligent Engine” technologies**
- **Critical technologies to be developed for controls and health management of propulsion systems are:**
 - Better understanding of the dynamic phenomenon to be controlled and models appropriate for use in development of diagnostics and control algorithms
 - Robust and adaptive control and diagnostic algorithms
 - Appropriate sensors to provide the information needed for control and diagnostics
 - Appropriate actuation schemes required to implement advanced control concepts
- **A system level approach is essential to ensure that various components of control or diagnostic system work together as an integrated system to achieve the desired objectives**

In conclusion, the above figure lists the major challenges currently being faced by the propulsion control design engineers. The Controls and Dynamics Technology Branch at NASA GRC is working in strong partnership with industry, academia and other government agencies to develop the propulsion control technologies that will help NASA meet the aggressive goals for civil aviation that have been set by the NASA administrator in the strategic roadmap for the NASA Office of Aero-Space Technology.