NASA/TM—2007-215028 AIAA–2007–5713

# Propulsion Controls and Diagnostics Research at NASA Glenn Research Center

*Sanjay Garg*
*Glenn Research Center, Cleveland, Ohio*

October 2007

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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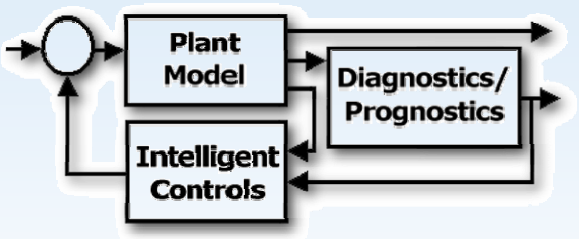


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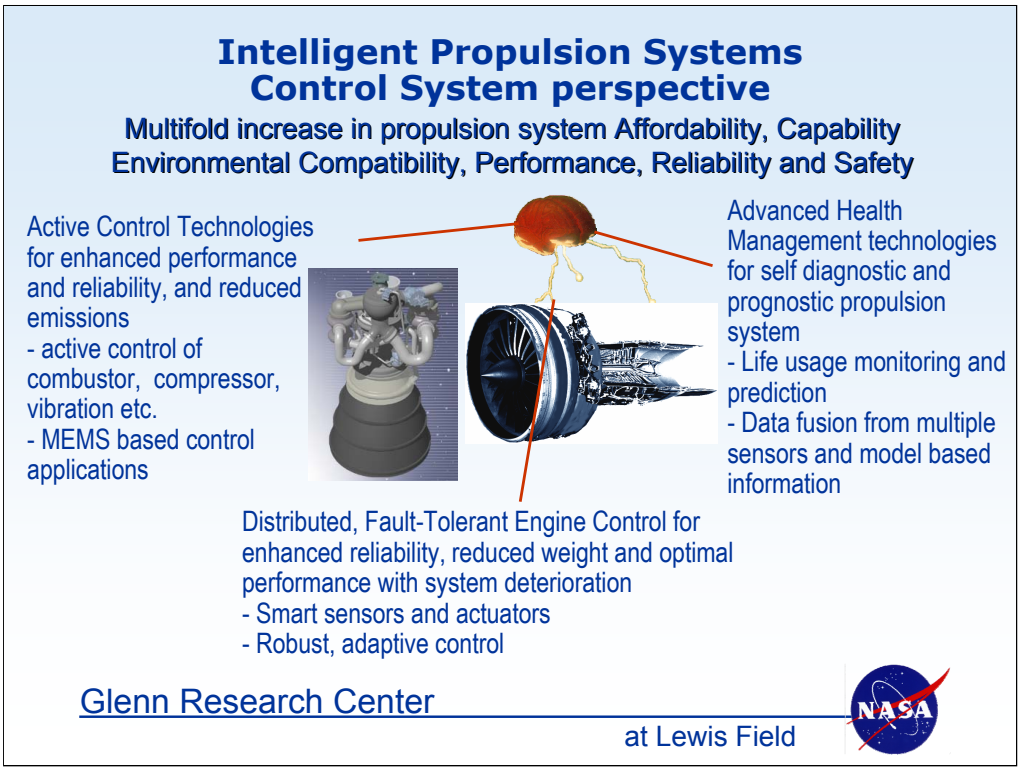
## Abstract

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. Also the propulsion systems required to enable the National Aeronautics and Space Administration (NASA) Vision for Space Exploration in an affordable manner will need to have high reliability, safety and autonomous operation capability. The Controls and Dynamics Branch (CDB) at NASA Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with other organizations within GRC and across NASA, the U.S. aerospace industry, and academia to develop advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. This paper describes the current activities of the Controls and Dynamics Branch under the NASA Aeronautics Research and Exploration Systems Missions. The programmatic structure of the CDB activities is described along with a brief overview of each of the CDB tasks including research objectives, technical challenges, and recent accomplishments. These tasks include active control of propulsion system components, intelligent propulsion diagnostics and control for reliable fault identification and accommodation, distributed engine control, and investigations into unsteady propulsion systems.




## Intelligent Propulsion Systems – Control System Perspective

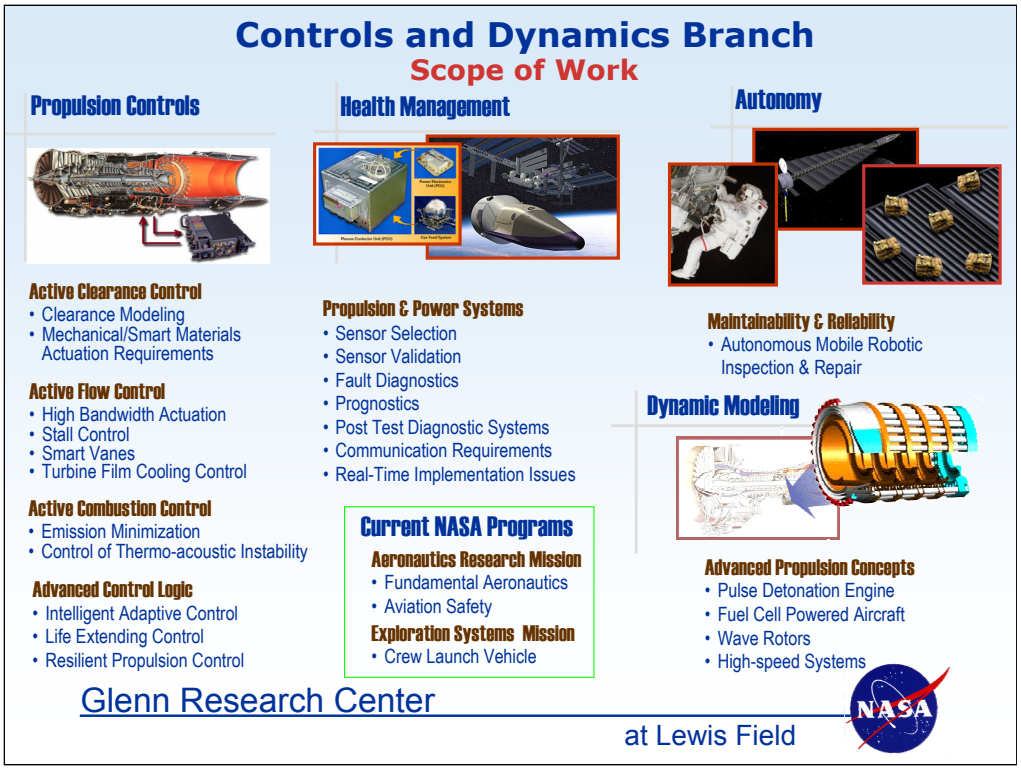
The control system enabling technologies for Intelligent Propulsion Systems are show above. These can be organized into three broad categories – active component control, advanced health management, and distributed fault tolerant control.

In the past engine components such as combustors, fans and compressors, inlets, nozzles 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 environment 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.

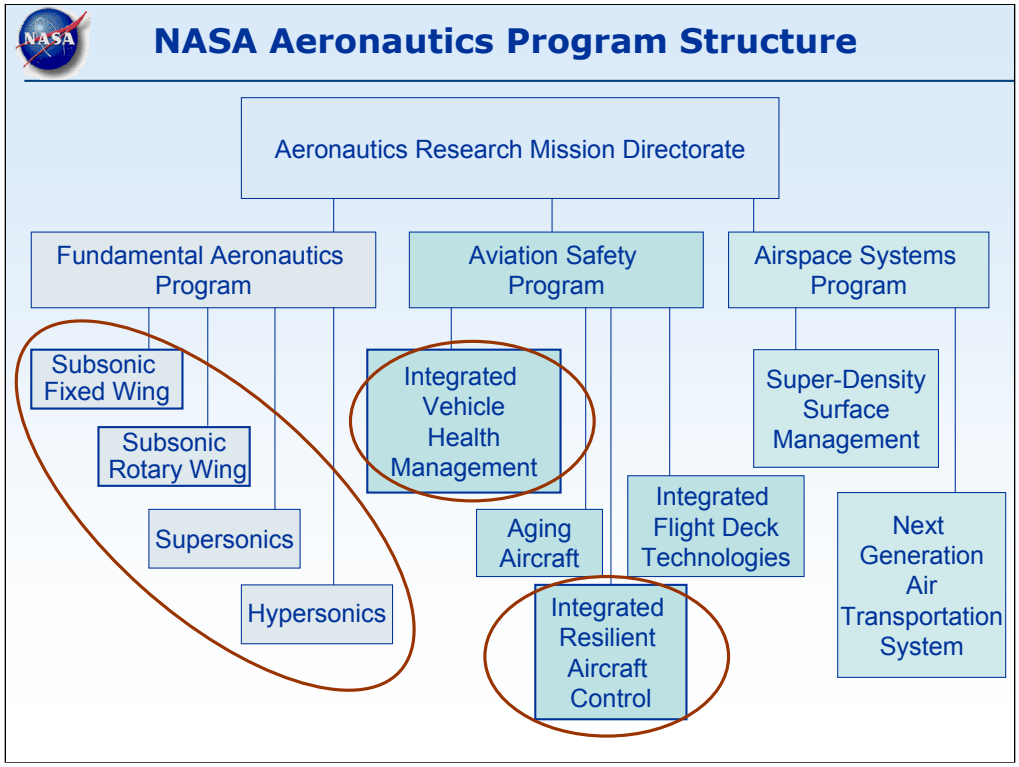
Implementation of of these concepts requires advancements in the area of robust and adaptive control synthesis techniques, and development of new hardware such as smart sensors and actuators. Attention will also need to be paid to integration of the active component control and diagnostics technologies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

Ref: Garg, S., "NASA Glenn Research in Controls and Diagnostics for Intelligent Aerospace Propulsion Systems," 2005 AIAA Infotech@Aerospace Conference, Arlington, VA, October 2005.




**Controls and Dynamics Branch – Scope of Work**

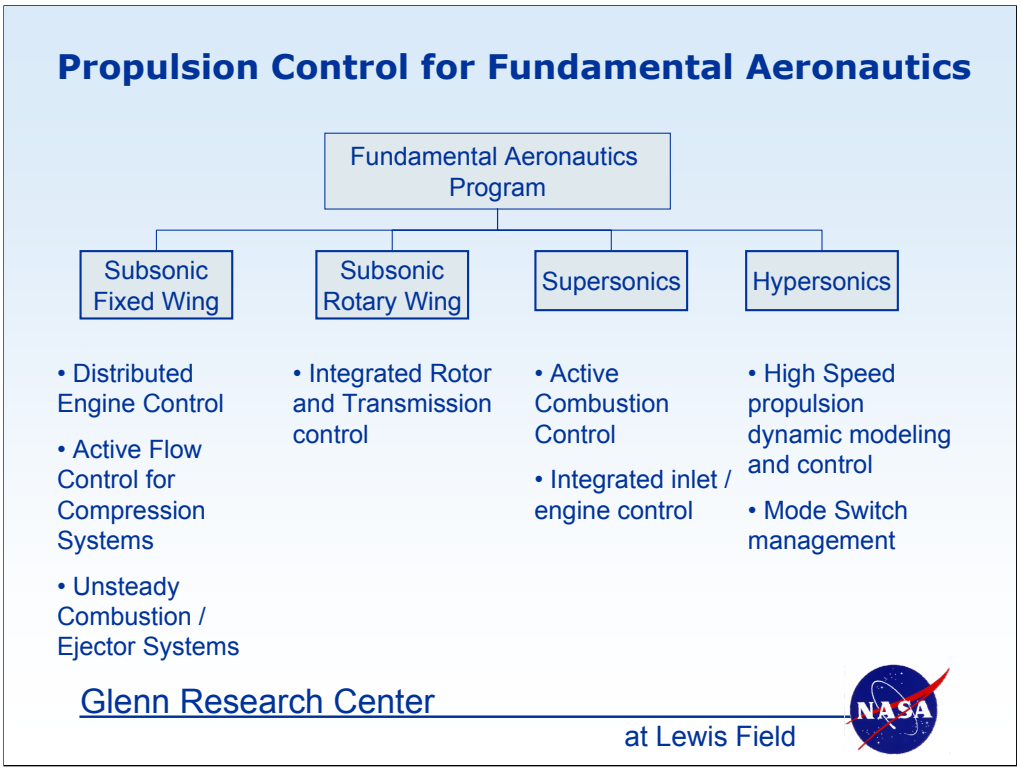
The CDB at GRC is actively involved in developing technologies that will help the aerospace industry make the concept of an "Intelligent Engine" into a reality. The main focus of CDB is in development of technologies for propulsion control, health management of propulsion and power systems, and dynamic modeling of advanced propulsion concepts. Additionally, the Branch is active in developing technologies for autonomous control of robotic systems. The various activities of the Branch in these areas are listed in the above figure. The NASA programs currently being supported by the CDB are highlighted on the chart.




## NASA Aeronautics Program Structure

The NASA Aeronautics programs have gone through a major restructuring in 2006 under the leadership of Dr. Lisa Porter, the new Associate Administrator for Aeronautics Research Mission Directorate. The restructuring is based on 3 guiding principles: NASA is dedicated to the mastery and intellectual stewardship of the core competencies of Aeronautics for the Nation in all flight regimes; Research will focus in areas that are appropriate to NASA's unique capabilities; NASA will directly address the needs of the Next Generation Air Transportation System (NGATS) in partnership with the member agencies of the Joint Planning and Development Office (JPDO).

The new Aeronautics program structure consists of 3 major programs: Fundamental Aeronautics (FA), Aviation Safety (AvS) and Airspace Systems, with each of these programs having 2 or more subprojects. The CDB activities are primarily under the various projects under FA (Subsonic Fixed Wing, Subsonic Rotary Wing, Supersonics, Hypersonics) and AvS (Integrated Vehicle Health Management (IVHM), Integrated Resilient Aircraft Control (IRAC)). The focus under FA is on developing new understanding and tools and techniques to enable design of revolutionary aeronautical vehicles. The focus under AvS is to develop tools and technologies that will enable multifold increase in aviation safety.




## Propulsion Control for Fundamental Aeronautics (FA)

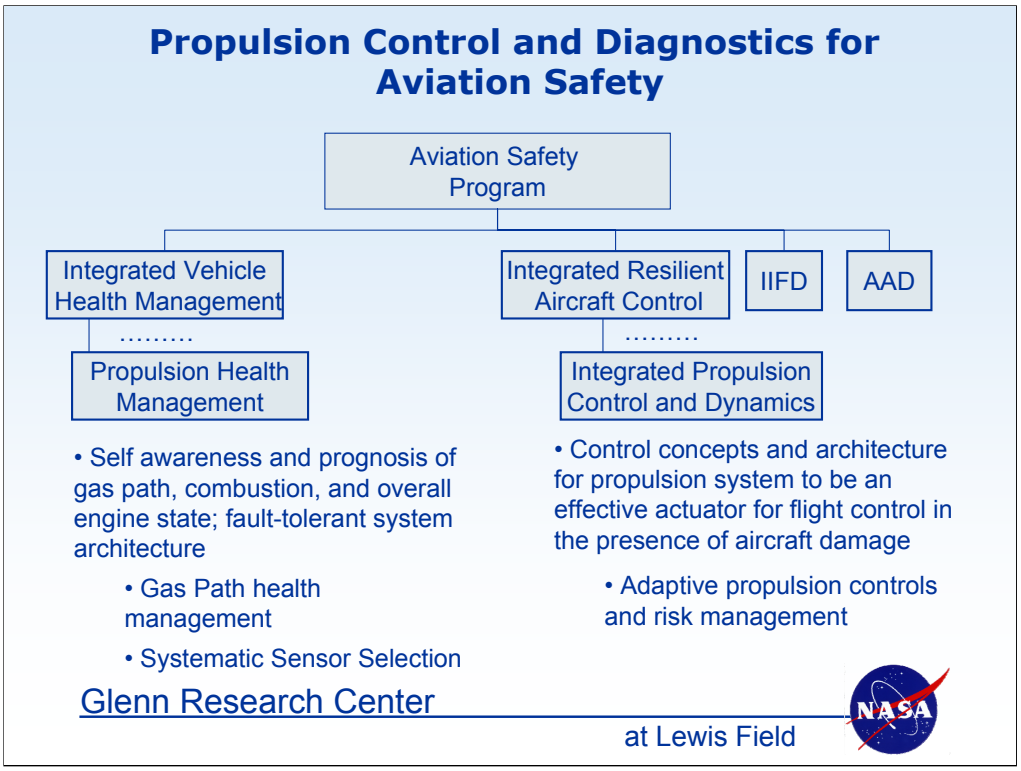
The CDB has tasks under all the four projects (Subsonic Fixed Wing (SFW), Subsonic Rotary Wing (SRW), Supersonics (SUP), and Hypersonics (HYP)) of the Fundamental Aeronautics program.

For the Subsonic Fixed Wing Project, the CDB activities are organized under the Controls and Dynamics element and consist of research in Distributed Engine Control (DEC), active flow control for compression systems, and unsteady combustion/ejector systems. The focus of these activities is to develop controls related technologies that will reduce the environmental impact, specially emissions, of aircraft engines.

For the Subsonic Rotary Wing project, the CDB activity is under the Flight Dynamics and Control element and consists of research to enable integrated rotor and transmission control for improved maneuverability of rotorcraft.

For the Supersonics project, CDB activity is under the Aero-Propulsion Servo-Elasticity element and consists of research on integrated inlet/engine control to minimize the affect of airframe flexible modes on engine thrust.

For the Hypersonics project, the CDB activity is under the Guidance, Navigation and Control element and consists of research in dynamic modeling and control of high speed propulsion systems, and inlet control for switching from supersonic to hypersonic mode. The emphasis here is to ensure reliable performance of the propulsion system throughout the various high speed operating modes.

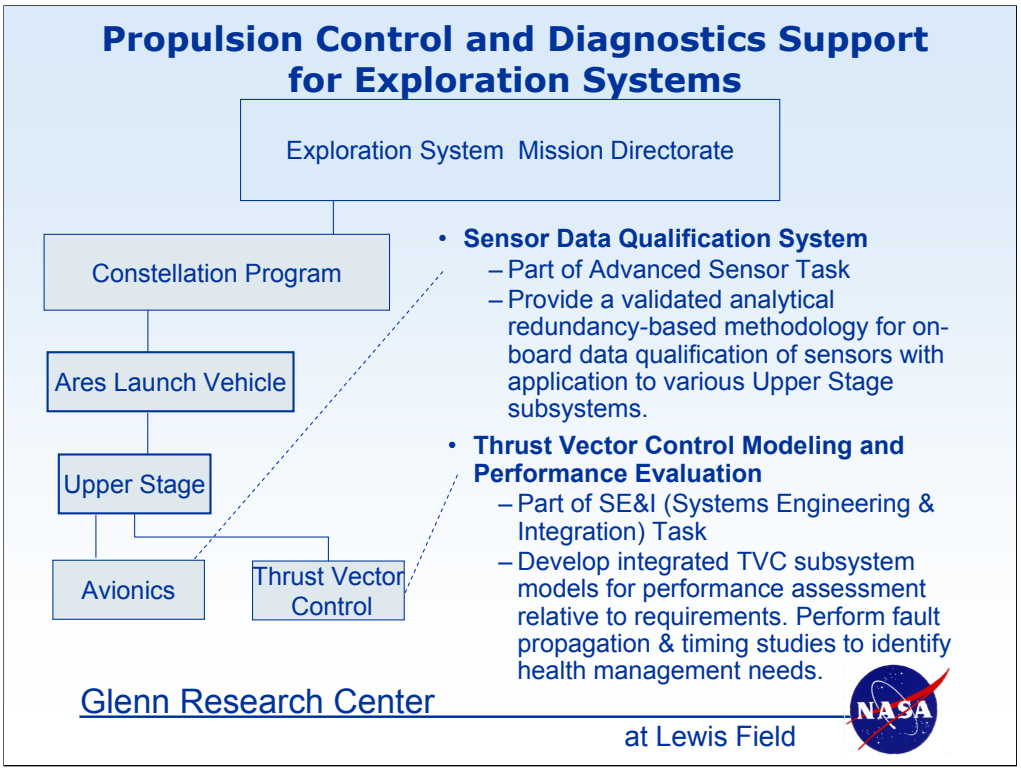



## Propulsion Control and Diagnostics for Aviation Safety (AvS)

The CDB has tasks under two of the projects (IVHM and IRAC) of the Aviation Safety program. Currently, members of the CDB also have the responsibility for the overall technical management of the Propulsion Health Management element under the IVHM project and the Integrated Propulsion Control and Dynamics element under the IRAC project.

The objective of the Propulsion Health Management element is to develop sensor and algorithm technologies that increase self-awareness and provide prognosis capabilities for the engine gas path, combustion, and overall engine system. The CDB activities under this element are focused on engine gas path health management to be able to reliably detect and isolate faults in sensors, actuators and engine components; and systematic sensor selection to identify what additional sensors beyond those currently used for gas path diagnostics can improve the diagnostics capability.

The objective of the Integrated Propulsion Control and Diagnostics element is to investigate control concepts and architectures that will enable effective use of the propulsion system as an actuator for flight control in the presence of damage to aircraft or flight control surfaces. The CDB activities under this element are focused on developing adaptive propulsion control and risk management that will provide enhanced engine response to meet the flight control requirements while ensuring that the engine can be safely operated for the desired period of time.

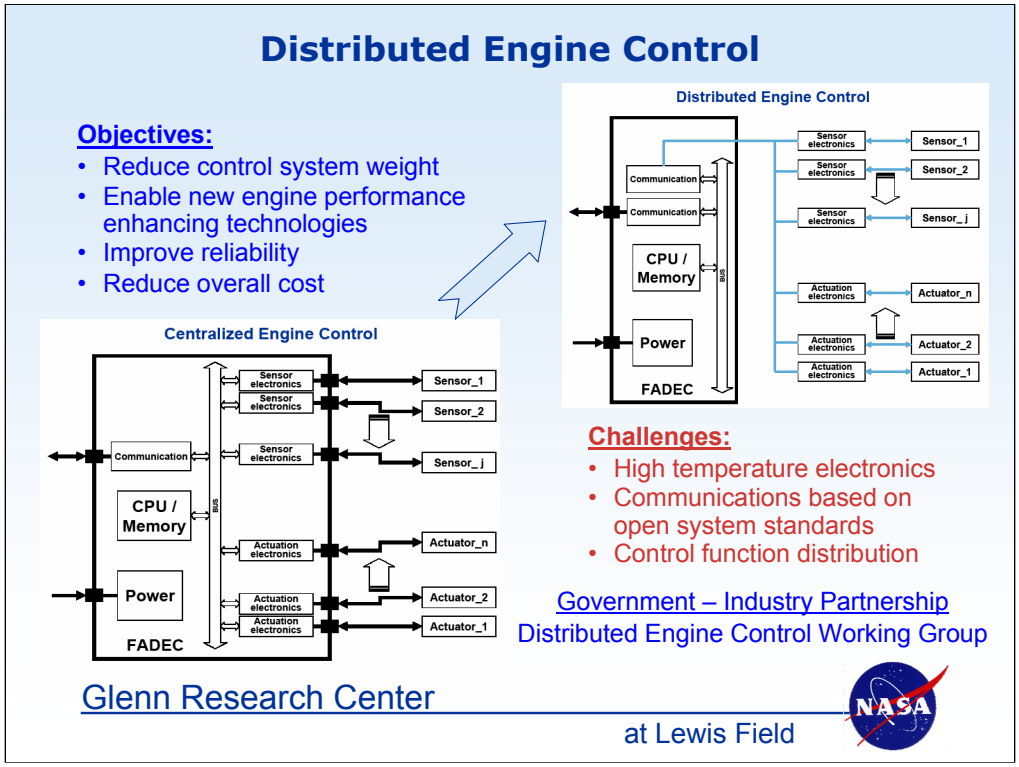



## Propulsion Control and Diagnostics Support for Exploration Systems

The NASA Exploration Systems Mission has the Constellation program as its main focus which consists of development of the Crew Launch Vehicle (named Orion), the Crew Launch Vehicle (named Ares) and the ground and space infrastructure for operation of Aries and Orion. The CDB role in the NASA Exploration Systems Mission is currently limited to support of Avionics and Thrust Vector Control elements of the Upper Stage for the Ares Launch Vehicle.

Under the Avionics element, CDB is developing a Sensor Data Qualification System (SDQS) which will provide a validated analytical redundancy-based methodology for on-board data qualification of sensors with potential application to various Upper State subsystems. This technology is expected to enhance the operability of the Upper Stage with a reduced requirement for hardware redundancy in sensors and improved capability to do on-board diagnostics.

Under the Thrust Vector Control (TVC) element, CDB is supporting the Systems Engineering and Integration task for the TVC actuation system. CDB is developing integrated TVC subsystem models to analyze performance of the TVC system relative to the thrust vectoring requirements for Upper Stage maneuvers and path control, performing fault propagation and timing studies to identify the needs for TVC health management system.



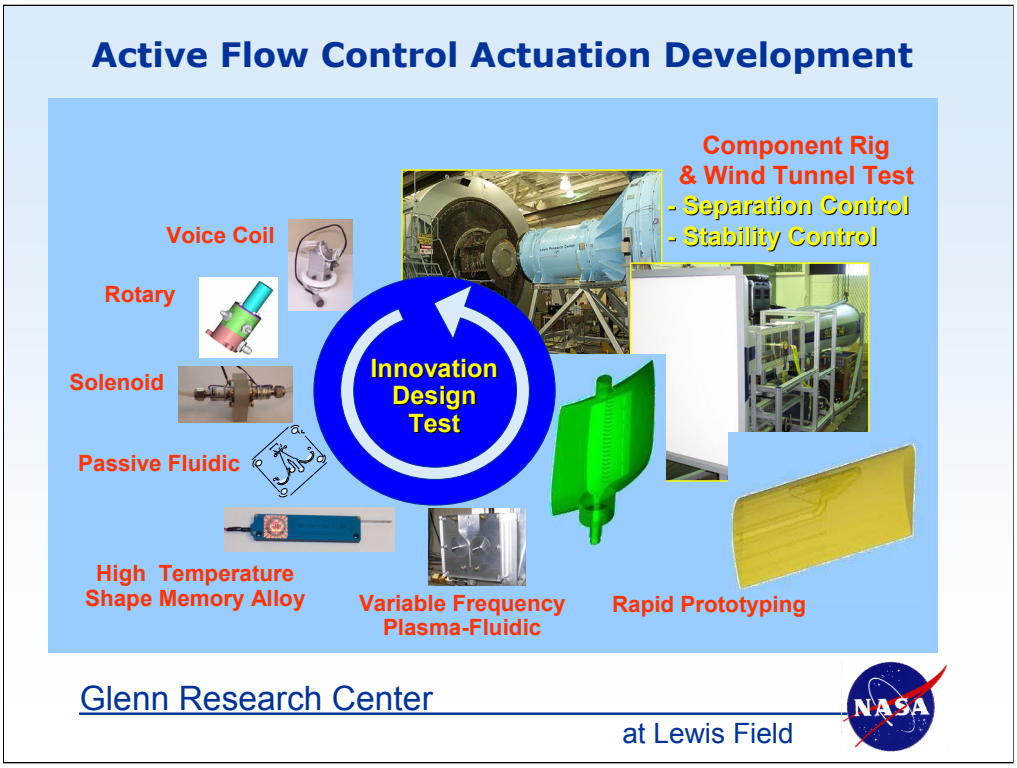

## Distributed Engine Control

Presently, engine control system architecture is based on a centralized design in which discrete sensors and effectors are directly wired to an engine-mounted electronics package. This avionics unit, often known as the Full Authority Digital Engine Control (FADEC), contains all the necessary circuitry to properly interface with engine control devices as well as cockpit command and data communications. The design of a centralized engine control system is primarily based on the single overriding concern of minimal control system weight because of its effect on overall vehicle performance.

In a distributed engine control (DEC) system architecture, any number of control elements are tied together through a common, standardized, communication interface. Sensors and effectors are replaced by control nodes which may provide sensor data, operate actuators, or perform combinations of both. The massive wiring harness which previously tied together the control element to interface circuitry in the engine-mounted avionics package is replaced by a simple but robust communication structure. Potential benefits of DEC include reduced control system weight, improved reliability, reduced operating cost, and flexibility to add new capability. Additionally, DEC is critical to integrate active component control technology with the overall engine system control.

CDB is working in collaboration with the aero-propulsion industry and major providers of FADEC technology under a Distributed Engine Control Working Group to help identify the key challenges for enabling DEC and provides directions for overall research.

Ref.: Behbahani, A., Culley, D. et al., "Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture," Paper 07ATC-267, SAE Aerotech Congress and Exhibition, Los Angeles, CA, Sept. 2007.



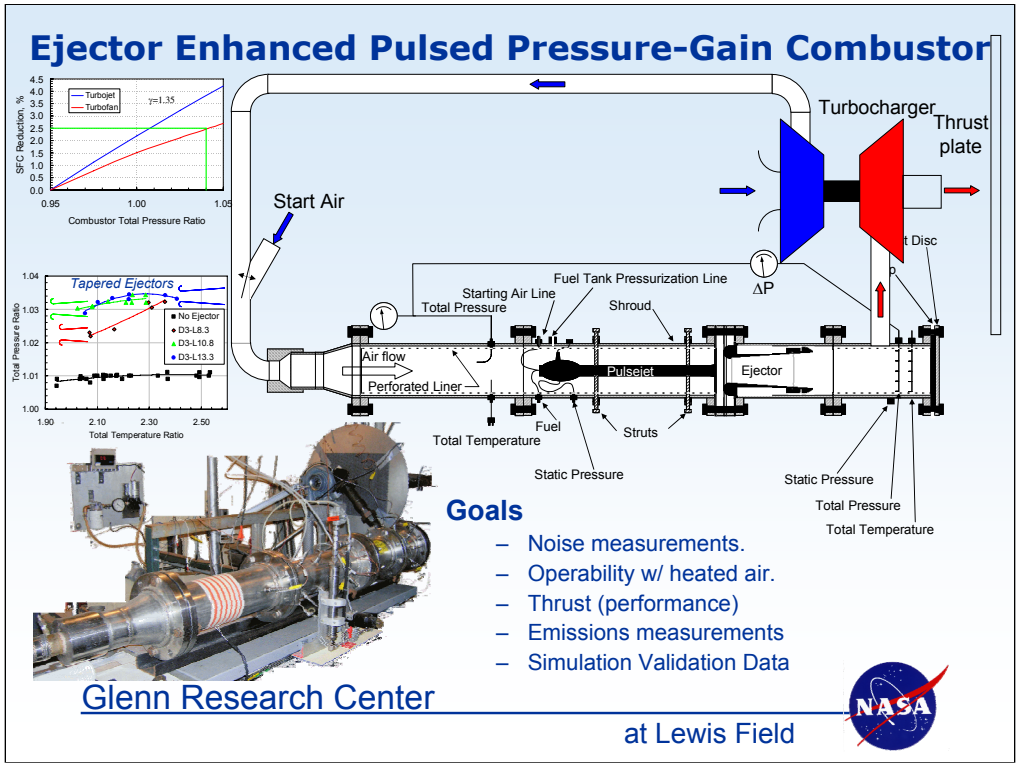

## Active Flow Control Actuation Development

Ongoing research activities at the GRC involve the investigation of active flow control technologies as applied to the internal aero-thermo-dynamic environment in a turbine engine. Active flow control involves the sensing of off-design conditions in the internal flow field which reduce engine efficiency and performance and applying corrective action to reduce or eliminate the condition. Corrective action is typically performed by air injection or aspiration and has been demonstrated to affect positive changes in such things as compressor stability, blade loading, and the distortion characteristics of inlets..

A major challenge to exploring and implementing active flow control in engine components is the lack of suitable actuation and control elements. Most current flow control investigations are carried out using the "brute force" method wherein existing commercial devices or concepts are crudely adapted to enable the exploration of simple first order effects over a limited range of study. Generally, little or no regard for feasibility is considered. The effect is two-fold; technology is demonstrated for which there is no known practical means of it being applied in a real-world environment, and quantifying the system benefits is difficult due to lack of information about the impact of implementation. The key to advancement in flow control technology is in the development of actuation (and sensing) devices which lend themselves to reliable and affordable implementation.

GRC is innovating new concepts in actuation technology that will lend themselves to integration in engine components where they would be most effective and carry the smallest penalty in terms of weight and power. These devices are based on new smart materials (high-temperature shape memory alloys and piezoelectrics) and high reliability methods (fluidics and plasma ).

Ref.: Culley, D., Braunscheidel, E., Bright, "Impulsive Injection for Compressor Stator Separation Control," AIAA-2005-3633, 41st Joint Propulsion Conference, July 10-13, 2005,Tucson, AZ.

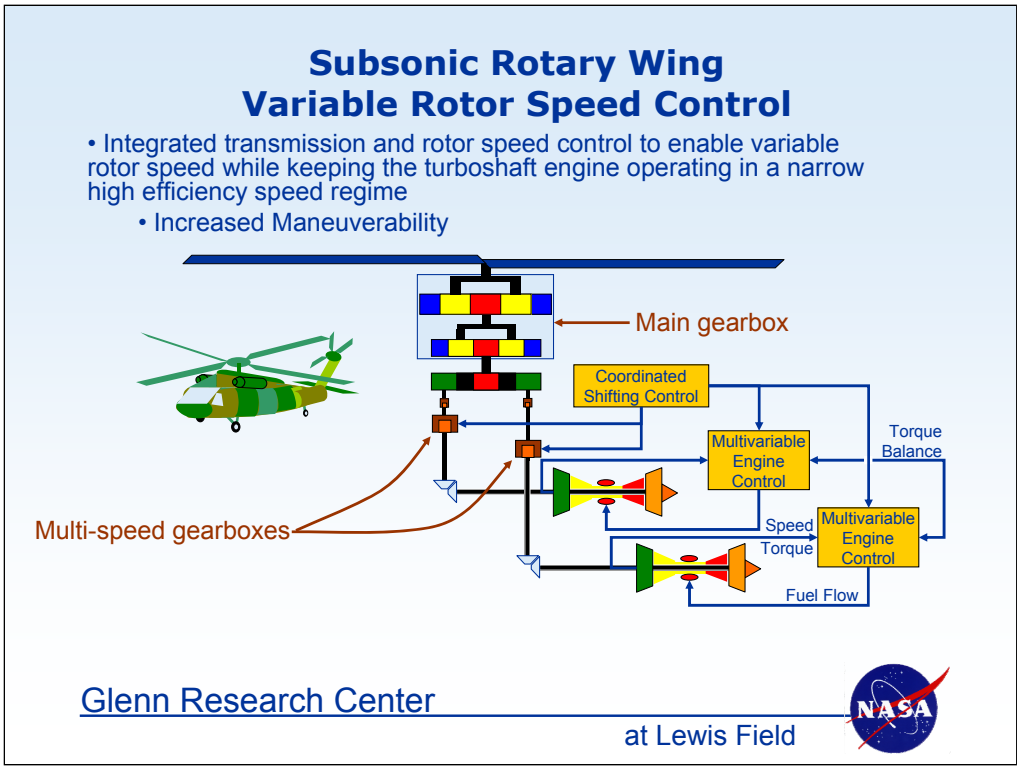



## Ejector Enhanced Pulsed Pressure-Gain Combustor

Pressure gain combustion has been under investigation for some time. The thermodynamic benefits of a pressure rise, rather than the usual 3 to 6% drop across the combustor are shown in the upper left plot. Here it is seen that a modest 4% rise, will reduce SFC by 2.5% in a modern turbofan application. In 2005, researchers at GRC presented a novel pressure gain combustor concept which capitalized on previously successful work with unsteady ejectors. Fundamentally, the combustor integrates a resonant pulsejet with an ejector inside a shroud. The ejector effectively mixes hot jet, and cooler bypass flow to present a relatively benign flow to a downstream turbine. Pressure ratios of 3.5% were obtained with this rig, as shown in the lower left plot which shows pressure ratio as a function of temperature ratio for the different ejectors tested.

Current research is focused on numerically modeling this type of device using the National Combustor Code (NCC), and in testing its operability in an actual gas turbine environment. The rig for the latter activity is shown schematically, and photographically above. Here a simple automobile turbocharger is shown coupled to the pressure-gain rig. The assembled unit has been operated with the compressor leg disconnected and with shop air supplied at the combustor inlet. Along with operability studies, it is hoped that turbine performance can be assessed. A key question with any unsteady combustion process is whether the (assumed) performance decrement from unsteadiness outweighs the thermodynamic benefit of pressure gain. The combustor concept shown above also holds the potential for low emissions since it can be operated as a Rich burn Quick quench Lean (RQL) combustion process. Emissions sampling is planned to verify this capability.

Ref.: Paxson, D.E, “Ejector Enhanced Pulsejet Based Pressure Gain Combustors: An Old Idea With a New Twist”, 41st Joint Propulsion Conference and Exhibit, Tucson, Arizona, July 10-13, 2005.



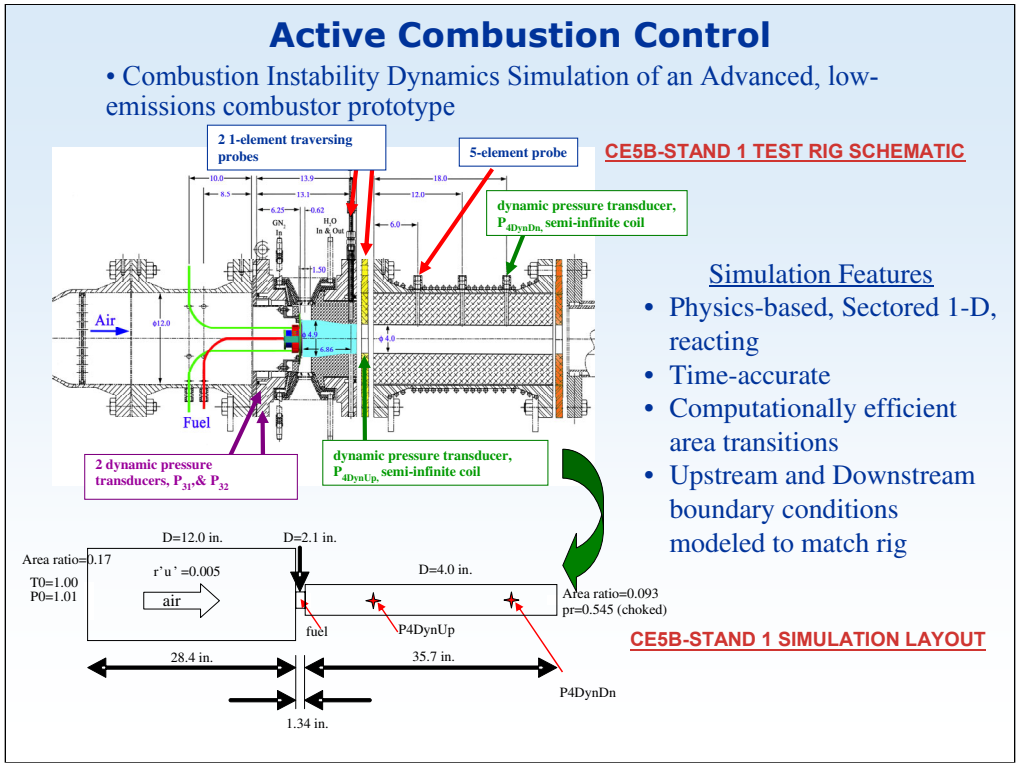

## Subsonic Rotary Wing – Variable Speed Control

Today's helicopters operate with a constant rotor speed, but future rotorcraft are anticipated to require variable rotor speed technology for heavy lift and high speed applications. Variable rotor speed, which is being investigated under NASA's Fundamental Aeronautics Subsonic Rotary Wing Program, is desirable for several reasons including improved maneuverability, agility, and noise reduction. However, it has been difficult to implement because turboshaft engines are designed to operate within a narrow speed band, and a reliable drive train that can provide continuous power over a wide speed range does not exist.

The new methodology, which is shown in the figure, is a sequential shifting control for twin-engine rotorcraft that coordinates the disengagement and engagement of the two turboshaft engines in such a way that the rotor speed may vary over a wide range, but the engines remain within their prescribed speed bands and provide continuous torque to the rotor. Two multi-speed gearboxes, which were added to a standard twin-engine configuration for this application, facilitate the wide rotor speed variation. The shifting process begins when one engine slows down and disengages from the transmission by way of a standard freewheeling clutch mechanism; the other engine continues to apply torque to the rotor. Once one engine disengages, its gear shifts, the multi-speed gearbox output shaft speed resynchronizes and it re-engages. This process is then repeated with the other engine. By tailoring the sequential shifting, the rotor may perform large, rapid speed changes smoothly.

Preliminary simulation results with timing determined by trial-and-error demonstrate that the approach is feasible. Work is continuing on a control law that will coordinate the engine speed commands and gear shifting to automate the rotor speed changing process.

Ref: Litt, J.S., Edwards, J.M., DeCastro, J.A., "A Sequential Shifting Algorithm for Variable Rotor Speed Control," American Helicopter Society 63rd Forum, Virginia Beach, VA, May 1-3, 2007.




## Active Combustion Control - Combustion Instability Dynamics Simulation

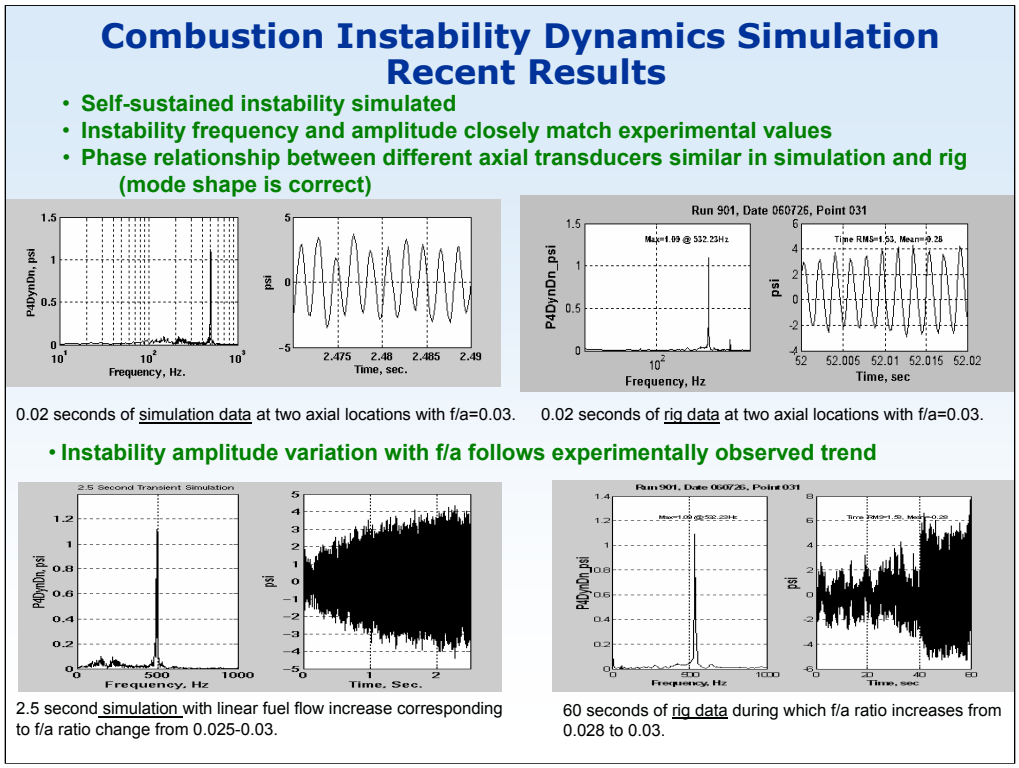
Previously, GRC, working in collaboration with industry and academia developed and demonstrated several key technologies for the active suppression of thermo-acoustic instability. These technologies included a high frequency fuel modulation valve, an actuator characterization rig, fuel delivery system dynamic models, combustion instability dynamic models, and control methods. A significant reduction in instability magnitude was demonstrated for both a high frequency (~500 Hz) engine-like instability and a lower frequency (~300 Hz) large amplitude instability. This was the first time such instability suppression had been demonstrated in an aero engine-like environment.

Current research is investigating the application of these instability suppression technologies to advanced ultra-low emissions combustors being designed by NASA and the aerospace industry. Key to the success of this effort are simulations that can capture the instability behavior of these advanced combustors.

A simulation has been developed which captures the thermo-acoustic instability behavior of an advanced, low-emissions combustor prototype as installed in the GRC CE5B flame tube. The simulation layout captures the relevant physical features of the combustor/rig. The physics-based simulation uses a Sectored 1-D approach, includes (simplified) reaction equations (as opposed to just an energy source term), and provides time-accurate results. A computationally efficient method is used for area transitions, which decreases run times.

Dynamic pressure "transducers" are at two different locations downstream of the fuel injector in both the rig and the simulation to allow the approximate mode shape to be captured and compared.

Ref.: DeLaat, J.C.; Chang, C.T.: "Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines," presented at the 16th International Symposium on Airbreathing Engines, NASA TM-2003-212611, ISABE-2003-1054, September 2003.




## Combustion Instability Dynamics Simulation – Recent Results

Comparison of the advanced, low-emissions combustor rig experimental data and the simulation data shows that the simulation captures the essentials of the dynamic behavior of the rig. The results show three important outcomes from the simulation:

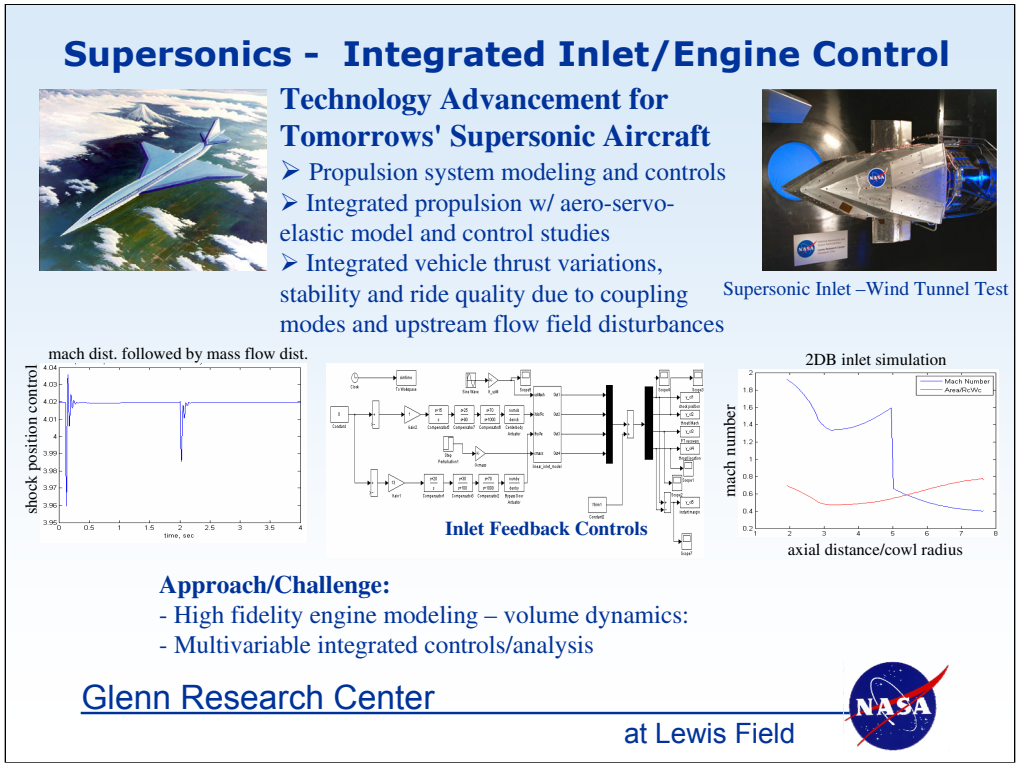
• The simulation exhibits a self-starting, self-sustained combustion instability. The instability is based strictly on the physics of the combustor and the coupling between heat addition and acoustics, that is, no forcing is required.

• As shown in the top pair of results, the simulated combustion instability closely matches the experimentally-observed combustion instability. The frequency and amplitude/shape of the instability closely agree as seen from amplitude spectrum and time history of combustor pressure.

• The bottom pair of results show that as fuel/air ratio is increased, the instability amplitude grows for both the simulation and the experimental combustor. This last outcome is particularly useful because currently the combustor is limited from achieving full-power operation due to instability increasing with increasing fuel/air. The simulation will be used, prior to testing with the combustor rig hardware, to investigate active instability suppression in order to enable full-power operation of the combustor

Comparing the pressure oscillations measured from pressure transducers at the two different axial locations showed the same phase relationship between the two locations in both the simulation and the experiment. This indicates that the correct oscillatory mode is being captured in the simulation. The simulation approach is documented in the reference below.

Ref.: Paxson, D.: "A Sectored-One-Dimensional Model for Simulating Combustion Instabilities in Premix Combustors," 38th Aerospace Sciences Meeting & Exhibit, AIAA-2000-0313, January 2000.



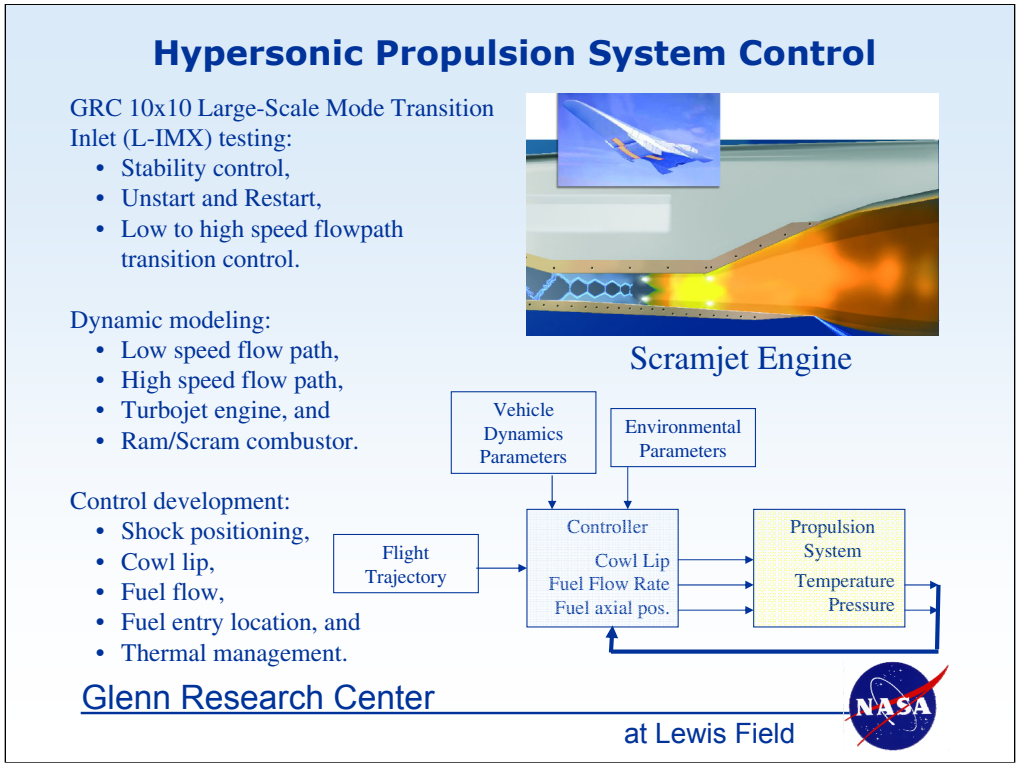

## Supersonics – Integrated Inlet/Engine Control

In supersonics, the overall objective is to perform the research and advance the technology, by 2012, so that the industry is in the position to develop supersonic cruise vehicles such as a civil transport. There are many technical challenges remaining for the supersonic vehicle technology development, such as emissions (NOx reduction), sonic boom reduction, fuel efficiency, materials, control and handling qualities, etc.

For the propulsion controls area, the objective is to design the control logic such that the integrated inlet/engine system is able to suppress upstream flow disturbances such as those due to atmospheric wind gusts, pitch and roll angle, as well as excitation modes coming from the slender body aircraft structure. The propulsion and integrated engine and aero-servo-elastic structure should not produce thrust variations that impact ride quality and aircraft stability.

The approach is to develop high fidelity propulsion system models - one dimension CFD for the inlet and stage-by-stage volume dynamics for the engine. These models will then be used to develop multivariable integrated control laws which meet the stringent performance requirements for inlet shock position control and minimizing thrust variations due to disturbances.

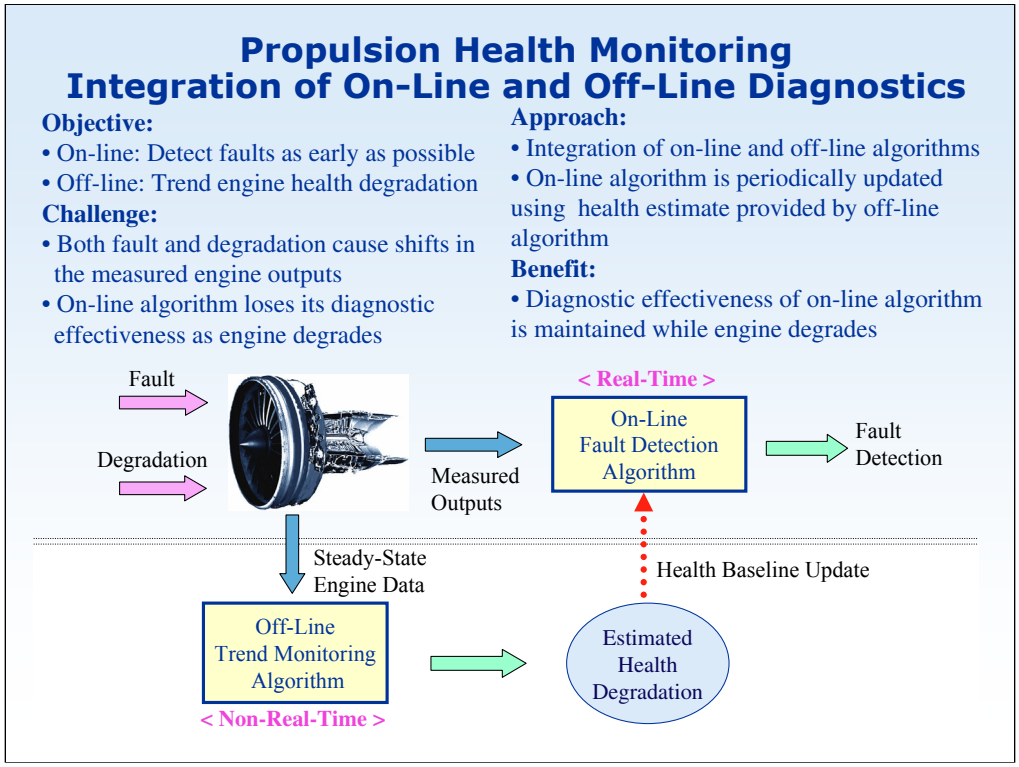
The inlet model is expected to be validated using the data from wind tunnel test. The figures show the typical Mach number axial distribution and results from a preliminary inlet shock position control design. The shock position control response due to upstream Mach number disturbance and downstream (at the engine phase) mass flow disturbance is shown.




## Hypersonic Propulsion System Control

Enabling High Mass Mars Entry Systems (HMMES) and Highly Reliable Reusable Launch System (HRRLS) are the two mission classes for focusing technology and methods development efforts under the NASA Hypersonic project. The focus of the GRC hypersonic propulsion control team is to support the HRRLS mission class by enabling air-breathing hypersonic vehicle flight.

The GRC hypersonic vehicle propulsion system control project is segmented into the following three elements: support the large scale mode transition inlet (L-IMX) testing; develop dynamic model of the high-speed propulsion system; and develop propulsion system control design to meet challenging requirements. The primary objective of the first element is to effectively transition from a low-speed turbine based propulsion system to a high-speed Ram/Scram combustor based propulsion system. This transition is a hypersonic flight enabling technological step. Controls will be instrumental for this activity to insure neither flow path unstarts, adequate pressure recovery is maintained, and thrust through the transition is smooth. To this end, a dynamic model will be needed to support controller design. Furthermore, dynamic models will be needed for the complete hypersonic propulsion system to support future vehicle designs and control studies; which is the second element. The third element, control design, is highly dependent on having good dynamic models that capture the essential physics of the system to be controlled. To date, the hypersonic systems tested in flight or test-stands have been point designs with open-loop control. The challenge is to formulate the propulsion control problem such that it provides for easy integration with the vehicle control.

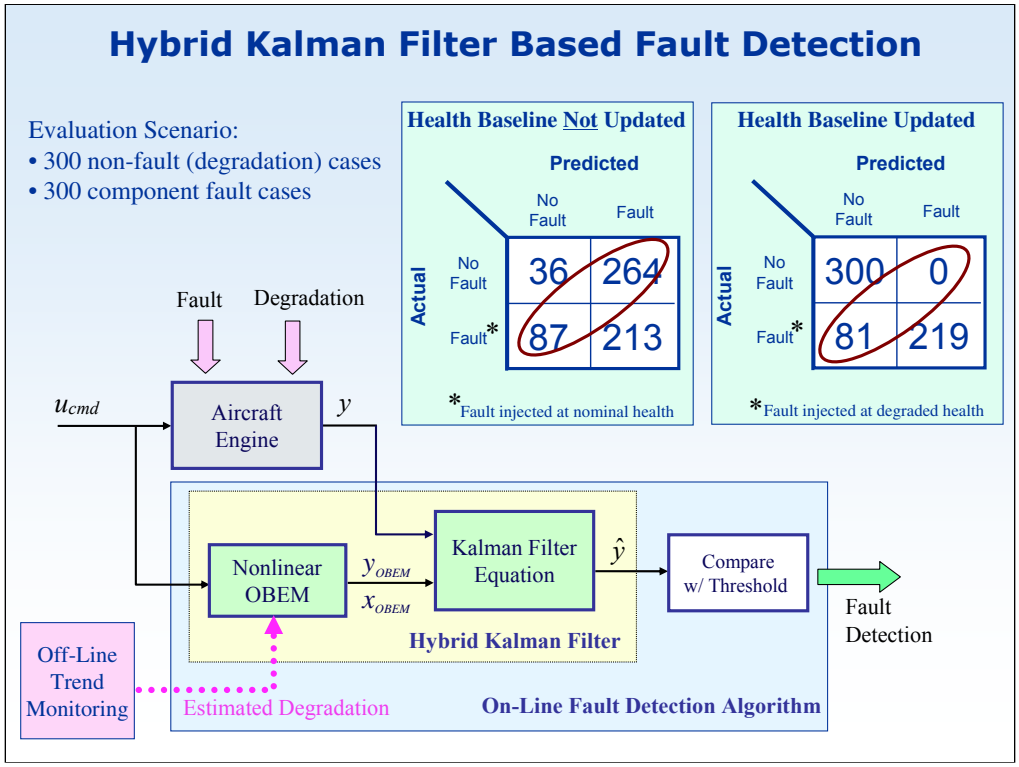



## Propulsion Health Monitoring
## Integration of On-Line and Off-Line Diagnostics

For engine gas path diagnostics, the objective is to detect faults as early as possible. To achieve this objective, the on-line algorithm continuously monitors engine outputs for anomalous signature induced by faults. The on-line algorithm must address a challenge in achieving reliable performance. This challenge arises from the fact that the measured engine outputs are influenced not only by faults but also by engine health degradation. Engine health degradation is a normal aging process that all aircraft engines will experience, and therefore it is not considered as a fault. Without a capability to discern the difference between fault-induced and degradation-induced measurement shifts, the on-line algorithm eventually loses its diagnostic effectiveness as the engine degrades over time.

To address this challenge, CDB has developed an approach wherein the on-line algorithm is integrated with the off-line trend monitoring algorithm. The objective of the off-line algorithm is to trend engine health degradation over the engine's lifetime. The off-line algorithm periodically estimates engine health degradation based on steady-state engine output data recorded during flight.

The estimated health degradation is used to update the health baseline (design health condition) of the on-line algorithm. Through this update, the on-line algorithm becomes aware of health degradation, and its effectiveness to detect faults can be maintained while the engine continues to degrade over time.



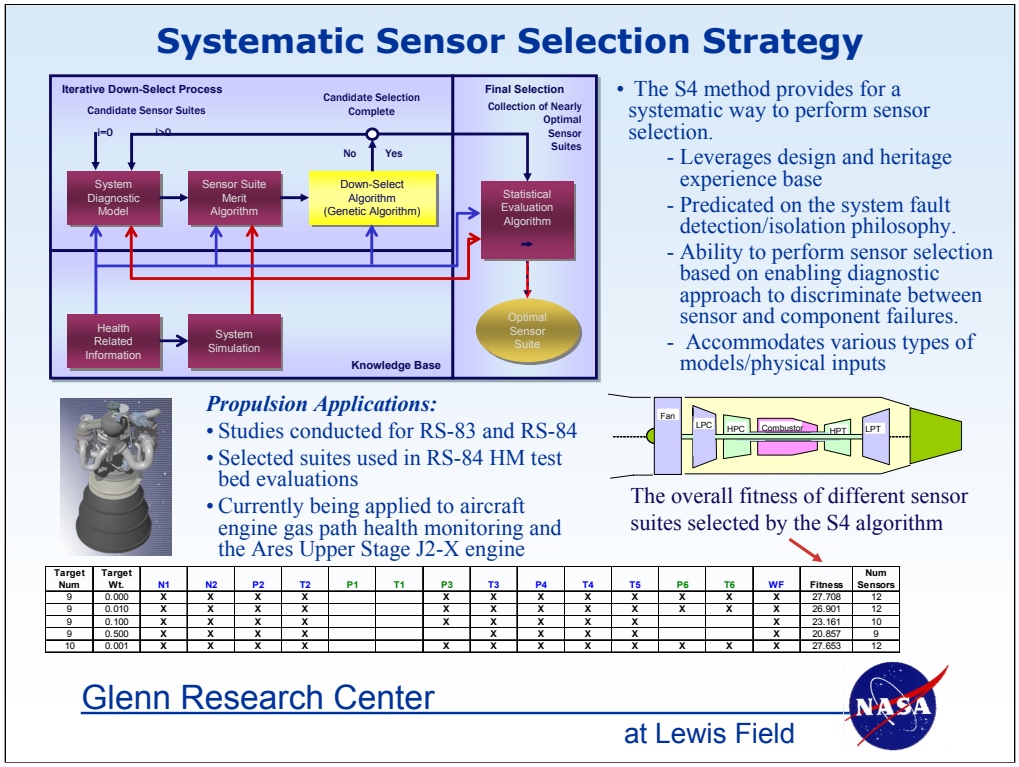

## Hybrid Kalman Filter Based Fault Detection

The on-line fault detection algorithm is based on the hybrid Kalman filter (HKF) approach. The HKF is a hybrid of a nonlinear on-board engine model (OBEM) and the linear Kalman filter equation. The main advantage of the HKF over the conventional piecewise linear Kalman filter is that the health baseline is updated through a relatively simple procedure by feeding the estimated health degradation values into the OBEM.

The diagnostics algorithm was evaluated using an engine simulation representative of a modern commercial turbofan engine. The on-line algorithm's capability to avoid false alarms was evaluated using 300 non-fault (degradation) cases. The evaluation was conducted for two conditions: 1) health baseline not updated and 2) health baseline updated. When the health baseline was not updated, the on-line algorithm incorrectly diagnosed health degradation as a fault in 264 cases out of 300 (88% false alarm rate). When the health baseline was updated, the on-line algorithm did not generate a false alarm.

The on-line algorithm's capability to detect faults was evaluated using 300 component fault cases. When the health condition of the engine and the health baseline of the on-line algorithm are at the nominal health (no health baseline update), the on-line algorithm detected 213 cases out of 300 (71% detection rate). When the health condition of the engine and the health baseline of the on-line algorithm are at degraded and estimated health conditions (health baseline updated), the on-line algorithm detected 219 cases out of 300 (73% detection rate). The example shows that updating the health baseline of the on-line algorithm does not result in any degradation of the fault detection capability.

Ref.: Kobayashi, T., and Simon, D., "Integration of On-Line and Off-Line Diagnostic Algorithms for Aircraft Engine Health Management," 2007 ASME Turbo Expo, Montreal, Canada, May 2007.



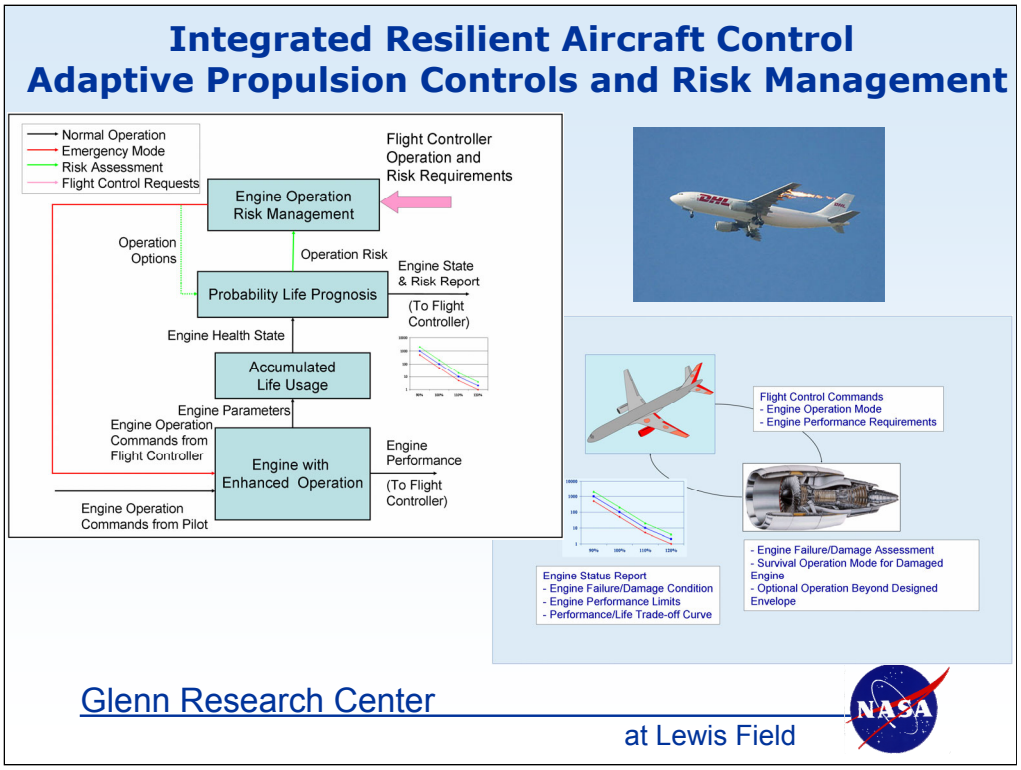

| Target Num | Target Wt. | N1 | N2 | P2 | T2 | P1 | T1 | P3 | T3 | P4 | T4 | T5 | P6 | T6 | WF | Fitness | Num Sensors |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 0.000 | X | X | X | X | | | X | X | X | X | X | X | X | X | 27.708 | 12 |
| 9 | 0.010 | X | X | X | X | | | X | X | X | X | X | X | X | X | 26.901 | 12 |
| 9 | 0.100 | X | X | X | X | | | X | X | X | X | X | | | X | 23.161 | 10 |
| 9 | 0.500 | X | X | X | X | | | | X | X | X | X | | | X | 20.857 | 9 |
| 10 | 0.001 | X | X | X | X | | | X | X | X | X | X | X | X | X | 27.653 | 12 |

## Systematic Sensor Selection Strategy

Sensor data are the basis for performance and health assessment of most complex systems. Careful selection and implementation of sensors is critical to enable high fidelity system health assessment. The CDB has developed a model-based procedure, termed the Systematic Sensor Selection Strategy (S4), that systematically selects an optimal sensor suite for overall health assessment of a designated host system. S4 can be logically partitioned into three major subdivisions: the knowledge base, the down-select iteration, and the final selection analysis. The knowledge base required for productive use of S4 consists of system design information and heritage experience together with a focus on components with health implications. The sensor suite down-selection is an iterative process for identifying a group of sensors that provide good fault detection and isolation for targeted fault scenarios.

The S4 approach was applied for sensor selection for health management of the Rocketdyne RS-84 engine concept under the NASA Next Generation Launch Vehicle technology program. The process identified a suite of 22 sensors from a candidate set of 59 sensors that maximized risk reduction potential. Currently, S4 is being applied to aircraft engine gas path health monitoring with the objective of identifying which additional sensors, beyond the ones currently used for engine control and health monitoring, will help improve the fault detection and isolation. The preliminary results in the chart above show the effect of adding new sensors on the merit algorithm being used for the aircraft engine application. For the results above, 14 sensors were considered including 9 typical FADEC sensors (shown in blue) plus 5 optional sensors (shown in green), and the S4 methodology was applied to determine the capability to detect 10 typical engine faults.

Ref.: Maul, W., Kopasakis, G., et al., “Sensor Selection and Optimization for Health Assessment of Aerospace Systems”, AIAA-2007-2849, AIAA Infotech@Aerospace 2007 Conference and Exhibit, Rohnert Park, California, May 7-10, 2007

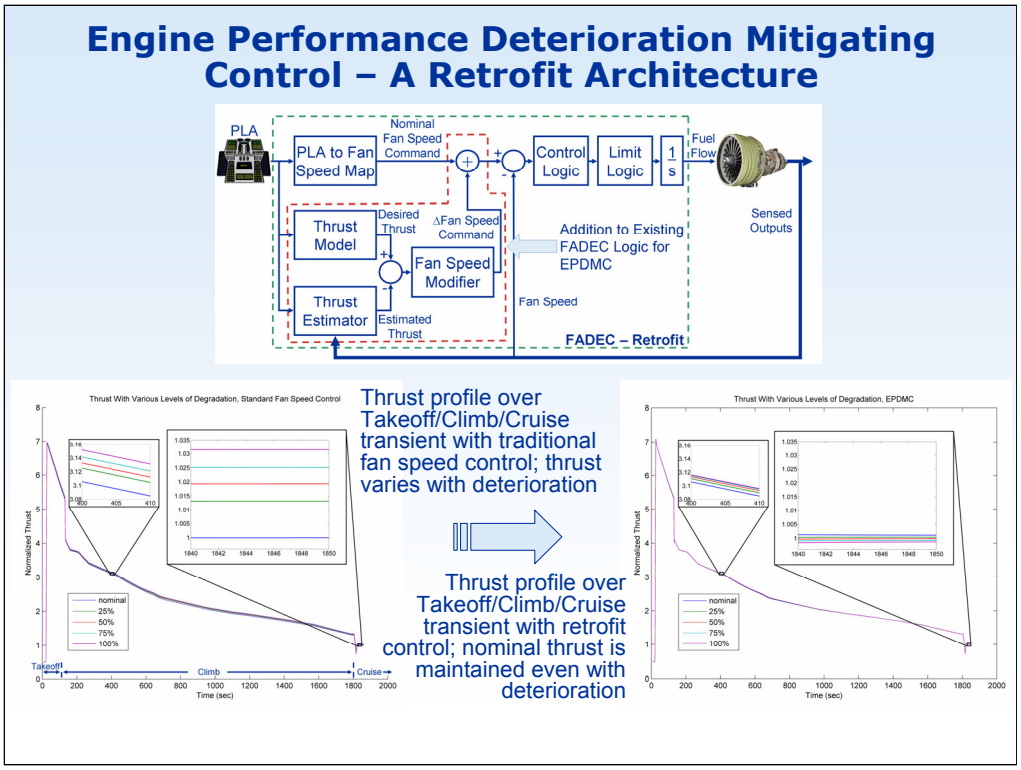



# Integrated Resilient Aircraft Control
# Adaptive Propulsion Controls and Risk Management

Real life aviation situations and past research have demonstrated that the propulsion system can be an effective flight control actuator in emergency situations, such as when hydraulic power is lost. While gas turbine engines are designed to provide sufficient safety margins to guarantee robust operation with an exceptionally long life, engine performance requirements may be drastically altered during abnormal flight conditions or emergency maneuvers. In some situations, the conservative design of the engine control system may not be in the best interest of overall aircraft safety; it may be advantageous to "sacrifice" the engine to "save" the aircraft. Motivated by this, the NASA Aviation Safety Program's Integrated Resilient Aircraft Control project is conducting propulsion control and dynamics research aimed at developing adaptive engine control methodologies to operate the engine beyond the normal domain to provide the enhanced thrust response needed for emergencies.

Several approaches are being pursued to achieve this goal. New ways to use existing actuators such as bleed valves and variable stator vanes, which are currently scheduled based on operating point, are being investigated to improve dynamic response. Also, adaptive propulsion control research is being conducted to study the impact of relaxing controller limits that affect engine life and operability for emergency operation. Relaxing limits would allow an engine to produce more thrust more quickly, but at the cost of consumed component life, enabling situation-dependent controller modifications to be implemented. Prognostic algorithms which estimate the risk of continued operation in the enhanced thrust mode would be incorporated, and can be used to determine the optimal safe landing strategy for the given scenario in real time.

Ref: Guo, T.-H., Litt, J.S., "Resilient Propulsion Control Research for the NASA Integrated Resilient Aircraft Control (IRAC) Project," AIAA-2007-2802, AIAA Infotech@Aerospace Conference, Rohnert Park, CA, May 7-10, 2007.



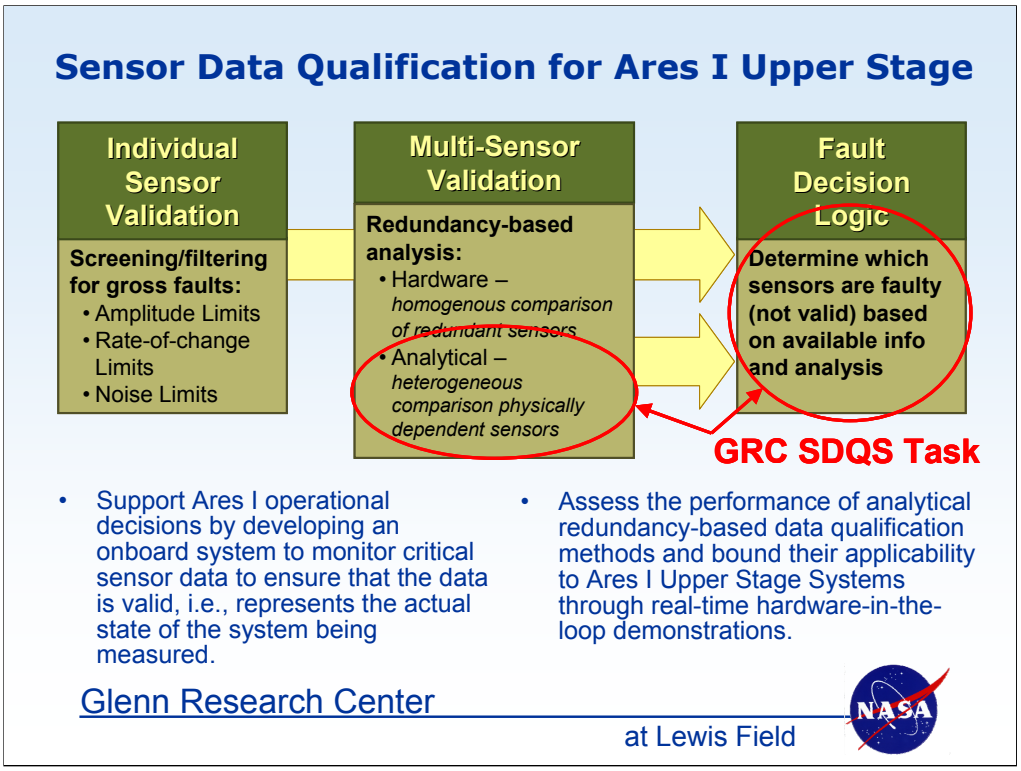

## Engine Performance Deterioration Mitigating Control A Retrofit Architecture

As an aircraft engine deteriorates with usage, there is noticeable change from the throttle setting to the thrust response. In a workshop sponsored by NASA to identify technology development needs for reducing pilot workload and increasing autonomy with respect to operation of aircraft engines, various pilots stated that the asymmetric thrust, caused by this deteriorated engine response, causes additional workload for them in having to make adjustments to individual throttles in a multi-engine aircraft. Since thrust is not measurable, typical engine control consists of tracking a fan speed command based on a throttle setting. The fan speed to thrust relationship varies with engines due to manufacturing tolerances and changes as the engines deteriorate with usage. For a multi-engine aircraft, this difference in fan speed to thrust relationship results in variations in throttle to thrust response for different engines.

The engine performance deterioration mitigation control (EPDMC) currently being developed at GRC, as part of the Integrated Resilient Aircraft Control project, provides a retrofit approach which leverages the existing FADEC logic. The main elements of EPDMC Outer Loop control are: i) A thrust estimator which provides an accurate estimate of the engine thrust based on available sensor measurements and actuator commands; ii) Thrust demand logic which estimates the thrust that a "nominal" engine will generate for a given throttle setting; and iii) a PI (Proportional plus Integral) control which provides an incremental fan speed command to the FADEC to compensate for the difference between estimated thrust and thrust demand.

The EPDMC approach has been applied to an engine simulation representative of a modern commercial aircraft engine and has been shown to maintain throttle to thrust response in the presence of engine degradation with usage.

Ref.: Litt, J.S., Sowers, T.S., Garg, S., "A Retro-fit Control Architecture to Maintain Engine Performance with Usage," XVIII ISABE Conference, Beijing, China, September 3-7, 2007.



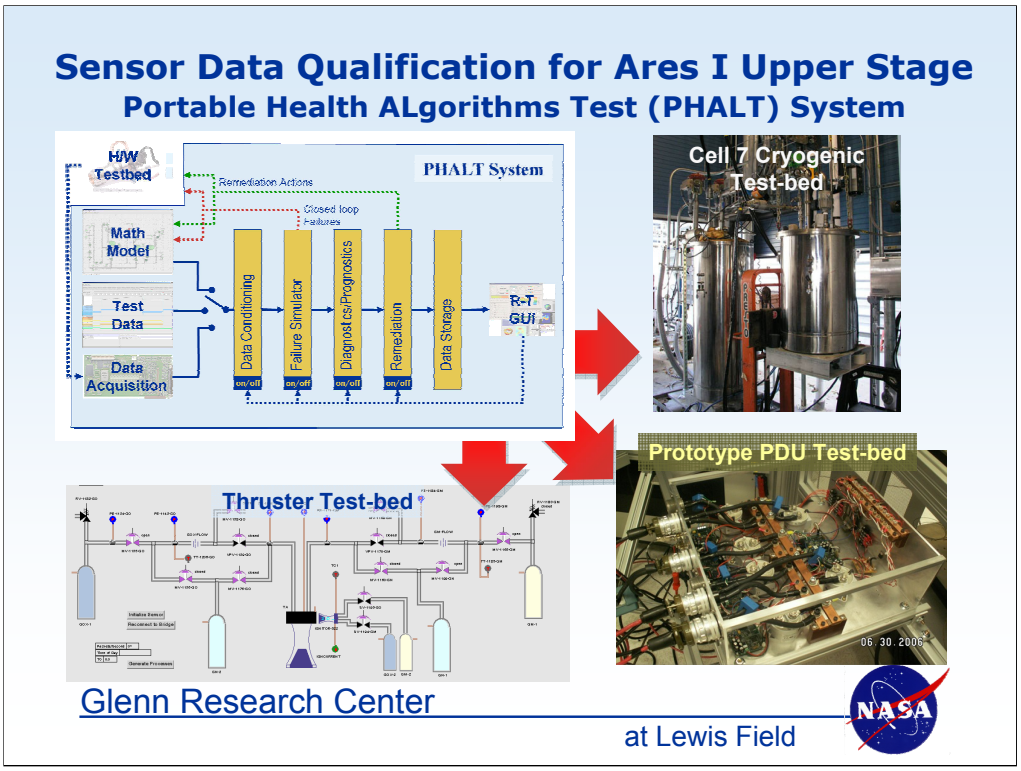

## Sensor Data Qualification for Ares I Upper Stage

Sensor data qualification is the process of analyzing sensor data to ensure that it accurately represents the state of the system being measured. The CDB at GRC is currently supporting the application of sensor data qualification methods to the upper stage of the new Ares I manned launch vehicle. The approach would extend the state-of-the-art, from red-lines and reasonableness checks that flag a sensor after it fails, to include analytical redundancy-based methods that can identify a sensor in the process of failing. The objectives of this effort are two fold.

The first objective is derived from the Ares I System Requirements Document. R.CLV.53 requires that detected failures that indicate an abort condition be confirm by ensuring that the detection system itself has not failed. This can be potentially be accomplished through one or more approaches, including the collaboration of different physical measurements (analytical redundancy).

The second objective builds on the first and is focused on understanding the proper application of analytical redundancy-based data qualification methods for onboard use in monitoring upper stage sensors. As part of a preliminary design phase, feasibility studies are being conducted to assess the performance and bound the applicability of these methods in a real-time context by applying them to test-beds that have relevance to Upper Stage systems.

Ref.: Maul, W.A.; Melcher, K.J.; Chicatelli, A.J.; and Sowers, T.S.: “Sensor Data Qualification for Autonomous Operation of Space Systems ,” Proceedings of the American Association for Artificial Intelligence 2006 Fall Symposium on Spacecraft Autonomy, October 13-15, 2006. AAAI Technical Report FS-06-07: 59-66.

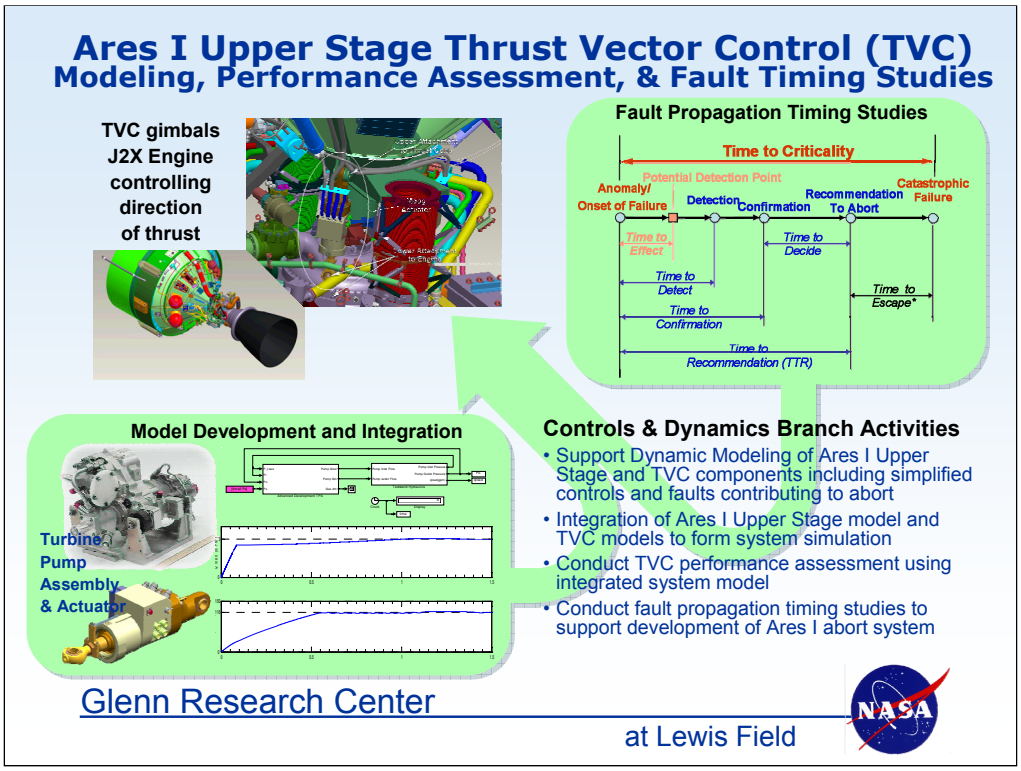



## Sensor Data Qualification for Ares I Upper Stage Portable Health Algorithms Test (PHALT) System

In order to apply the Sensor Data Qualification (SDQ) approach to various test-beds, it was first necessary to develop a real-time monitoring hardware/software platform. To meet that need, NASA developed the Portable Health ALgorithms Test (PHALT) system. It was also necessary to identify and obtain access to relevant test-beds. This proved more of a challenge than expected. Most test-beds have limited instrumentation and little or none of the sensor redundancy found in space flight. A number of test-beds were considered and most were deemed unusable for reasons including but not limited to: lack of sufficient analytical redundancy; lack of potential to increase redundancy; lack of real-time access to the sensor data.

As of this report, several studies have been completed. In the late FY06, SDQ algorithms were applied - first using real-time test data playback, then via hardware-in-the-loop to a Power Distribution Unit Test-bed that is a prototype for the Orion crew exploration vehicle. Real-time test data playback has also been used to demonstrate the methods with a small thruster test-bed located at Stennis Space Center and the Cell 7 cryogenic facility at Glenn Research Center. A hardware-in-the-loop test relevant to the Ares I main propulsion system is planned for the summer of 2007. These test are addressing various issues related to SDQ, eg.: Which is better, one large or several small sensor networks?; Can the failure of a sensor used for closed-loop feedback be clearly identified in a timely manner?; Can the SDQ algorithms be executed within the limits of space computational hardware (lines of code, CPU usage, memory requirements etc.)?

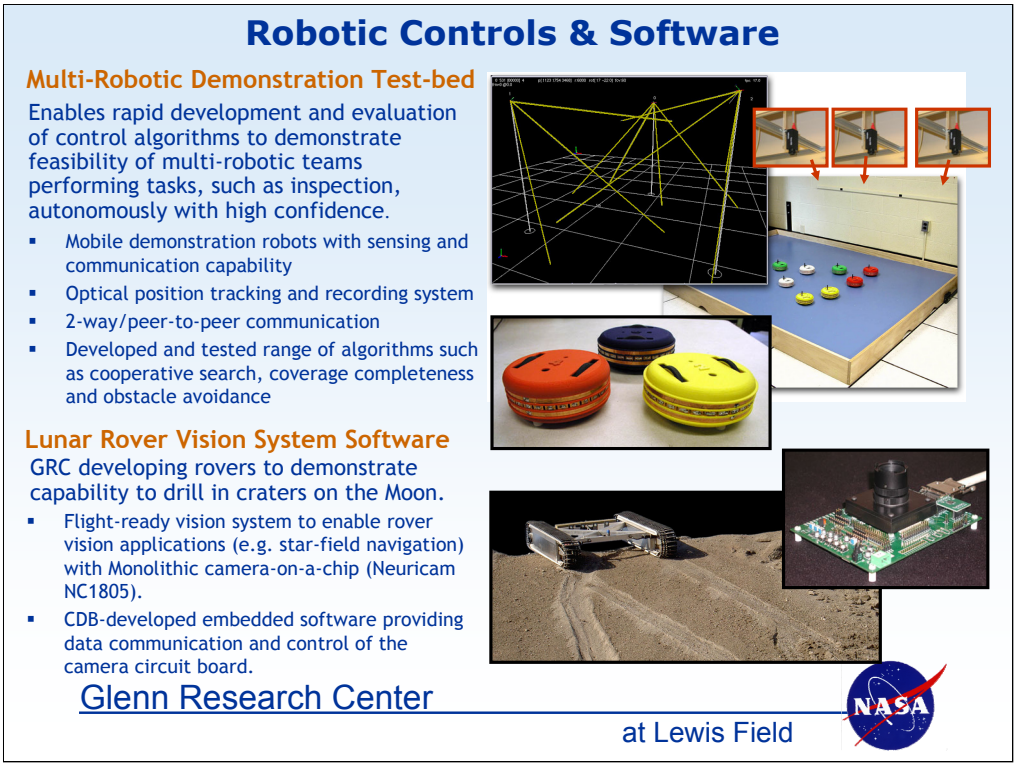
Ref.: Melcher, K.J.; Fulton, C.E.; Maul, W.A.; Sowers, T.S.: "Development and Application of a Portable Health Algorithms Test System," 54th Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting, May 14-18, 2007.




## Ares I Upper Stage Thrust Vector Control (TVC) Modeling, Performance Assessment, & Fault Timing Studies

In the current design of the Ares I Upper Stage (US), a Thrust Vector Control (TVC) system is used to gimbal the US engine, thus controlling the direction of the thrust. The TVC design effort is being led by GRC. As currently planned, the TVC consists of three primary components: actuator, hydraulic, and turbine pump assembly. The actuator subsystem includes two actuators (rock and tilt) offset 90-degrees to gimbal the engine in two dimensions (a reaction control system is used to control roll). The hydraulic subsystem provides power to the actuators. The turbine pump assembly is driven by propellant from the main propulsion system and provides power to the hydraulic system.

The CDB is supporting the design of the TVC system through two efforts: Dynamic modeling and Control performance Assessment; and, Fault Propagation Timing Studies. Under the first task, CDB is supporting other GRC organizations that are developing models of US and TVC components. CDB will then integrate these models to create an integrated TVC system model and will also integrate the TVC model with the US model. CDB will then use integrated US/TVC model to conduct assessments focused on ensuring the TVC system design can meet current performance requirements. CDB will also use the TVC system model to conduct fault propagation timing studies focused on providing early data needed to develop fault detection, decision, and response algorithms. The fault timing study is being coordinated with the Ares abort management effort being led by Ames Research Center. The TVC fault timing study will determine the high probability TVC subsystem faults and how these propagate through the upper stage systems. This will allow the onboard abort logic to calculate the resulting time available to make an abort decision should one of those failures occur.




## Robotic Controls and Software

CDB is leveraging its controls and real-time software development expertise to enable robotic technology in a variety of applications at GRC. In one effort, a robotics demonstration test-bed has been constructed that will allow robotics researchers to implement and test collaborative multi-robotic algorithms on a real hardware system and enable them to validate the feasibility of using autonomous robotic sensor platforms to perform high-confidence inspection operations. Researchers under this effort have developed and tested a range of algorithms to address pertinent control objectives such as cooperative search, coverage completeness and obstacle avoidance. Algorithms range from those that require centralized coordination and communication to those that take a more distributed approach.

In another effort, CDB is applying its controls and software experience to enable GRC and its partners to demonstrate the ability of robotic rovers to explore and drill the icy craters at the Moon's poles in future NASA missions. Key to these rovers' ability to navigate and localize their positions will be the ability to sense the surroundings. To address this, GRC is developing a flexible, flight-ready vision system that will enable applications such as star field navigation. The system is comprised of a monolithic camera-on-a-chip sensor supported by a custom-designed circuit board that interfaces with a radiation hardened single-board computer. CDB is instrumental in developing the embedded microcontroller software that provides data communication and control of the camera circuit board.

Ref.: Wong, E., Saad, A and Litt, J. S., "Towards Autonomous Inspection of Space Systems Using Mobile Robotic Sensor Platforms," AIAA Space 2006 Conference, San Jose, CA, September 2006.

## Concluding Remarks

- The Controls and Dynamics Branch is conducting cutting edge research in propulsion control and diagnostics in support of NASA Aeronautics Research and Exploration Systems Missions.
  - Active component control approaches such as active combustion control and active flow control for compression systems, and distributed engine control architecture are critical enabling technologies to meet the challenging goals of reducing aircraft engine emissions
  - Integrated control of inlet and engine systems is key for achieving safety and performance goals of high speed propulsion systems
  - Intelligent propulsion control and diagnostics can significantly increase aircraft safety and improve operational reliability of space launch systems
- It is essential that the controls and diagnostics expertise be integrated early into the system concept development to enable system intelligence in the design.
- A multidisciplinary cross-organizational collaborative approach is essential for successful development and demonstration of Intelligent Propulsion System technologies
- A system level approach is essential to ensure that various components of a control or diagnostic system work together as an integrated system to achieve the desired objectives

Glenn Research Center

at Lewis Field

# Concluding Remarks

The Controls and Dynamics Branch at GRC is working in strong partnership with industry, academia and other government agencies to develop the propulsion control and health management technologies that will help make the vision of "Intelligent Propulsion Systems" a reality to enable NASA's Space Exploration and Aeronautics Research Mission objectives. Our aim is to use the public resources in a most efficient manner to make a significant contribution to the aggressive goals that have been set by the administrator in the latest strategic plan for NASA, and to ensure that our activities are aligned with the goals of the NASA Missions that we participate in. We take a systems level approach to ensure that the various components of a control or diagnostic system work together as an integrated system to achieve the desired objectives.

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**13. SUPPLEMENTARY NOTES**

**14. 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. Also the propulsion systems required to enable the National Aeronautics and Space Administration (NASA) Vision for Space Exploration in an affordable manner will need to have high reliability, safety and autonomous operation capability. The Controls and Dynamics Branch (CDB) at NASA Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with other organizations within GRC and across NASA, the U.S. aerospace industry, and academia to develop advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. This paper describes the current activities of the CDB under the NASA Aeronautics Research and Exploration Systems Missions. The programmatic structure of the CDB activities is described along with a brief overview of each of the CDB tasks including research objectives, technical challenges, and recent accomplishments. These tasks include active control of propulsion system components, intelligent propulsion diagnostics and control for reliable fault identification and accommodation, distributed engine control, and investigations into unsteady propulsion systems.

**15. SUBJECT TERMS**
Engine control; Health management; Adaptive control; Intelligent systems; Fault diagnostics

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