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Propulsion Controls and Diagnostics Research in Support of NASA Aeronautics and Exploration Mission Programs

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NASA STI Program . . . in Profile

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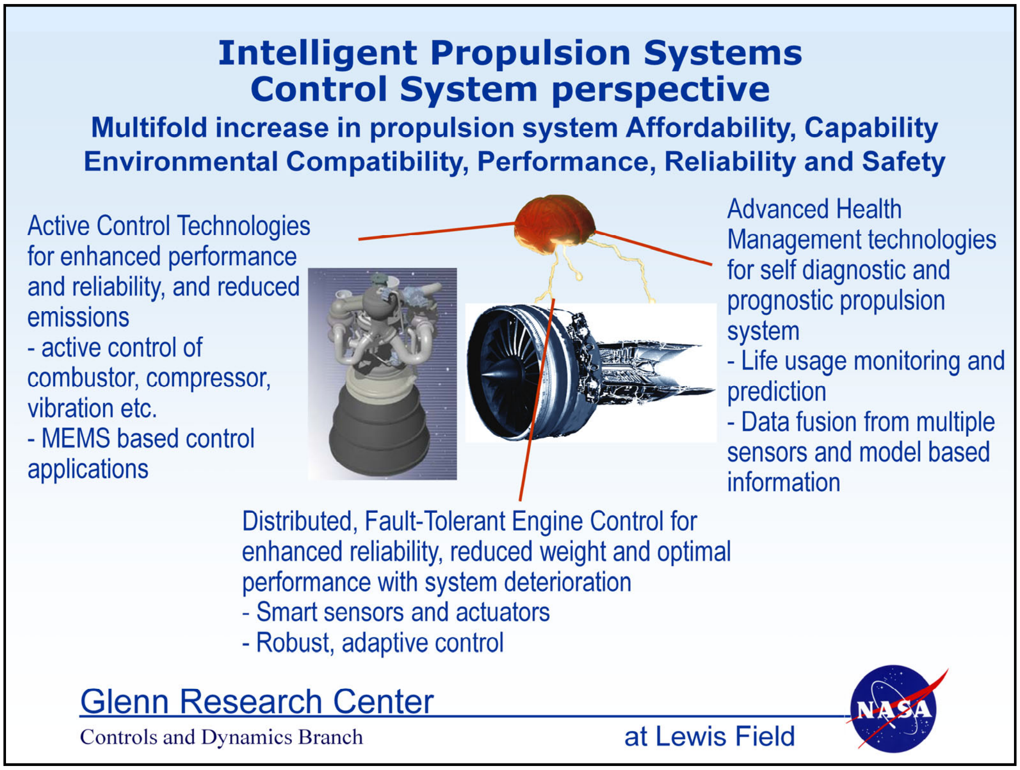
Abstract

The Controls and Dynamics Branch (CDB) at National Aeronautics and Space Administration (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 propulsion controls and diagnostics technologies that will help meet the challenging goals of NASA programs under the Aeronautics Research and Exploration Systems Missions. This paper provides a brief overview of the various CDB tasks in support of the NASA programs. 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

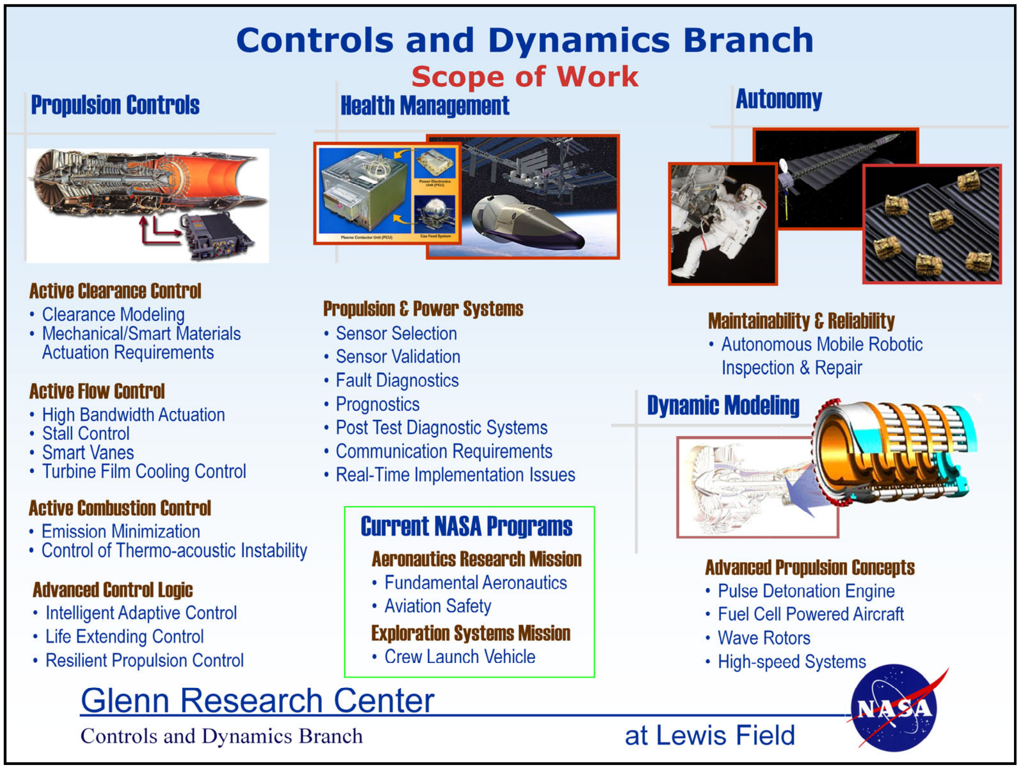
The control system enabling technologies for Intelligent Propulsion Systems are show above. These can be organized into three broad categories—active component control, advanced health management, and distributed fault tolerant control.

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.

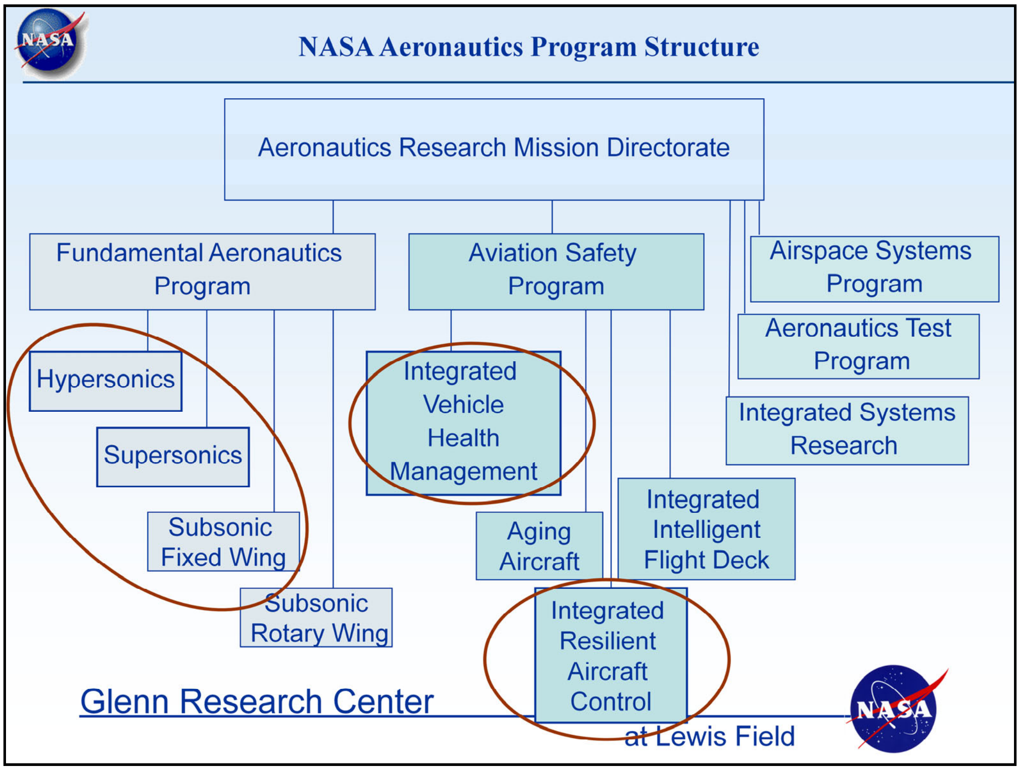
Implementation of these concepts requires advancements in the area of robust and adaptive control synthesis techniques, and development of new hardware such as smart sensors and actuators. Attention will also need to be paid to integration of the active component control and diagnostics technologies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

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

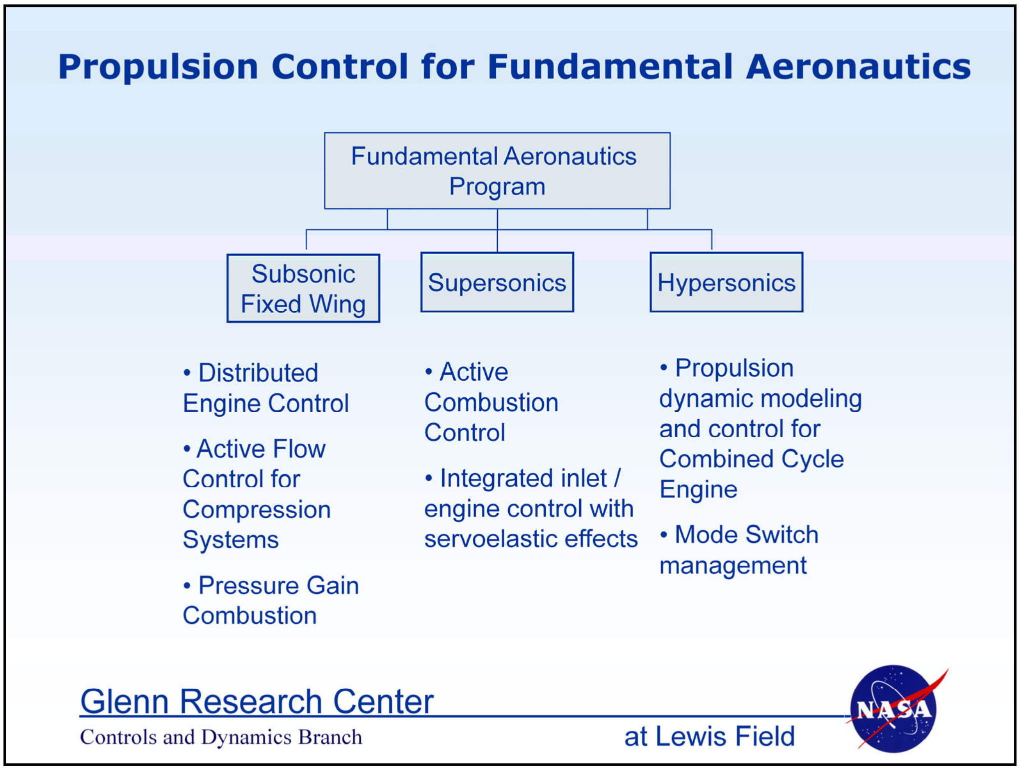


NASA Aeronautics Program Structure

The NASA Aeronautics programs went through a major restructuring in 2006 under the leadership of the then Associate Administrator (AA) for Aeronautics Research Mission Directorate (ARMD). The restructuring was based on three 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 program structure was further modified under the current ARMD AA in response to feedback received from the industry to have NASA play a stronger role in development of mid to higher TRL (Technology Readiness Level) technologies.

The current Aeronautics program structure consists of five major programs: Fundamental Aeronautics (FAP) , Aviation Safety (ASP), Airspace Systems, Aeronautics Test, and Integrated Systems Research, with each of these programs having two or more subprojects. The CDB activities are primarily under the various projects under FAP (Subsonic Fixed Wing, Supersonics, Hypersonics) and ASP (Integrated Vehicle Health Management (IVHM), Integrated Resilient Aircraft Control (IRAC)). The focus under FAP is on developing new understanding and tools and techniques to enable design of revolutionary aeronautical vehicles. The focus under ASP is to develop tools and technologies that will enable multifold increase in aviation safety. CDB also has a small role in one of the projects , Environmentally Responsive Aviation, under the new Integrated Systems Research Program.

It is worthwhile to note here that a new structure for the Aviation Safety Program is currently under development and will be implement in the 2011 Fiscal Year. However, the CDB research activities are expected to continue under the new structure.



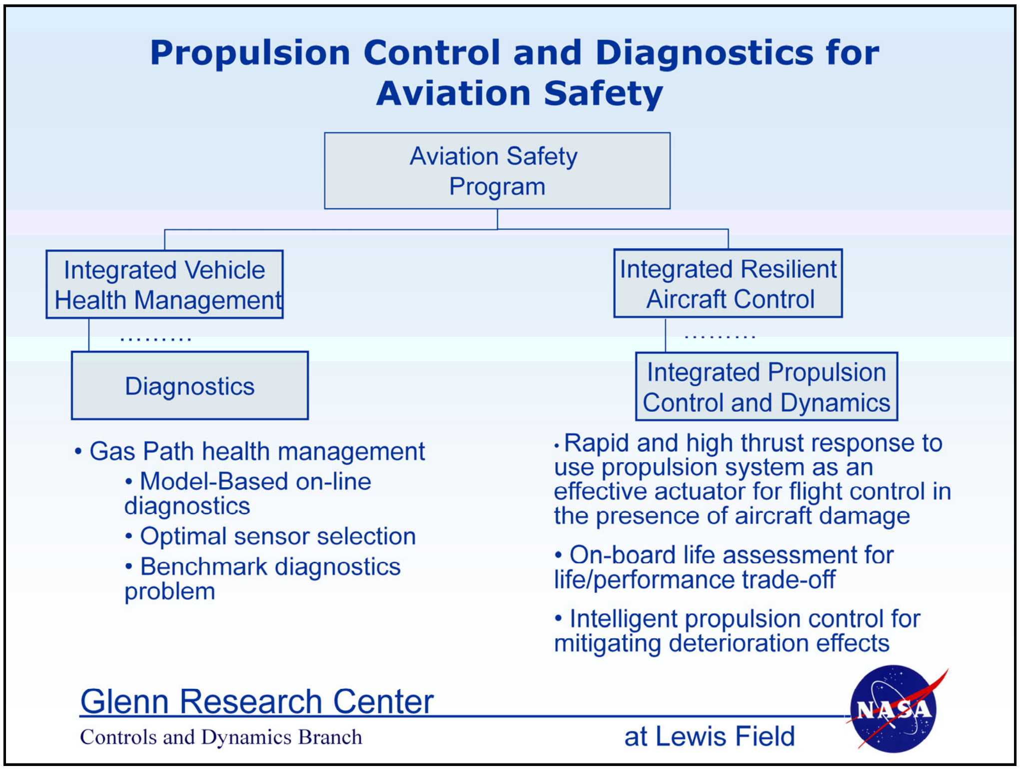
Propulsion Control for Fundamental Aeronautics Program (FAP)

The CDB has tasks under three projects (Subsonic Fixed Wing (SFW), 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 pressure gain combustion systems. The focus of these activities is to develop controls related technologies that will reduce the environmental impact, specially emissions, of aircraft engines. The DEC and the pressure gain combustion efforts are described in this paper. The active flow control research effort is mainly focused on development of numerical models of fluidic actuation devices and is expected to come to an end in the current fiscal year.

For the Supersonics project, CDB activities are active combustion control research to enable safe operation of low emissions combustors throughout the operating envelope, under the High Altitude Emissions element, and research on integrated inlet/engine control to minimize the affect of airframe flexible modes on engine thrust, under the Aero-Propulsion Servo-Elasticity element. The active combustion control research is also supported by the ERA (Environmentally Responsive Aviation) project under the new Integrated Systems Research Program, with a focus on collaborating with industry to mature the technology.

For the Hypersonics project, the CDB activity is under the Guidance, Navigation & Control (GN&C) element and consists of research in propulsion system dynamic modeling and control for CCE (Combined Cycle Engine), 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.

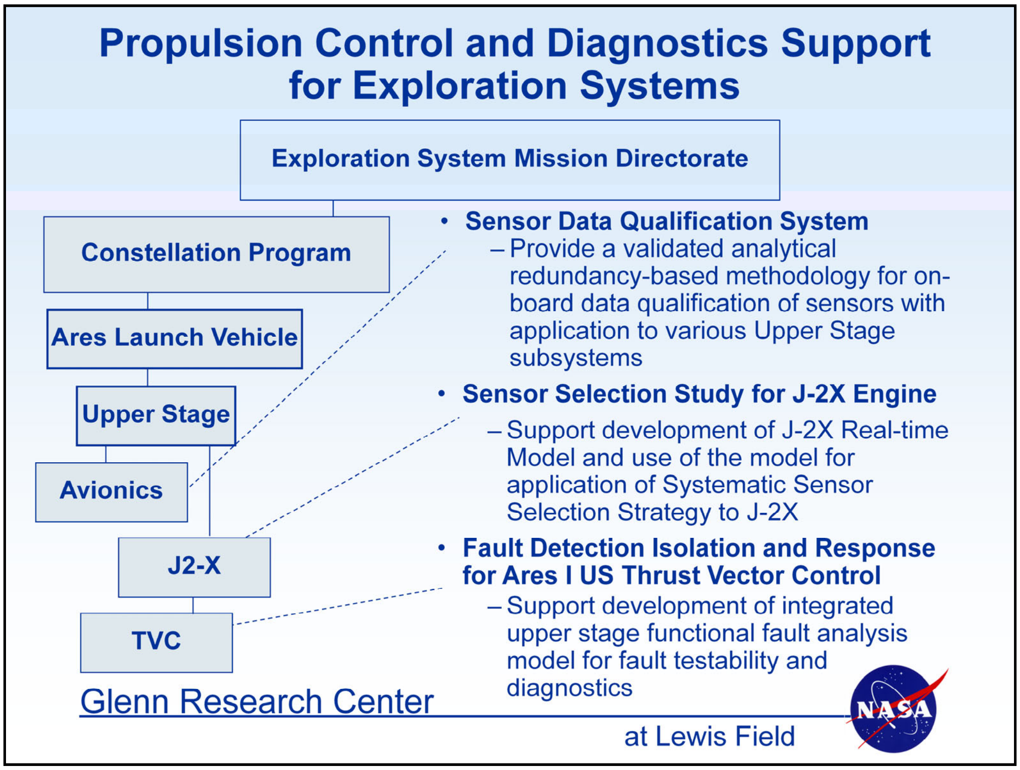


Propulsion Control and Diagnostics for Aviation Safety Program (ASP)

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 Integrated Propulsion Control and Dynamics element under the IRAC project.

For the IVHM project, the CDB activities are under the Diagnostics element and consist of research 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.

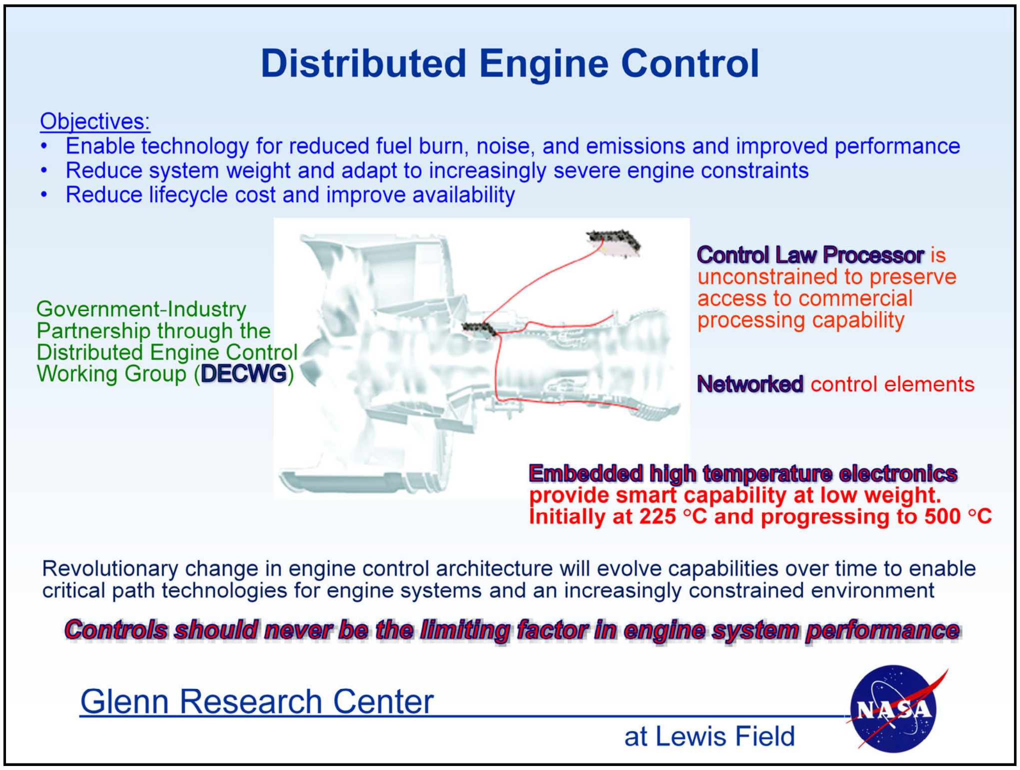


Propulsion Control and Diagnostics Support for Exploration Systems

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, J2-X Engine and Thrust Vector Control elements of the Upper Stage (US) for the Ares Launch Vehicle.

Under the Avionics element, CDB is developing a Sensor Data Qualification (SDQ) system 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 performing fault propagation and timing studies to identify the needs for TVC health management system, and supporting development of integrated US functional fault analysis for fault testability and diagnostics.

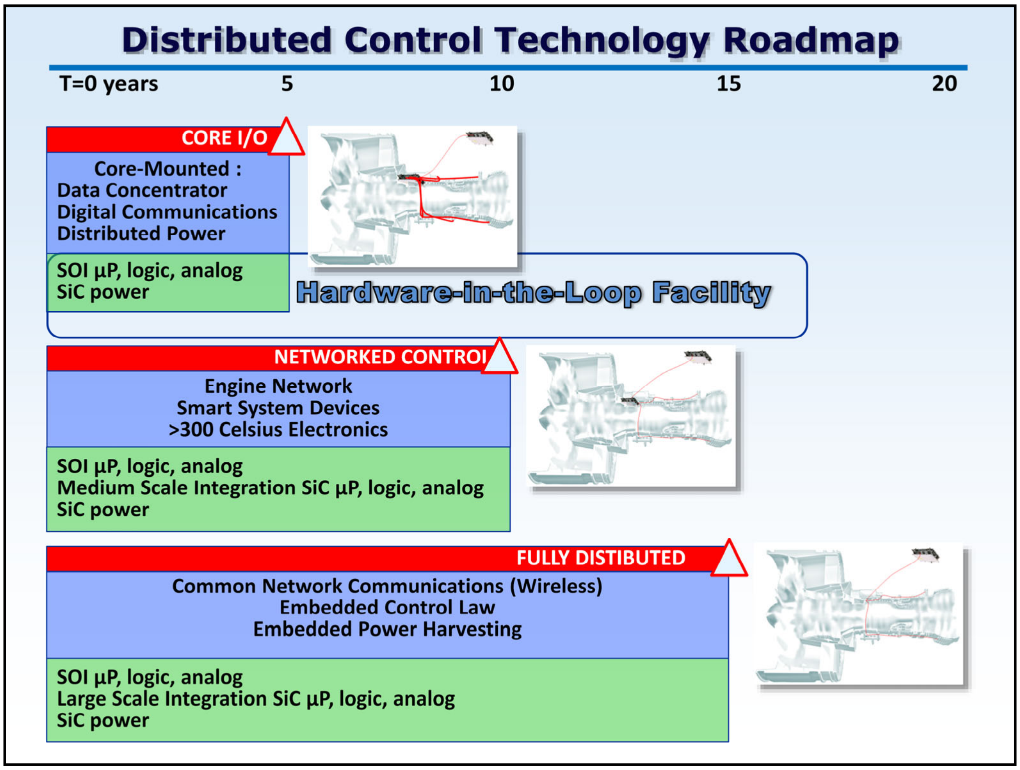


Distributed Engine Control

Control system architecture is a major contributor to future propulsion engine performance enhancement and life cycle cost reduction. The control system architecture can be a means to effect net weight reduction in future engine systems, provide a streamlined approach to system design and implementation, and enable new opportunities for performance optimization and increased awareness about system health. The transition from a centralized, point-to-point analog control topology to a modular, networked, distributed system is paramount to extracting these system improvements. Distributed engine control technology addresses the continuing need for more complex control on turbine engine systems. It is intended to preserve access to commercial electronics for cost-effective processing capability while minimizing the thermal management weight penalty associated with silicon electronics. It provides for flexible and scalable control systems through networked communications and standard interfaces. It improves control capability by embedding functionality within local devices.

GRC has been instrumental in establishing the industry-government partnership through DECWG . This partnership is essential for leveraging a common interest in developing pre-competitive controls technologies, establishing standards for continued collaboration, and identifying requirements for electronics. Objectives are driven by system level needs to improve fuel burn, reduce emissions, reduce noise, and improve vehicle metrics for field length. GRC is also conducting in-house research in some of the areas that are critical to enabling distributed control in the harsh operating environment of the aircraft engine – these include development of high temperature electronics, communication requirements and proper partitioning of control and signal processing functions into a distributed architecture.

Reference: Culley, D.E., and Behbahani, A.R., "Communication Needs Assessment for Distributed Turbine Engine Control," AIAA-2008-5281, 44th Joint Propulsion Conference and Exhibit, Hartford, CT, Jul. 21-23, 2008.



Distributed Control Technology Roadmap

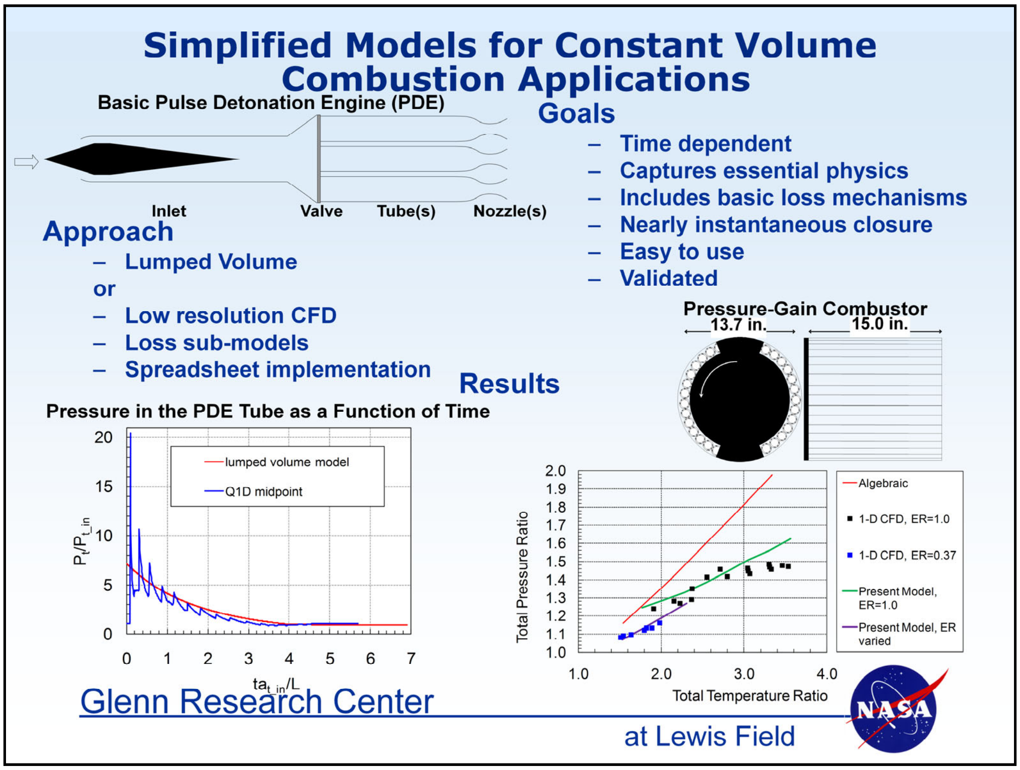
Working in collaboration with the DECWG NASA has developed a roadmap for maturing critical technologies to move the engine control architecture from the current centralized to a future fully distributed one. The steps in this progression are expected to be: 1) 5-yr, Core I/O (Input/Output); 2) 10-yr, Networked Control; 3) 15 to 20-yr, Fully Distributed. These are briefly described in the following. Apart from developing the technologies to enable distributed engine control, it will also be important to develop a hardware-in-the-loop facility which can be used to test and investigate integration aspects of various components of the distributed control. The industry is expecting the government to take the lead in developing such a facility and NASA is in discussions with the Air Force Research Lab and the best way to make this happen.

Core I/O: This architecture breaks the Engine Control Unit (ECU) into two components – a Control Logic Processor (CLP) and a Data Concentrator. This is designed to achieve early success with the distributed architecture by limiting the scope of hardware changes and keeping most of the supply chain of control components intact. The CLP can be located off-board the engine thus reducing the requirements to withstand the harsh engine environment .

Networked Control: In this architecture, the CLP remains as a modular device capable of integrating new commercial technology as it becomes available, while the Data Concentrator is simplified by distributing the data conversion functions out to the control elements. The control elements are expected to have increased complexity requiring embedded electronics, however, the increased system modularity and reliability, and decreased overall weight are expected to offset this complexity.

Fully Distributed: In this architecture, the function of the Data Concentrator becomes obsolete as the embedded electronics in the smart devices become capable of doing all the signal processing functions locally and communicate directly to the CLP.

Reference: Culley, D.E., "Transition in Gas Turbine Control System Architecture: Modular, Distributed and Embedded," GT2010-23226, ASME Turbo Expo 2010, Glasgow, UK, Jun.14-18, 2010.



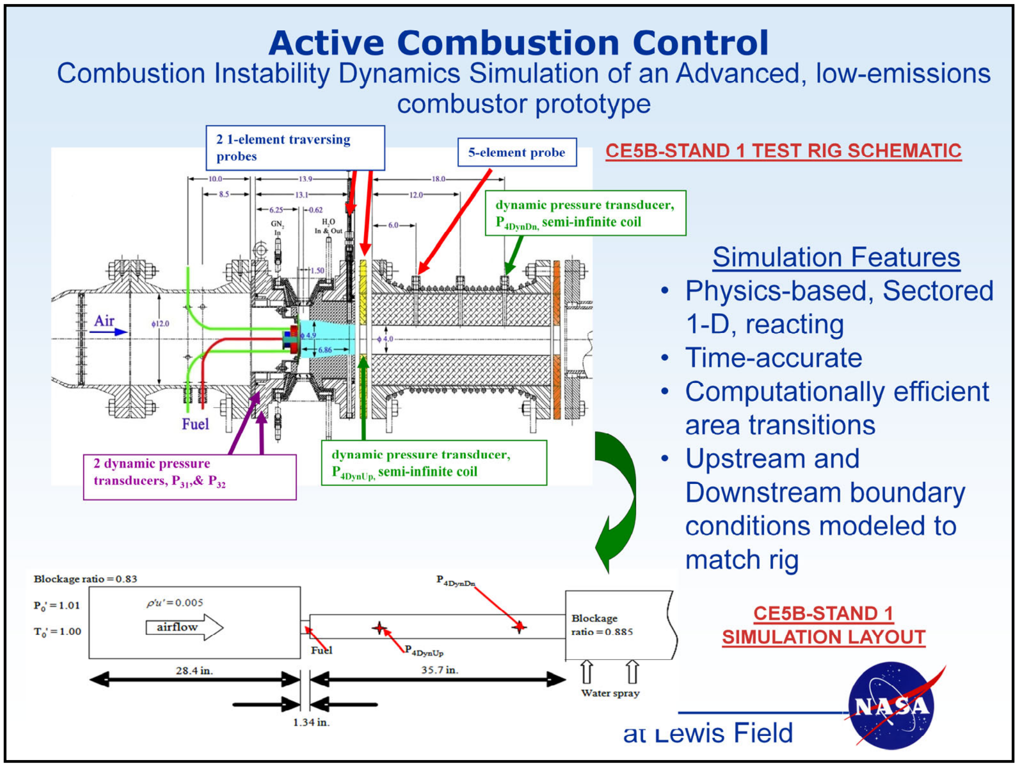
Simplified Models for Constant Volume Combustion Applications

Constant Volume Combustion (CVC), whether by detonation or deflagration, is under investigation for flight applications ranging from pure propulsion to pressure-gain combustion for gas turbines. In any potential application, system studies must be undertaken. These require component models which can generate meaningful performance predictions, over a range of flight conditions and parameter variations. Furthermore, due to their being exercised over many parameters, these models must compute solutions very quickly. This is a particular challenge in CVC application which are fundamentally unsteady, and therefore require time integration to close. Solutions are limit cycles, not single, steady state points.

The modeling effort illustrated above has taken the least complex approach possible, while maintaining this essential time dependence. The project has produced several codes (one of which has been released as NASA software) that close in approximately the time it takes to click a mouse, and which produce performance estimates consistent with higher fidelity CFD (Computational Fluid Dynamics) models. Furthermore, being simplified, they require fewer input parameters to run, and can thus be configured in minutes.

The left figure shows pulse detonation engine combustion chamber pressure over the course of one cycle. The present lumped volume model approach is shown in red, and is compared with results from a high fidelity CFD computation. The results compare favorably both in terms of cycle time and pressure magnitude. Not surprisingly, the thrusts computed are within 2% of one another. The right figure compares mixed total pressures as a function of mass averaged total temperature ratio for several different equivalence ratios in a pressure-gain combustor application. The symbols represent high resolution CFD results. The solid lines are generated by the present code. The red line labeled ‘Algebraic’ represents data from a non-time dependent algebraic code. It substantially over-predicts performance. It is shown here to illustrate the necessity for capturing the essential physics of CVC devices.

Reference: Paxson, D., “Progress in Government Developed Pulse Detonation Engine Performance Codes,” JANNAF Conference, La Jolla, CA, Dec. 7-10, 2009



Active Combustion Control—Combustion Instability Dynamics Simulation

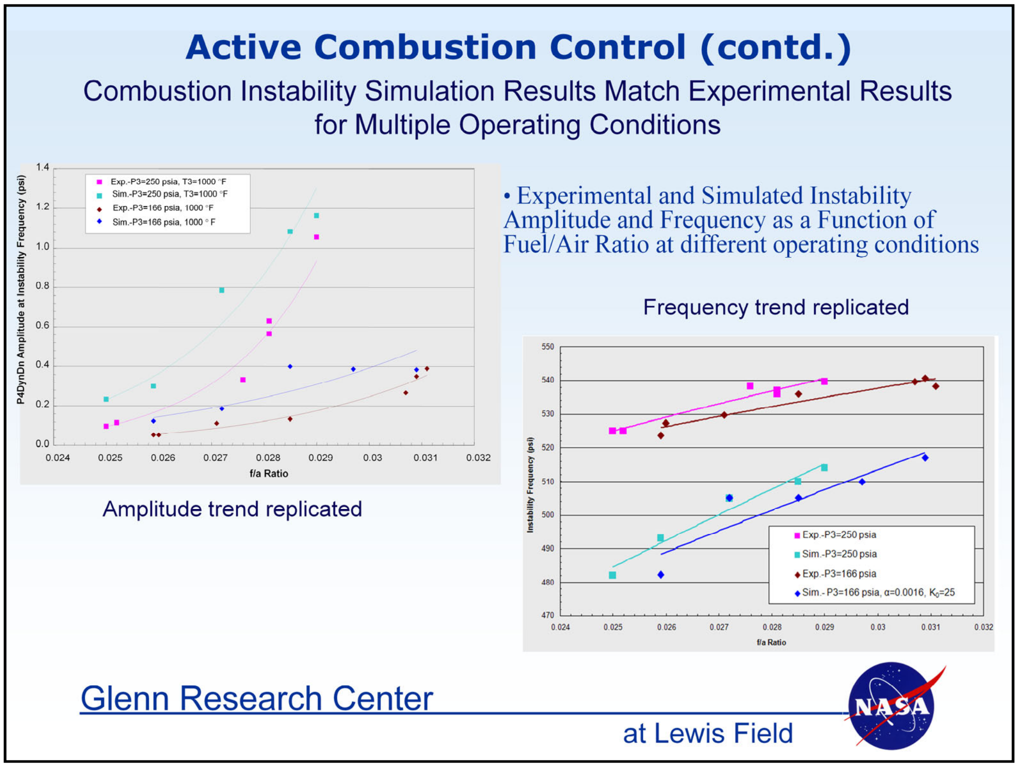
Previously, GRC, working in collaboration with industry and academia developed and demonstrated several key technologies for the active suppression of thermo-acoustic instability. These technologies included a high frequency fuel modulation valve, an actuator characterization rig, fuel delivery system 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.

Reference: DeLaat, J.C., Chang, C.T., “Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines,” NASA TM-2003-212611, ISABE-2003-1054, 16th International Symposium on Airbreathing Engines, Sep. 2003.



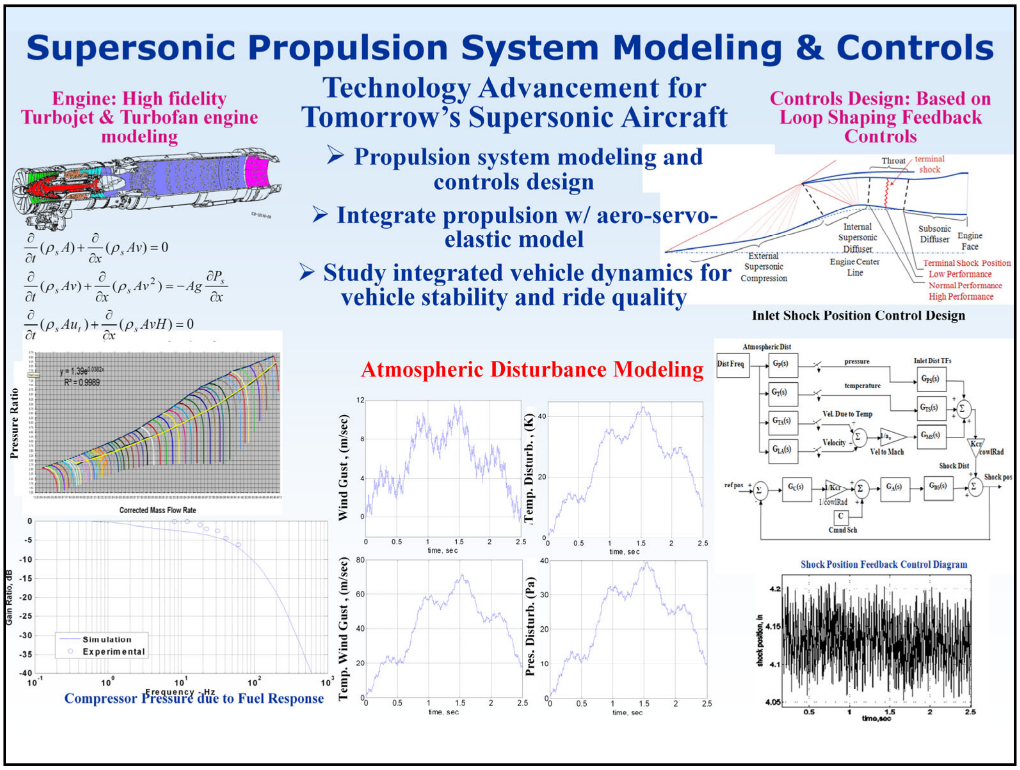
Combustion Instability Simulation Results Match Experimental Results for Multiple Operating Conditions

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 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.

Results comparing simulated and experimentally measured thermoacoustic oscillation amplitudes for two different operating conditions, as functions of fuel/air ratio are shown. Considering first the high pressure data (magenta and light blue square symbols), it is seen that the simulation and experiment show comparable amplitudes, and trend similarly. Additional tuning of the exit blockage could have potentially matched the amplitude more exactly. However, an exact match in amplitude was not deemed as physically relevant as a similar amplitude and similar amplitude trend. Relatively good agreement was also obtained for the low pressure condition. Shown also are the simulated and experimentally measured combustor instability frequencies. Again, reasonable agreement is obtained in the frequency values and also the trend vs. fuel/air ratio.

The combustion instability simulation is currently being incorporated into a MATLAB/Simulink S-Function for use in designing controllers to suppress combustion instability. Plans are to experimentally demonstrate these control methods with the advanced, low-emissions combustor rig.

Reference: DeLaat, J.C., Paxson, D.E.,“Characterization and Simulation of the Thermoacoustic Instability Behavior of an Advanced, Low Emissions Combustor Prototype”, AIAA-2008-4878, NASA/TM—2008-215291, 44th Joint Propulsion Conference and Exhibit, July 2008.



Supersonic Propulsion System Modeling and Control

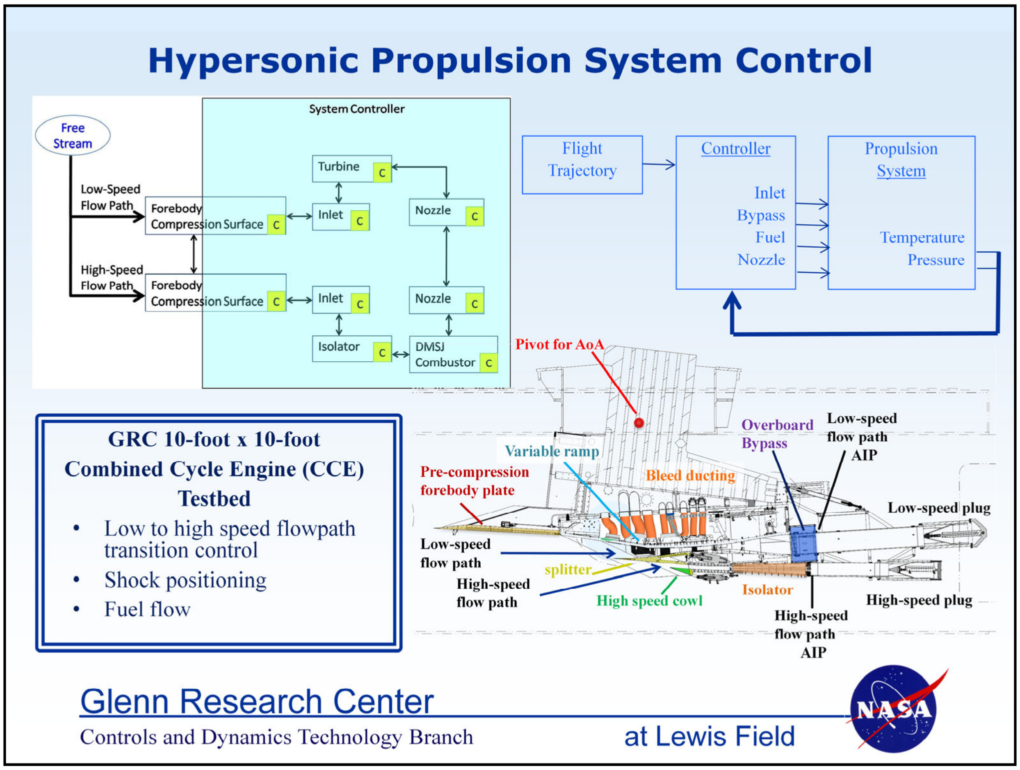
For the NASA Supersonics, project, the overall objective is to perform the research to advance the technology so that the industry will be in position to develop supersonic cruise vehicles such as a civil transport. There are many technical challenges remaining for the supersonic vehicle technology development,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

For the supersonic propulsion system area, the objective is to develop the models and design the controls so that the inlet and engine perform as desired, especially as the inlet is the most crucial component of a supersonic engine. The integrated inlet/engine control design should be 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, such as flutter. 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 (1-D CFD for the inlet and stage-by-stage volume dynamics for the engine) that can be used for controls methodology development and application. To date both a turbojet and a turbofan engine model have been modeled, control designs and schedules have been developed to operate the engine throughout it's expected operating envelop, atmospheric turbulence models have been developed, and a quasi 1-D CFD supersonic inlet model has been developed for internal compression inlets. Also an innovative loop shaping feedback controls design has been developed that maximizes system performance based on hardware capability. This controls approach has been applied to design engine speed control as well as inlet shock position controls in the presence of atmospheric disturbances.

The plots show engine operation transitioning through the compressor map, a dynamic engine response compared to experimental data, atmospheric disturbance plots, and an inlet shock position closed loop control response.

Reference: Kopasakis, G., and Connolly, J., "Shock Positioning Controls Design for a Supersonic Inlet," 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Denver, CO, Aug. 2-5, 2009.

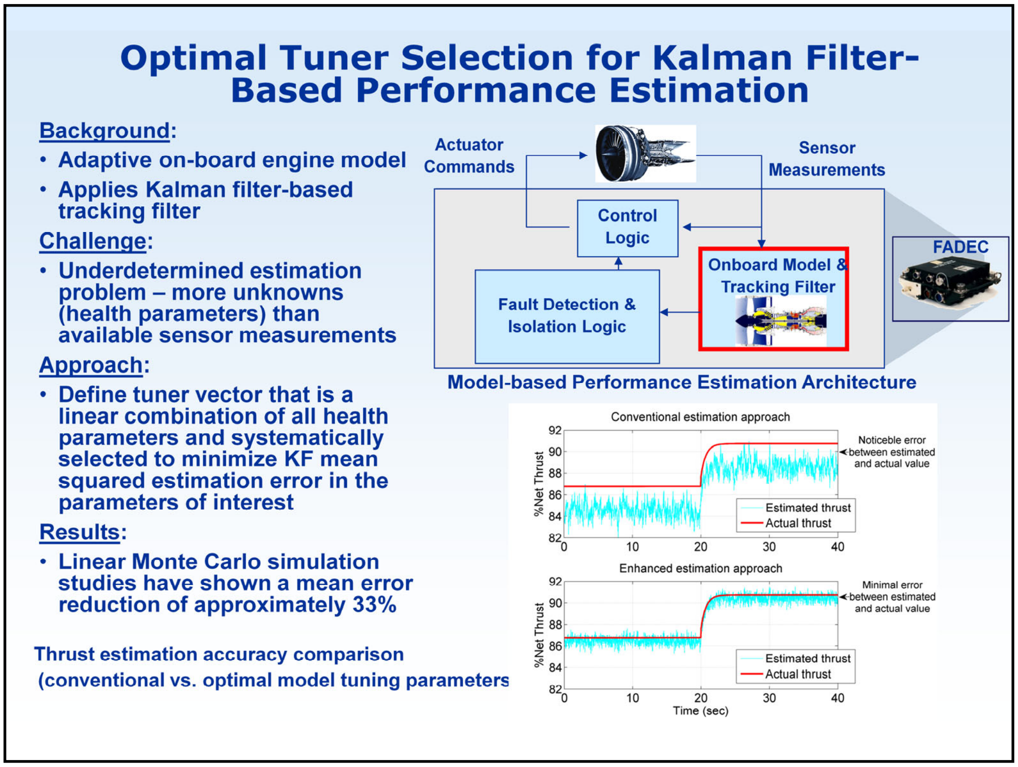


Hypersonic Propulsion System Control

Control research for a Turbine Based Combined Cycle (TBCC) propulsion system is the current focus of the NASA Hypersonic GN&C discipline team. The ongoing work is to develop tools to aid the design of control algorithms to manage a TBCC airbreathing propulsion system during the critical operating period when the propulsion system transitions from one cycle to another, referred to as mode transition. The first step underway is developing computational models for each component of the propulsion system. These component models will be collected under a common programming format for an overall propulsion system computational model.

Current research is focused on developing the computational models to simulate an airbreathing TBCC propulsion system inlet. The TBCC inlet aerodynamic design being modeled is that of the Combined-Cycle Engine (CCE) Testbed. The CCE Testbed is a large-scale hardware model of an aerodynamic design that was verified in a small-scale screening experiment. The CCE Testbed has been designed for experiments in the GRC 10- by 10-ft Supersonic Wind Tunnel (SWT). This mixed compression inlet system is suitable for experiments focusing on mode transition studies. The modeling approach includes employing existing state-of-the-art simulation codes, developing new dynamic simulations, and performing system identification experiments on the CCE Testbed in the SWT. The developed computational models will be available for control studies prior to hardware buildup. The system identification experiments will characterize the necessary dynamics to be represented in the models for control design. The primary objective for the CCE Testbed is to experimentally investigate and develop methods of mode transition for a TBCC type propulsion system. Ideally, these hardware tests will result in a demonstration of an inlet system capable of maintaining inlet operability and safety margins with maximum performance through all flight conditions including mode transition. To support this objective, the research of the NASA GN&C team is towards developing a TBCC feedback control system that maintains propulsion system stability and maximizes performance throughout a mission including the mode transition event.

Reference: Stueber, T.J., Vrnak, D.R., Le, D.K., and Ouzts, P.J., “Control Activity in Support of NASA TBCC Research,” NASA/TM—2010-216109, Jan. 2010.



Optimal Tuner Selection for Kalman Filter-Based Performance Estimation

An emerging approach in the field of aircraft engine controls and health management is the use of real-time on-board models for direct control of unmeasured parameters such as thrust and to tailor the control laws for the specific engine. A major challenge for using model-based controls and diagnostics is that an aircraft engine's performance is affected by its level of degradation, generally described in terms of unmeasurable health parameters such as efficiencies and flow capacities related to each major engine component. Through Kalman filter-based estimation techniques, the level of engine performance degradation can be estimated, given that there are at least as many sensors as parameters to be estimated. However, in an aircraft engine the number of sensors available is typically less than the number of health parameters, presenting an under-determined estimation problem. A common approach to address this shortcoming is to estimate a sub-set of the health parameters, referred to as model tuning parameters. Although this approach enables the Kalman filter to tune the on-board model so that its outputs track measured (sensed) engine outputs, there can be significant error in estimation of unmeasured engine outputs because the impact of the entire vector of health parameters will not be accurately represented within the Kalman filter model.

NASA has developed an innovative methodology that creates a tuning parameter vector defined as a linear combination of *all* health parameters and of appropriate dimension to enable Kalman filter estimation. Selection of this tuning parameter vector is performed using a multi-variable iterative search routine that minimizes the theoretical mean-squared estimation error in the parameters of interest. The new methodology was validated in simulation using an aircraft turbofan engine model. The simulation results demonstrated that applying the enhanced tuning parameter selection methodology resulted in a 31.6% reduction in average estimation error compared to the conventional approach of selecting a subset of health parameters as tuners.

Reference: Simon, D.L., and Garg, S., "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," GT2009-59684, ASME Turbo Expo Conference, Jun. 8-12, 2009, Orlando, FL.

Optimal Sensor Selection for Performance Estimation

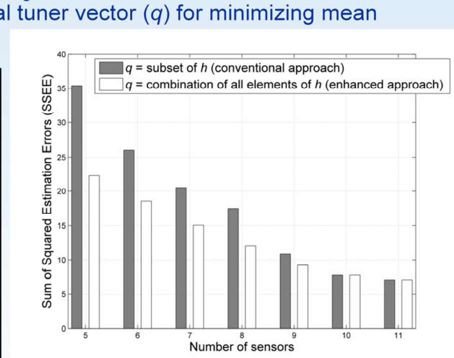
Objective: Minimize health parameter (h) estimation error

Approach: Apply integrated sensor and tuner selection

- Apply an exhaustive search considering all candidate sensor suites
- For each sensor suite choose optimal tuner vector (q) for minimizing mean squared estimation error

# Sensors	sensors added to baseline						Health Parameter Mean Sum of Squared Estimation Errors (SSEE)	
	P24	T30	P45	P50	T50	P15	Conventional Approach (q = subset of h)	Enhanced Tuner Approach (q = linear combination of all elements of h)
5							**35.40**	**22.30**
6			○		x		**26.01**	**18.53**
7		⊗	○		x		**20.51**	**15.06**
8		⊗	⊗		⊗		**15.28**	**11.95**
9		⊗	⊗		⊗	⊗	**10.90**	**9.22**
10	⊗	⊗	⊗		⊗	⊗	**7.77**	**7.77**
11	⊗	⊗	⊗	⊗	⊗	⊗	**7.11**	**7.11**

Sensor Selection Legend:
×= Sensor selected when applying conventional tuner selection approach
○= Sensor selected when applying enhanced tuner selection approach



Results:

- Estimation accuracy improves as additional sensors are added
- Enhanced tuner selection approach provides superior estimation accuracy
- Optimal sensor suite is dependent on the tuner selection approach applied

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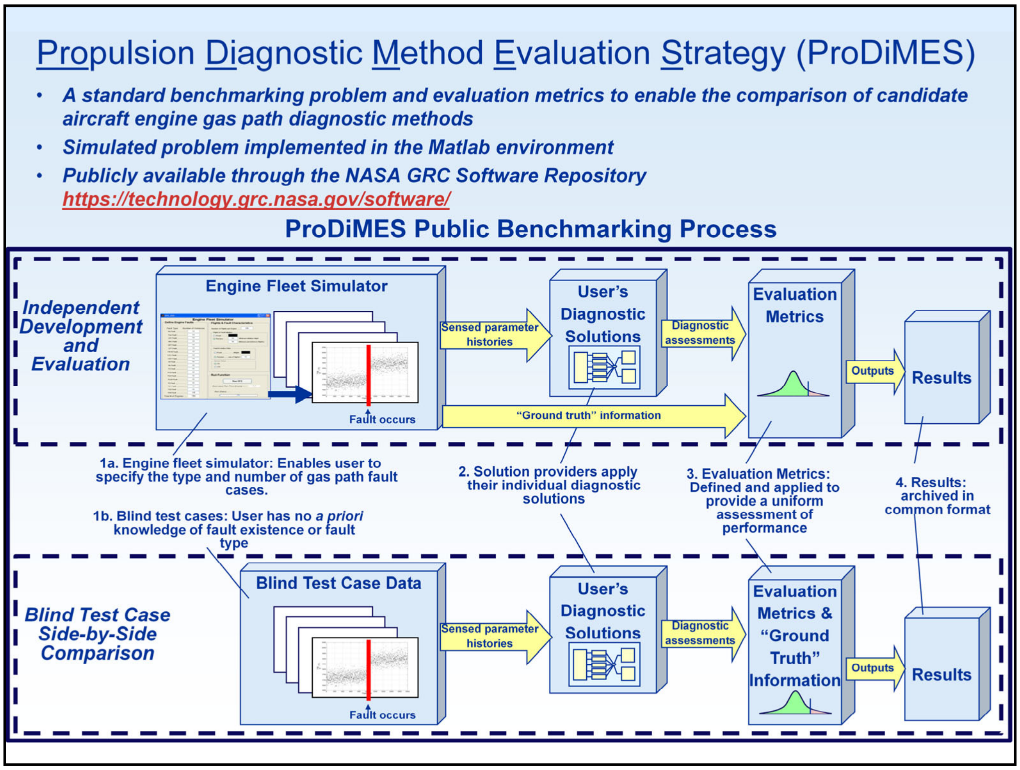
Optimal Sensor Selection for Performance Estimation

The previous section discussed a systematic approach for selecting an optimal model tuner vector for on-board model-based aircraft gas turbine engine performance estimation. Another way to improve model-based performance estimation accuracy is to add additional gas path measurements. In general, estimation accuracy will improve as additional sensors are added. However, adding sensors adds cost, weight, and complexity to the overall engine design. Therefore, instead of simply adding sensors in an ad hoc fashion, a systematic approach to sensor selection is desired. To address this need, the tuner selection methodology was extended to also enable optimal sensor selection. Such a tool can assist system designers in assessing the relative merits of including different sensors in their engine designs.

Like the previously presented tuner selection methodology, the sensor selection methodology is analytically based upon the theoretical mean squared estimation error of the Kalman filter. This error is a function of the available engine sensor suite. The optimizing objective is to choose the sensor suite that minimizes the estimation error. This objective is satisfied by applying an exhaustive search that considers all candidate sensor suites as defined by the end user. The sensor selection methodology has been validated in simulation using an aircraft turbofan engine model. In this study combined sensor and model tuner selection was considered—for each candidate sensor suite the corresponding optimal tuner vector that minimizes the Kalman filter mean squared estimation error is chosen. The above figure shows sensor selection results from this study. This study quantified the estimation accuracy improvement that could be gained as additional sensors were added to the baseline. The study showed that when fewer sensors are available, the optimal tuner selection approach provides significantly superior estimation accuracy relative to the conventional approach of selecting the tuner vector as a subset of health parameters.

Reference: Simon, D.L., Garg, S:, "A Systematic Approach to Sensor Selection for Aircraft Engine Health Estimation," ISABE-209-1125, International Society of Air Breathing Engines Conference, Sep. 7-11, 2009 Montreal, QC, Canada.



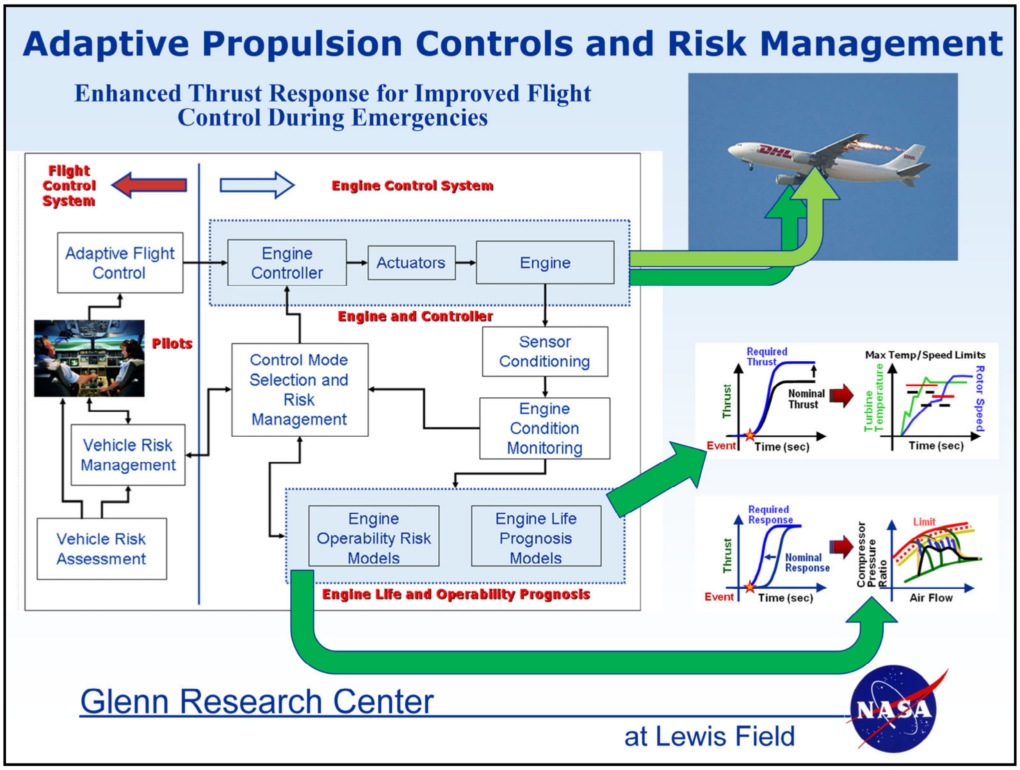
Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Many of the propulsion gas path diagnostic method solutions published in the open literature are applied to different platforms, with different levels of complexity, addressing different problems, and using different metrics for evaluating performance. As such, it is difficult to perform a one-to-one comparison of candidate approaches. Furthermore, these inconsistencies create barriers to effective development of new algorithms and the exchange of results. To help address these issues, the Propulsion Diagnostic Method Evaluation Strategy (ProDiMES) software tool has been specifically designed with the intent to be made publicly available. In this form it can serve as a reference, or theme problem, to aid in propulsion gas path diagnostic technology development and evaluation. The overall goal is to provide a tool that will serve as an industry standard, and will truly facilitate the development and evaluation of significant EHM (Engine Health Management) capabilities. The ProDiMES tool is coded in the Matlab environment and consists of the following functions: a) Engine Fleet Simulator (EFS) which emulates the collection of data at takeoff and cruise from a fleet of engines over their lifetime of use; b) User provided diagnostic solutions designed to process the simulated parameter histories produced by the EFS, and generate a diagnostic assessment for each engine; c) Software program which automatically evaluates and archives performance of diagnostic solutions against established metrics; and e) A set of blind test case data to enable the side-by-side comparison of diagnostic solutions developed by multiple users.

Individuals can request ProDiMES, free of charge, through the GRC Software Repository: https://technology.grc.nasa.gov/software/index.asp .

User's will be asked to submit their blind test case diagnostic assessments to NASA. In exchange participants will receive their metric results, plus the anonymous results of other participants.

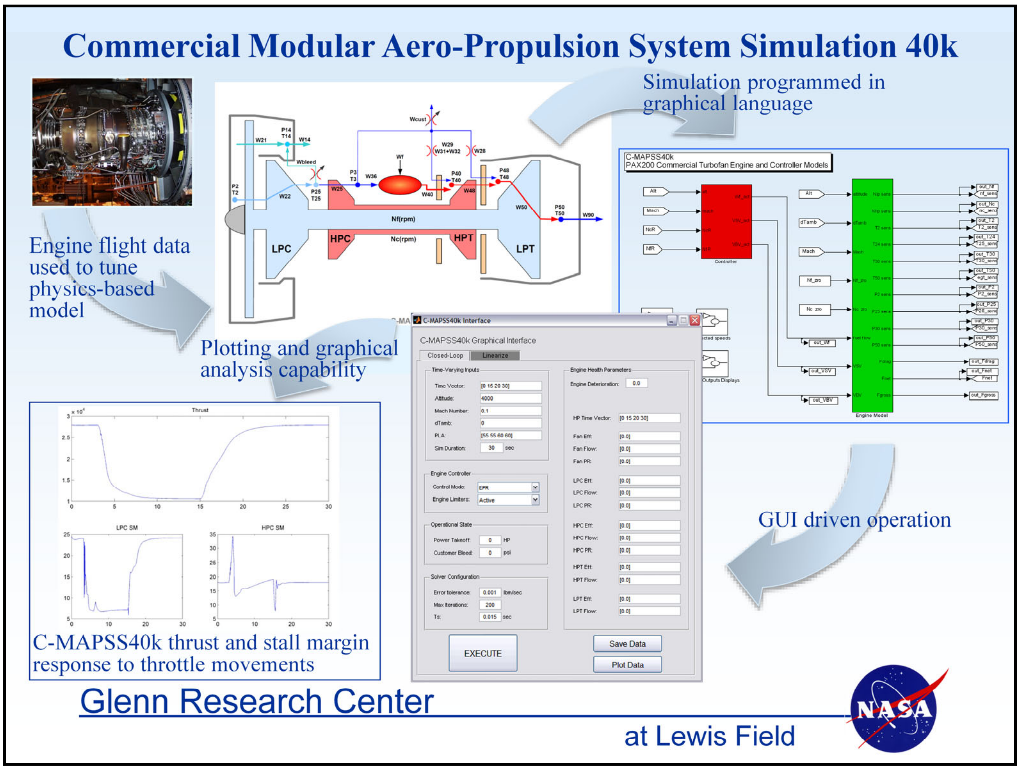
Reference: Simon, D.L., Bird, J., Davison, C., Volponi, A., Iverson, R.E., "Benchmarking Gas Path Diagnostic Methods: A Public Approach," NASA/TM—2008-215271, GT2008-51360, 2008 ASME Turbo Expo, Berlin, Germany, Jun. 9-13, 2008.



Adaptive Propulsion Controls and Risk Management

Aviation accidents and incidents as well as past research have demonstrated that the propulsion system can help the pilot recover from upset conditions or in-flight airframe damage when used as a flight control effector. However, gas turbine engines are operated conservatively so that they give acceptable, repeatable performance over a long life, which precludes their use as practical flight control effectors because their response time is too slow. Because engines are operated conservatively, additional performance that could be utilized under emergency circumstances is usually available, but using it would come at the cost of reduced life and increased risk of stall. If this excess capacity could be harnessed to help recover the aircraft in an emergency, the overall risk to the vehicle and passengers could be reduced by enabling flight operation that would otherwise not have been possible, even with the additional risk to the propulsion system. To take advantage of this unexploited potential, the Integrated Resilient Aircraft Control project under the NASA Aviation Safety Program is developing enhanced engine control algorithms to enable faster response and thrust boost capabilities for emergency situations. Several approaches are being pursued to achieve this goal. Studies are being performed on relaxing controller limits—limits that exist to protect the engine from stall or component damage—to allow faster response or extra thrust. Additionally, new ways to use existing actuators such as bleed valves and variable stator vanes, and even the addition of new actuators, are being investigated to improve the dynamic response of the engine. For each enhanced control mode, appropriate prognostic algorithms are being developed to estimate the risk of utilizing that mode, which allows the overall risk to the system to be managed and minimized while providing the safest achievable flight operation under the given circumstances.

Reference: Guo, T.-H, Litt, J.S., “Risk Management for Intelligent Fast Engine Response Control,” AIAA-2009-1873, AIAA Infotech@Aerospace Conference, Seattle, WA, Apr. 6-9, 2009.



Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)

C-MAPSS40K is a new high-fidelity simulation of a generic 40,000 lbf thrust class commercial engine with a representative controller. It is based on dynamic flight test data from a highly instrumented engine and previous engine simulations developed at GRC. It was created especially for the development and evaluation of control strategies to use the engine as a flight control effector during emergencies.

C-MAPSS40k introduces a number of new features including an iterative solver and detailed compressor stall models. The iterative engine solver enforces mass flow balance through the engine at every time step. This feature produces a realistic simulation while allowing the user the ability to configure the solver for the specific test, such as small throttle steps, and still maintain faster-than-real-time operation. The detailed compressor stall models include the compressor map stall line as well as a number of stall margin debits such as stall line change due to engine deterioration, stall margin change due to rotor tip clearance changes, and the transient debit due to heat transfer between the mass flow and rotor blades and compressor casing. The inclusion of these debits allows control developers to have a good estimate of the required stall margin stack-up by eliminating some of the uncertainty.

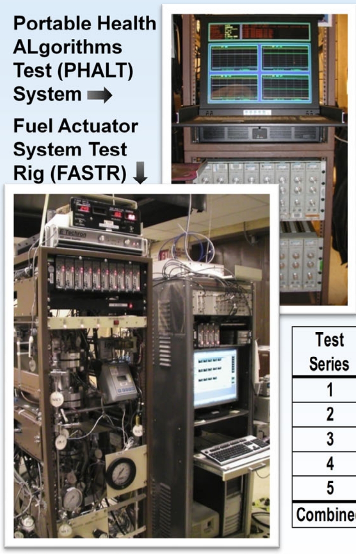
C-MAPSS40k also includes an “industry standard” controller for use as a baseline against which to compare new controllers and architectures. This baseline controller follows the most common design principles in current commercial engine controllers and produces realistic transient behavior at conditions across the engine’s flight envelope. With these capabilities, users in academia, industry, and government have access to a generic, high-fidelity engine simulation that can be used to quickly develop, simulate, and test new control system components and architectures, and diagnostic algorithms.

Reference: May, R. D., Csank, J. T., Lavelle, T. M., Litt, J. S., Guo, T. -H., “A High-Fidelity Simulation of a Generic Commercial Aircraft Engine and Controller,” Joint Propulsion Conference, Nashville, TN, Jul. 25-28, 2010.

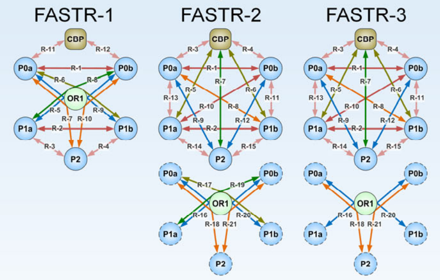
Ares I Real-time Data Qualification Studies using CDB-developed PHALT & FASTR Platforms

Portable Health ALgorithms Test (PHALT) System ➡

Fuel Actuator System Test Rig (FASTR) ⬇



Analytical Redundancy Relationship Networks evaluated and summary of results



Test Series	No. Tests	FASTR-1			FASTR-2			FASTR-3		
		Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
1	13	100%	0%	0%	62%	38%	0%	92%	0%	8%
2	4	0%	25%	75%	0%	25%	75%	100%	0%	0%
3	2	100%	0%	0%	100%	0%	0%	100%	0%	0%
4	2	0%	0%	100%	0%	0%	100%	50%	0%	50%
5	8	50%	50%	0%	50%	13%	38%	75%	25%	0%
Combined	29	66%	17%	17%	48%	24%	28%	86%	7%	7%

Glenn Research Center

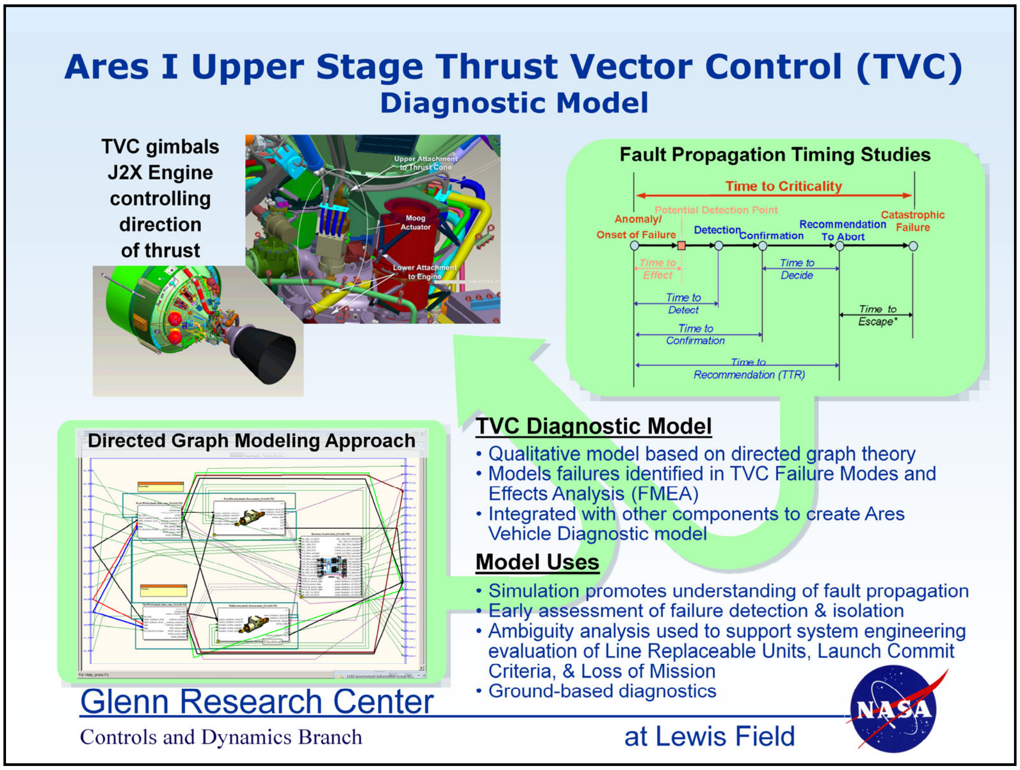
Controls and Dynamics Branch

at Lewis Field

Ares I Real-Time Data Qualification Studies

Sensor data qualification is the process of analyzing sensor data to insure that it accurately represents the state of the system being measured. Sensors that are not representative of the true system state are flagged as failed so that the bad data is not used as the basis for operational decisions. The CDB at GRC is currently supporting the application of sensor data qualification methods to the new Ares I launch vehicle. The proposed approach would extend the state-of-the-art from red-lines and reasonableness checks - algorithms that flag a sensor after it has failed - to include analytical redundancy-based (ARB) methods that can identify a sensor in the process of failing. Various proof-of-concept studies have been conducted to support the application of ARB methods to Ares systems. Most recently ARB methods were implemented in real-time on the CDB developed Portable Health ALgorithms Test (PHALT) System and were used to qualify sensors on the Fuel Actuator System Test Rig (FASTR) at GRC. The PHALT System was developed to support the implementation and testing of vehicle health monitoring algorithms in a real-time test environment. FASTR provided a high-pressure, incompressible fluid-based test rig that is considered relevant to the low pressure side of a launch vehicle main propulsion system. Three ARB sensor network configurations were investigated to determine the best approach for qualifying a system of pressure and flow sensors. Results provided insight into similar Ares I applications. For this analysis, the detection capability is evaluated using three categories. Green indicates the correct detection of failed sensors.; Yellow indicates the correct detection of failed sensors with one or more other unfailed sensors indicating a non-persistent fault; and Red indicates that one or more sensors are incorrectly indentified as failed or a failure was not detected.

Reference: Maul, W.A., Bickford, R.L., and Melcher, K.J., “Use of Analytical Redundancy Relationship Networks for Sensor Data Qualification.” Proceedings of the Commercial & Government Responsive Access to Space Technology Exchange, Dayton, Ohio, Oct. 26-29, 2009 (NASA/TM—2010-216067).

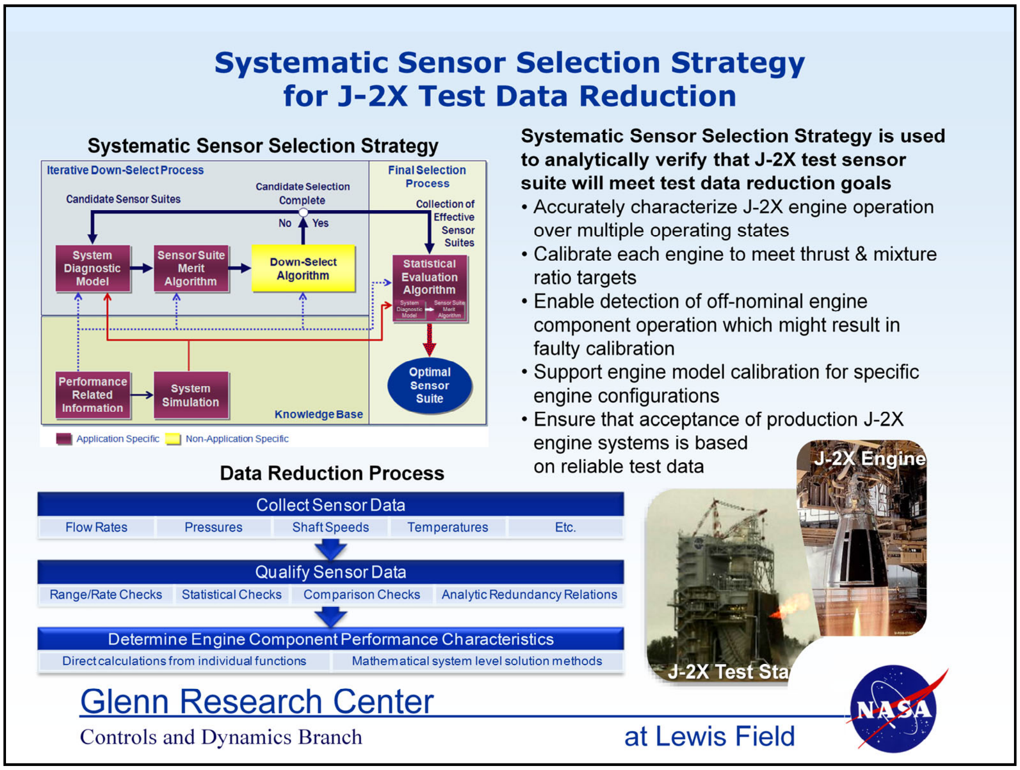


Ares I Upper Stage Thrust Vector Control (TVC)—Diagnostic Model

In the current design of the Ares I US, a TVC system is used to gimbal the US engine, thus controlling the direction of the thrust. GRC leads the TVC design effort. 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 at 90° 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, in part through the development of TVC Diagnostic Model. The TVC Diagnostic Model is an attempt to address gaps in fault detection and isolation requirement verification. It is a qualitative directed graph representation of failure effect propagation paths within the vehicle architecture and represents the system's fundamental failure-space behavior. The diagnostic model integrates design information (e.g., system schematics, instrumentation and command list and system specification and requirements documents), traditional systems engineering analysis (e.g., FMEA and Hazard Analysis) and operations information into a formal analysis and modeling tool that enables the assessment of both in-flight and on-pad diagnostics. The model representation provides valuable information during the system design and early development stage when recommended changes will have the least impact to cost and schedule. The model can qualitatively represent the failure effect propagation paths across all types of system physics, and it can be used to provide ambiguity analysis, as well as, fault detection and isolation information in support of launch vehicle safety, reliability and availability requirements.

Reference: Maul, W.A., Melcher, K.J., Chicatelli , A., and Johnson, S.B., "Application of Diagnostic Analysis Tools to the Ares I Thrust Vector Control System," 2010 AIAA InfoTech@Aerospace conference, Atlanta, GA, Apr. 20-22, 2010.

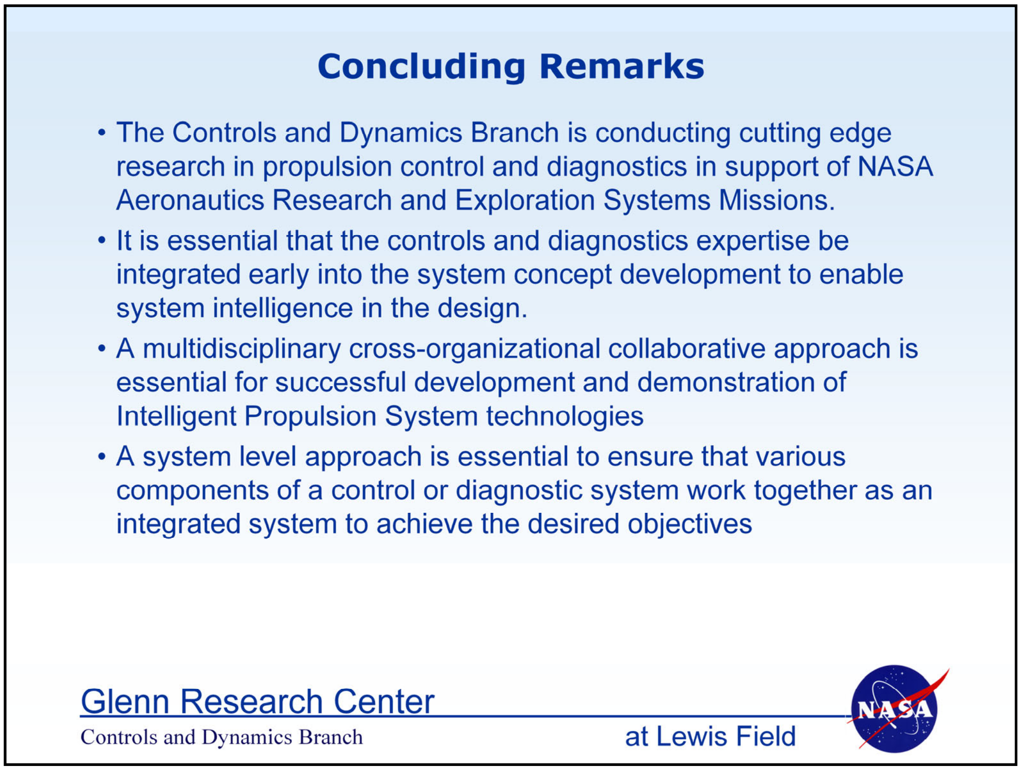


Systematic Sensor Selection Strategy for J-2X Test Data Reduction

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 assessment of system performance and health. The CDB has developed a model-based procedure, termed the Systematic Sensor Selection Strategy (S4), that systematically selects an optimal sensor suite for overall performance or health-related assessment of a designated host system. S4 can be logically partitioned into three major subdivisions: the Knowledge Base, the Iterative Down-Select Process, and the Final Selection Process. The Knowledge Base is used to define and construct the sensor selection process using system design and heritage experience information. The Iterative Down-Select Process is a low-resolution, first-step optimization procedure which identifies a set of sensor suites that provide good fault detection and identification capability for the targeted fault scenarios. During the Final Selection Process, the highest scoring sensor suites are re-evaluated using a more comprehensive analysis process from which the optimal sensor suite is selected.

The modularity of S4 is being utilized to support test data reduction for future J-2X hot-fire acceptance tests. Test data reduction will characterize component performance of each production J-2X engine to enable engine calibration to achieve thrust and mixture ratio targets. The reliability of the test data reduction process depends in large measure upon the selection of well-placed sensors of the proper type. The S4 process is being employed to verify that the selected test sensor suite will satisfy test data reduction objectives. In addition, S4 for test data reduction will: a) be able to identify anomalous sensor data that might introduce error into the engine calibration process; b) support the calibration of analytical engine models for specific engine configurations; and c) ensure that acceptance of production J-2X engine systems is based on reliable test data.

Reference: Sowers, T., Santi, L., Butas, J., "Selection of Sensors for J-2X Test Data Reduction," IPS-I-04, 54th JANNAF Propulsion Meeting, Orlando, FL, Dec. 8-12, 2008



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. 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 system. Intelligent propulsion control and diagnostics can significantly increase aircraft safety and improve operational reliability of space launch systems

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
The Controls and Dynamics Branch (CDB) at National Aeronautics and Space Administration (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 propulsion controls and diagnostics technologies that will help meet the challenging goals of NASA programs under the Aeronautics Research and Exploration Systems Missions. This paper provides a brief overview of the various CDB tasks in support of the NASA programs. 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
Turbofan engines; Sensors; Actuators; Fault detection; Engine control

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