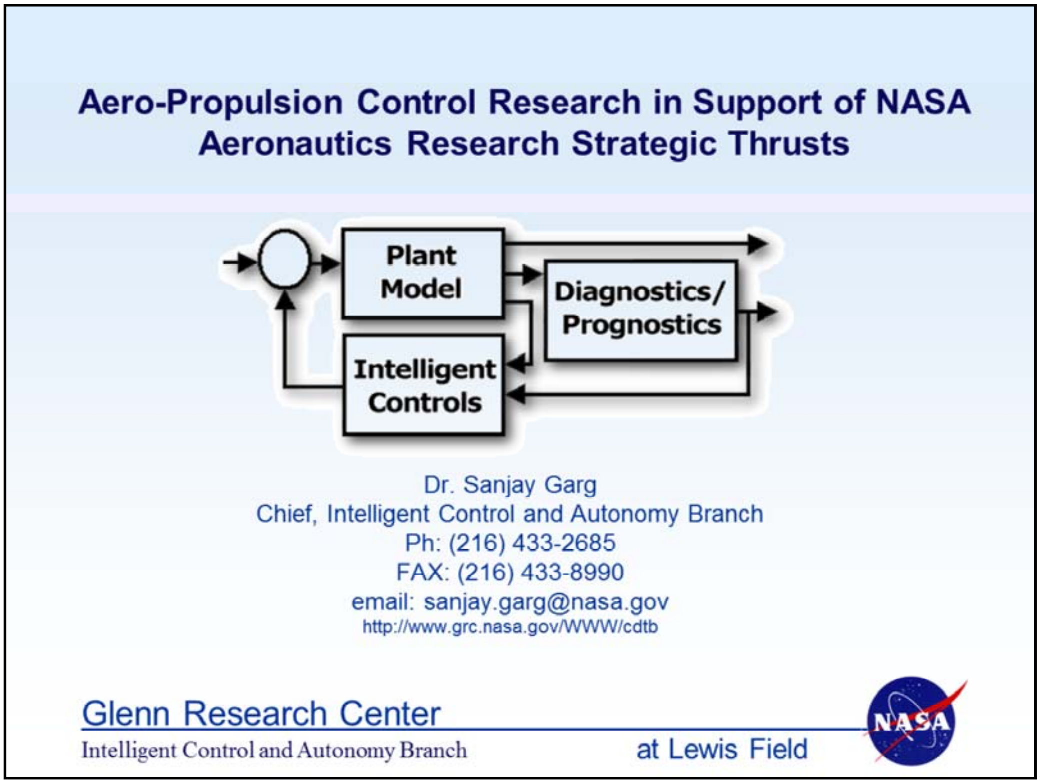


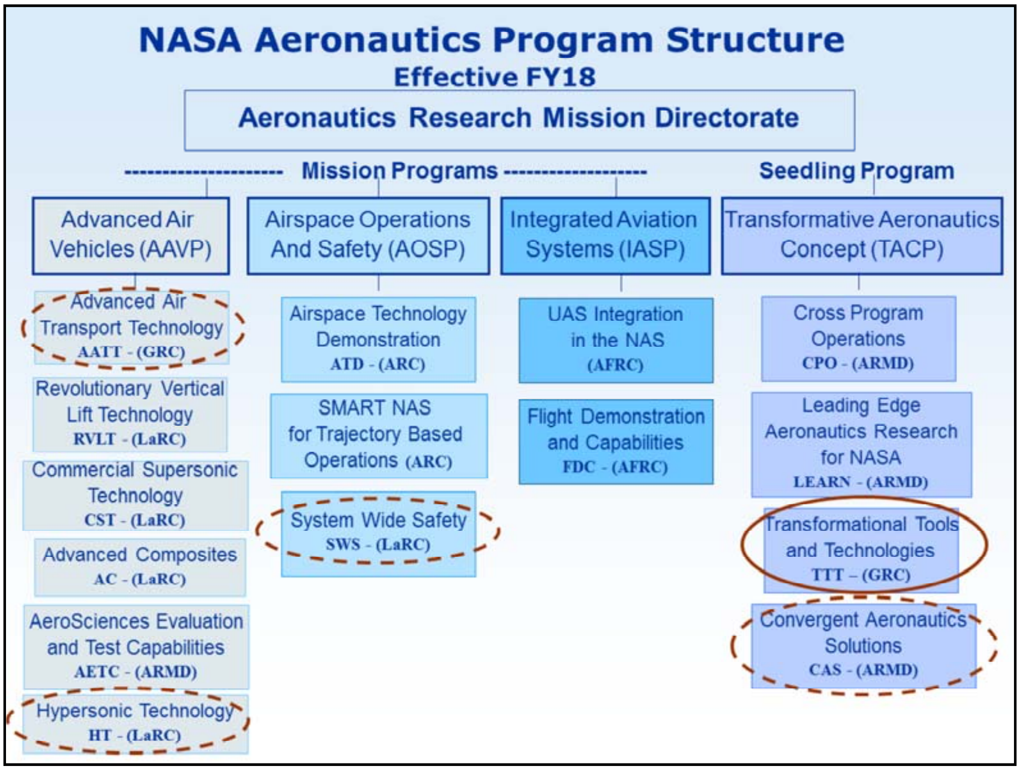
Abstract

In the past few years, NASA (National Aeronautics and Space Administration) Aeronautics Research Mission Directorate (ARMD) has introduced and updated a “New Blueprint for Transforming Global Aviation” [1]. This blueprint consists of six NASA Aeronautics Research Strategic Thrusts – “The updated vision is designed to ensure that through NASA's aeronautical research the United States will maintain its leadership in the sky and sustain aviation so that it remains a key economic driver and cultural touchstone for the nation.” In mid-2016, technology development roadmaps were developed by ARMD for each of the strategic research thrusts and these roadmaps are continually being updated based on feedback from the broader aeronautics research community [2]. The NASA Aeronautics research vision is implemented through a set of 4 programs – Advanced Air Vehicles Program (AAVP), Airspace Operations and Safety Program (AOSP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP). The Intelligent Control and Autonomy Branch (ICAB) 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 for aero-propulsion systems that will help meet the goals of the ARMD programs. These efforts are primarily under the various projects under AAVP, AOSP, and TACP. The ICAB current research tasks in support of ARMD program are described in this paper. The paper provides motivation, background, technical approach and recent accomplishments for these tasks, as well as a couple of tasks completed in the previous fiscal year.

Refs:

[1] https://www.nasa.gov/aero/strategic_vision

[2] https://www.nasa.gov/aeroresearch/strategy



NASA Aeronautics Program Structure

This chart provides an overview of the NASA Aeronautics Research Mission program structure.

The mission programs are meant to be Technology Readiness Level 2-6, while the seedling program is meant for investigating new innovative ideas. The Leading Edge Aeronautics Research for NASA (LEARN) program is for funding proposals from industry and academia. Each of the projects listed under the Mission programs typically has NRAs (NASA Research Announcements) requests focused on very specific technology needs to meet the project goals. Go to http://www.aeronautics.nasa.gov/nra.htm to see the list of open NRAs.

The red ovals around the projects represents projects where Intelligent Control and Autonomy Branch has research tasks associated with propulsion controls and diagnostics technologies. The solid oval indicates a project which is supporting research in propulsion controls as a discipline, while the dashed ovals indicate areas where our research supports other tasks. The NASA centers listed in parenthesis for each project is where the project is managed. The centers are: AFRC – Armstrong Flight Research Center, ARC – Ames Research Center, GRC – Glenn Research Center, and LaRC – Langley Research Center.

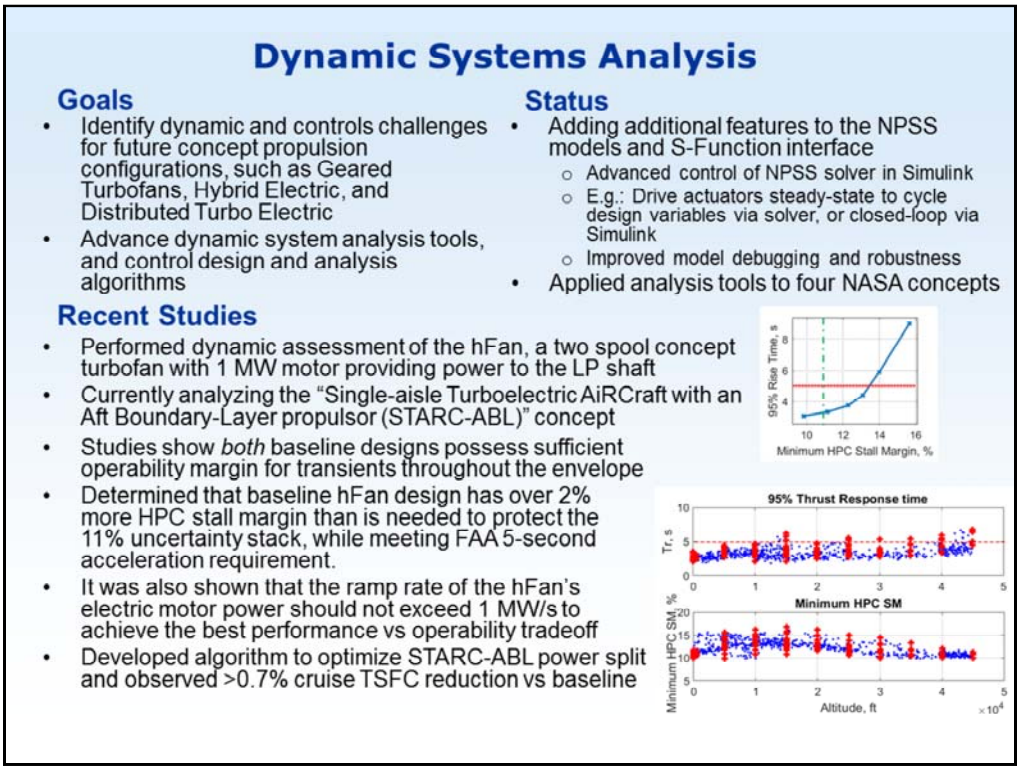
ICAB FY18 "Aero Controls" Tasks

The Intelligent Control and Autonomy Branch (ICAB) tasks under the NASA Aeronautics Research Mission Directorate programs, and the program/project that support these tasks, are listed above. These tasks, except for the tasks under the HTP (Hypersonic Technology Project) are described in the rest of the paper in terms of task objectives and current progress. The work under the HTP falls under ITAR (International Traffic in Arms Regulations) and cannot be discussed in public forums.

The other project acronyms are: AATT – Advanced Air Transport Technology, TTT – Transformational Tools and Technologies, CAS – Convergent Aeronautics Solutions.

The tasks listed with * at the end are expected to conclude at the end of FY18 – September 2018, although current project planning indicates an interest in continuing the Active Turbine Tip Clearance Control task into the future years. Most of the tasks are led by ICAB team members except a couple indicated by ** where ICAB staff is in a supporting role of a task led by another group. Many of the tasks are multi-disciplinary in nature with ICAB staff working with members of various other organizations at GRC, specially members of the Branches under the Propulsion Division.

The paper also includes a description of two tasks that were completed at the end of FY17. These are: Engine Icing Mitigation and Detection, and Run Time Assurance of Advanced Control Logic.



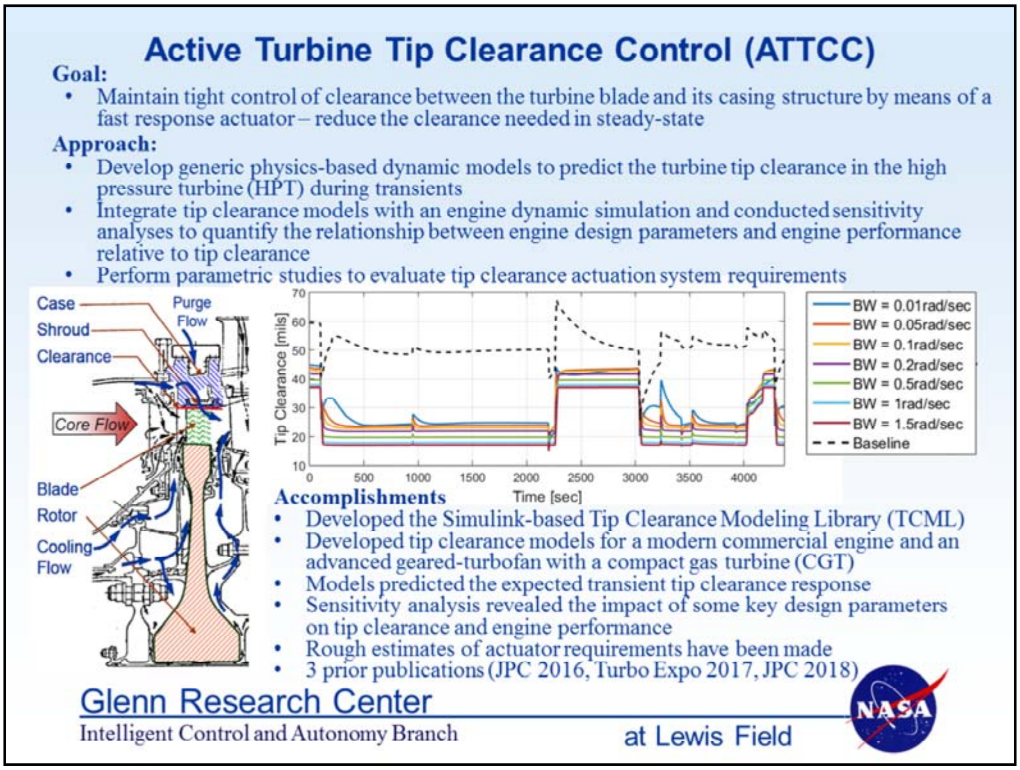
Dynamic Systems Analysis

Systems Analysis is typically done with steady state performance in mind. However, for complex systems such as aircraft engines, the capability to meet transient performance requirements over a wide operating envelope and a long operating life is critical. The steady-state performance based system analysis approaches do not capture the capability of a system to meet such requirements. The objective of the Dynamic Systems Analysis (DSA) task is to develop tools and techniques that can be used to evaluate competing configurations and technologies from the perspective of being able to meet transient performance, operational life and safety requirements. DSA studies provide information to inform the propulsion system design process.

Previously, the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) was developed as an initial step for DSA. It is a semi-automated control design tool for aircraft engine simulations. The purpose of this tool is to provide the user a preliminary estimate of the transient performance of an engine model without the need to design a full nonlinear controller. The application of the tool provided a means to analyze the trade-off available between engine responsiveness and minimum stall margin requirements for a given engine. Additional analysis tools have since been developed into an in-house version of TTECTrA to enable transient analysis of a variety of NASA N+3 concept propulsion systems.

More recent studies have been conducted to answer questions about the transient behavior and operability of hybrid- and turbo-electric concepts. First, the transient feasibility of these concepts was demonstrated by developing full-envelope closed-loop controllers for these systems, and verifying the resulting closed-loop system protects transient operability margins while meeting performance requirements. Beyond this, it was shown that the hFan concept system possesses over 2% more HPC (High Pressure Compressor) stall margin than necessary to protect its uncertainty stack stall margin while meeting performance requirements, and that the rate limit of the hFan's motor power should be limited to 1 MW/s in order to obtain the optimal tradeoff between performance (acceleration response time) and operability (HPC stall margin). A method was also developed for optimizing the steady-state power split in the STARC-ABL system, that delivers a TSFC reduction between 0.7 and 1% versus the baseline power split developed based on simplified relationships between cycle design variables.

Ref: George Thomas, Dennis Culley, Jonathan Kratz, and Kenneth Fisher, "Dynamic Analysis of the hFan, a Parallel Hybrid Electric Turbofan Engine," 2018 AIAA Joint Propulsion Conference, Cincinnati, OH, July 9-11, 2018.



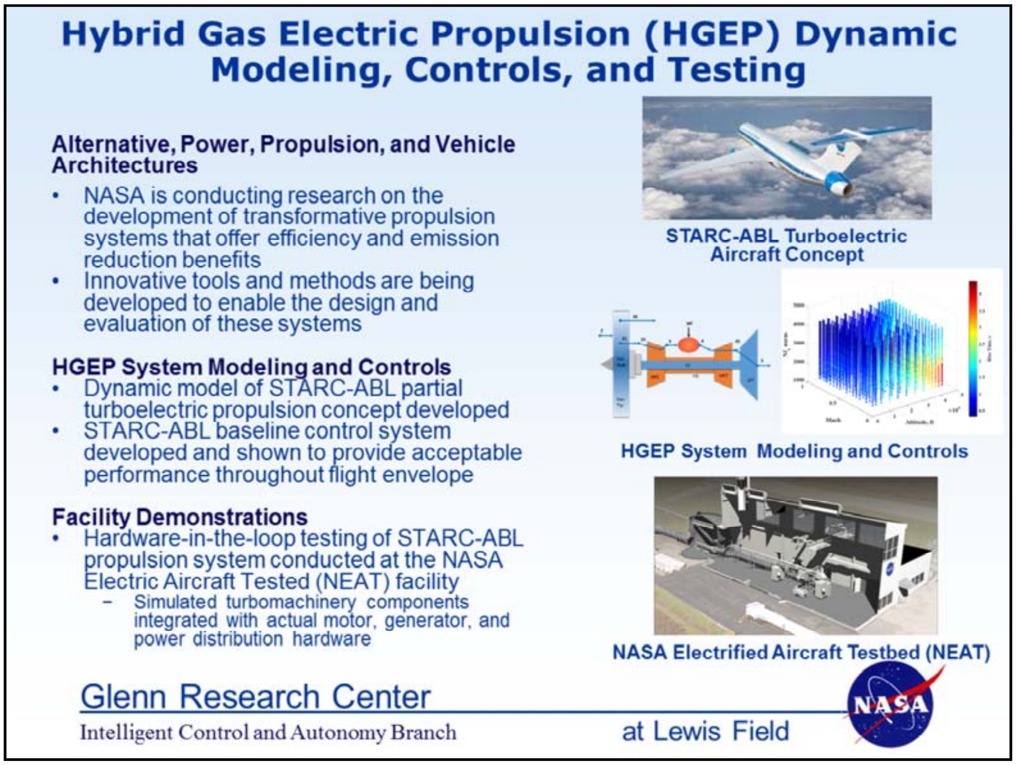
Active Turbine Tip Clearance Control (ATTCC)

Gas turbine blade tip clearance for axial turbines has been a major concern in aircraft engine design due to the direct correlation between effective tip clearance and turbine efficiency. There is a desire to actively control turbine tip clearance. During engine operation, maintaining a tip clearance that is close enough to effectively seal while also far enough to reduce the possibility of the rotating blade unintentionally rubbing the static structure is a design objective. Studies have shown that for a high bypass turbofan, a 10 mil (.01 in) reduction of clearance can result in a SFC (Specific Fuel Consumption) improvement of 1%.

NASA research effort has focused on developing modeling tools and system level models for turbine tip clearance. This modeling approach utilizes engine flow temperatures, rotational speeds, assumed geometries, and material properties to calculate the transient expansion and contraction of engine structures, such as the rotor, turbine blades, or engine casing. This provides generic physics-based dynamic models to predict the tip clearance variation in the high pressure turbine (HPT) which are then integrated with the respective engine dynamic simulation to conduct various studies. The studies include sensitivity analyses to quantify the relationship between engine design parameters, tip clearance, and performance, and parametric studies to evaluate requirements for turbine tip clearance actuation systems.

Through this research effort there have been several noteworthy accomplishments. The turbine tip clearance modeling approach has been put into a Simulink-based software package known as the Tip Clearance Modeling Library (TCML) and should be available for download soon. Integrated engine and tip clearance models have been developed for applications to a modern high-bypass turbofan using the Commercial Modular Aero Propulsion System Simulation (C-MAPSS40k) and an advanced geared turbofan with a compact gas turbine using the newly developed Advanced Geared Turbofan 30,000lb Thrust (AGTF30) simulation. In both cases the model has demonstrated the ability to predict the expected transient tip clearance response. Sensitivity analysis has helped us to understand the impact that some key design parameters have on tip clearance and engine performance, and parametric analysis of actuator parameters have placed rough requirements on tip clearance actuation systems.

Ref: Kratz, J., and Chapman, J., "Active Turbine Tip Clearance Control Trade Space Analysis of an Advanced Geared Turbofan Engine," 2018 AIAA Joint Propulsion Conference, Cincinnati, OH, July 10-12, 2018.



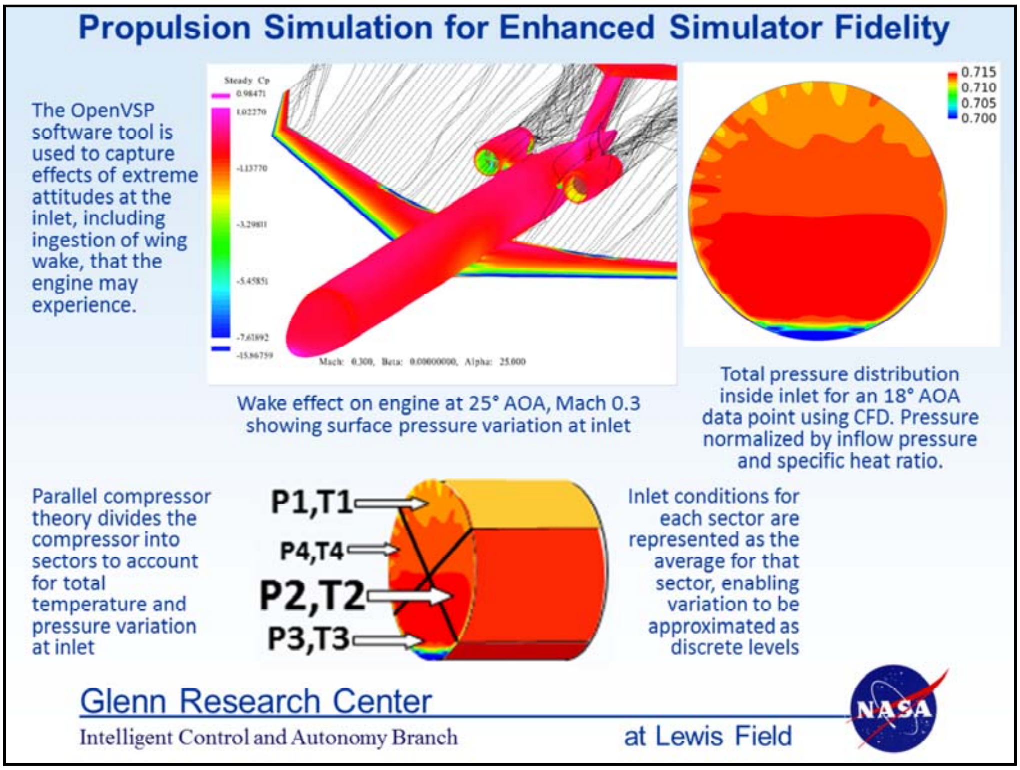
Hybrid Gas Electric Propulsion (HGEP) Dynamic Modeling, Controls, and Testing

NASA is conducting research on the development of clean, transformative aircraft propulsion systems with synergistic vehicle-level integration. This includes hybrid gas electric propulsion (HGEP) designs, which have the potential to provide significant efficiency and emission reduction benefits. One NASA HGEP concept vehicle under consideration is the Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL). STARC-ABL applies a simple distributed turboelectric aircraft propulsion concept consisting of two wing mounted turbofan engines plus an electrically driven boundary layer ingesting tailfan.

To help assess the potential benefits of advanced concepts such as STARC-ABL, NASA has been developing innovative modeling and control development tools. These tools permit the construction of detailed models that capture the coupled dynamic interaction between turbine and electrical subsystems, and the development of integrated control strategies to ensure the operability and performance of the system. These tools have been applied to develop a dynamic model and controller for the STARC-ABL propulsion system. Initial simulation evaluations have shown that the system is capable of providing the required dynamic thrust response over the operating envelope of the aircraft while maintaining safe operation.

Further maturation of the STARC-ABL control design is ongoing through real-time hardware-in-the-loop testing at the NASA Electric Aircraft Testbed (NEAT). NEAT has been developed to enable end-to-end development and testing of a full-scale electric aircraft powertrain. A demonstration of the STARC-ABL propulsion system architecture was recently conducted at the NEAT facility. This concept vehicle consisted of both simulated and actual hardware components. The turbofan and tailfan turbomachinery along with the control system were run in simulation and interfaced to actual electrical system hardware reflecting the power generation and distribution throughout the system. This initial demonstration served as a proof-of-concept for the operation of the STARC-ABL design. Follow-on work will be pursed to further mature the design, including maturation of the control system to ensure optimal dynamic operation.

Ref: Connolly, J., Stalcup, E., “Dynamic Modeling, Controls, and Testing for Electrified Aircraft,” Energy Technology (EnergyTech) Conference, Oct 31-Nov 2, 2017, Cleveland, OH.



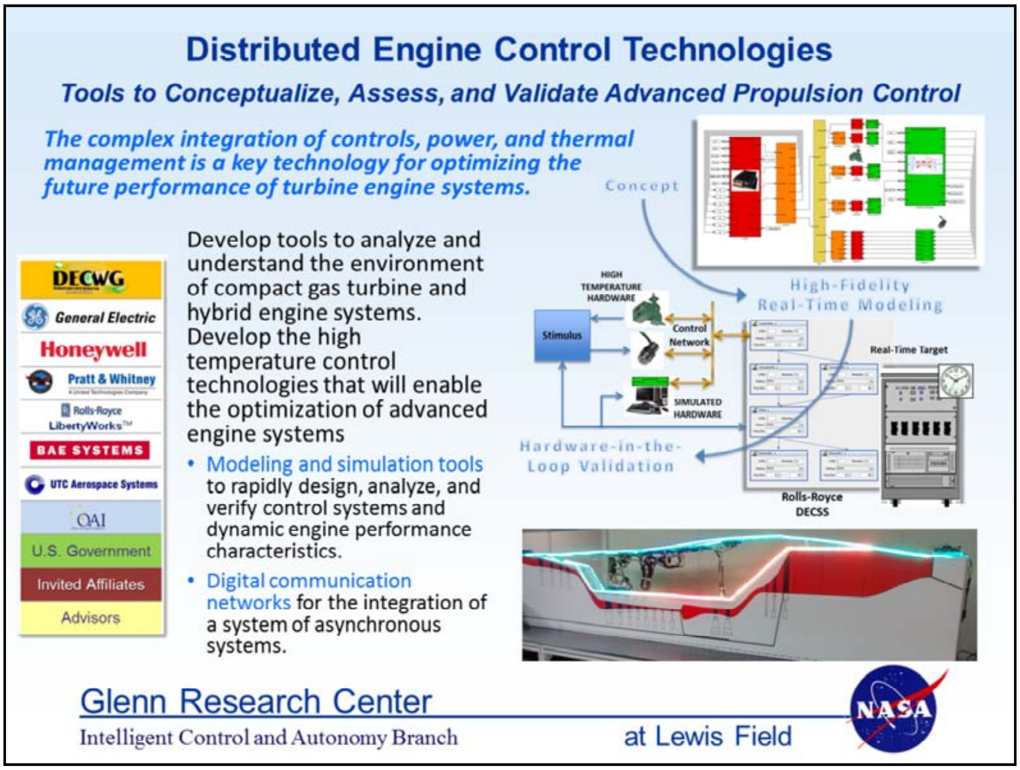
Propulsion Simulation for Enhanced Simulator Fidelity

In 2011, the Commercial Aviation Safety Team (CAST) recommended multiple safety enhancements related to transport aircraft. NASA, in conjunction with the FAA and industry, is working on several of them, including Safety Enhancement (SE) 209: Airplane State Awareness - Simulator Fidelity, with the goal of reducing accidents and incidents due to loss of airplane state awareness and improving pilot performance during recovery from a full stall. The objective of SE 209 is: “To improve pilot performance during recovery from a full Stall, the aviation industry should perform research to determine the benefits of using various levels of prototype advanced aerodynamic modeling of full stall characteristics to perform full stall recovery training.”

NASA’s role under SE 209 is to sponsor and undertake research to define aerodynamic model parameters, along with their availability and associated uncertainties, necessary for replicating full-stall flight characteristics of various aircraft models. While SE209 primarily focuses on aerodynamic stall, it is important to understand engine performance in these situations as well. The propulsion system is impacted by unusual aircraft attitude, such as high angle of attack (AOA) and sideslip. Commercial engines are designed to operate over a limited range of AOA. As AOA gets larger, the airflow into the engine is reduced, resulting in reduced thrust and stability. The purpose of this work is to investigate commercial aircraft engine performance under extreme attitude conditions, taking into account such things as inlet distortion and wake effects. This will result in characterization of the inlet conditions over a range of attitudes for a given aircraft configuration, and through appropriate modeling techniques such as parallel compressor theory, understanding the impact of these conditions on engine performance.

Published work covers the modeling of the effect of high AOA on engine operation using the C-MAPSS40k engine simulation representative of a 40,000 lb thrust class engine. The current emphasis is on developing the models for an engine used in a T-tail short haul aircraft.

Ref: Cunningham, K. S., Shah, G. H., Hill, M. A., Pickering, B. P., Litt, J. S., Norin, S. B., "A Generic T-tail Transport Airplane Simulation for High-Angle-of-Attack Dynamics Modeling Investigations," AIAA-2018-1168, AIAA SciTech Forum, 8-12 January, 2018, Kissimmee, FL.

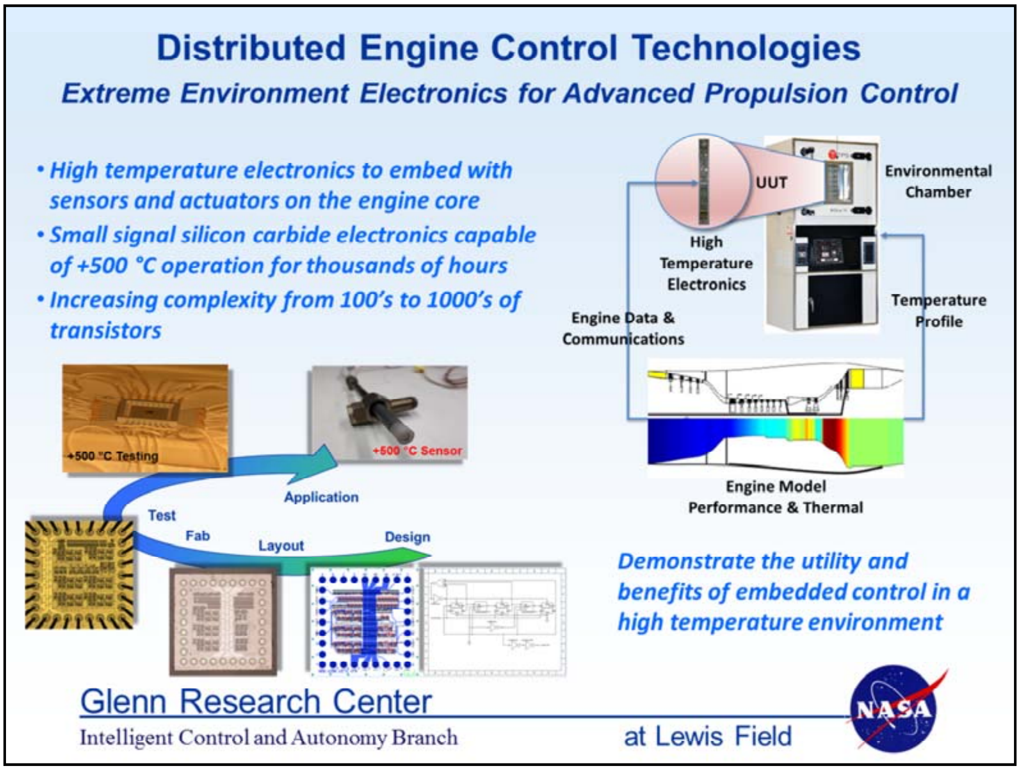


Distributed Engine Control Technologies

Distributed engine control is a hardware technology that radically alters the architecture for aircraft engine control systems from a centralized processing approach to one employing a system of distributed local processors working in unison. Of its own accord, it does not change the function of control, rather it seeks to address the implementation issues for weight-constrained vehicles that can limit overall system performance and increase life-cycle cost. An inherent feature of this technology is the inclusion of a digital communication network, which alters the flow of information between critical elements of the closed-loop control. Whereas control information has been available continuously in conventional centralized control architectures through virtue of analog signaling, moving forward, it will be transmitted digitally in serial fashion over networks from distributed controllers that perform the analog data acquisition.

These changes are being implemented to mitigate system constraints resulting from the rapid advance of propulsion engine technologies that are resulting in more compact, higher performance, higher temperature engines. Distributed control enables a modular control system design that reduces control system design time, lowers maintenance costs, improves availability, and simplifies technology upgrades.

Ref: Culley, D.E., Thomas, G., Aretskin-Hariton, E., “A Network Scheduling Model for Distributed Control Simulation,” 52nd AIAA/SAE/ASEE Joint Propulsion Conference ; 25-27 Jul. 2016; Salt Lake City, UT.

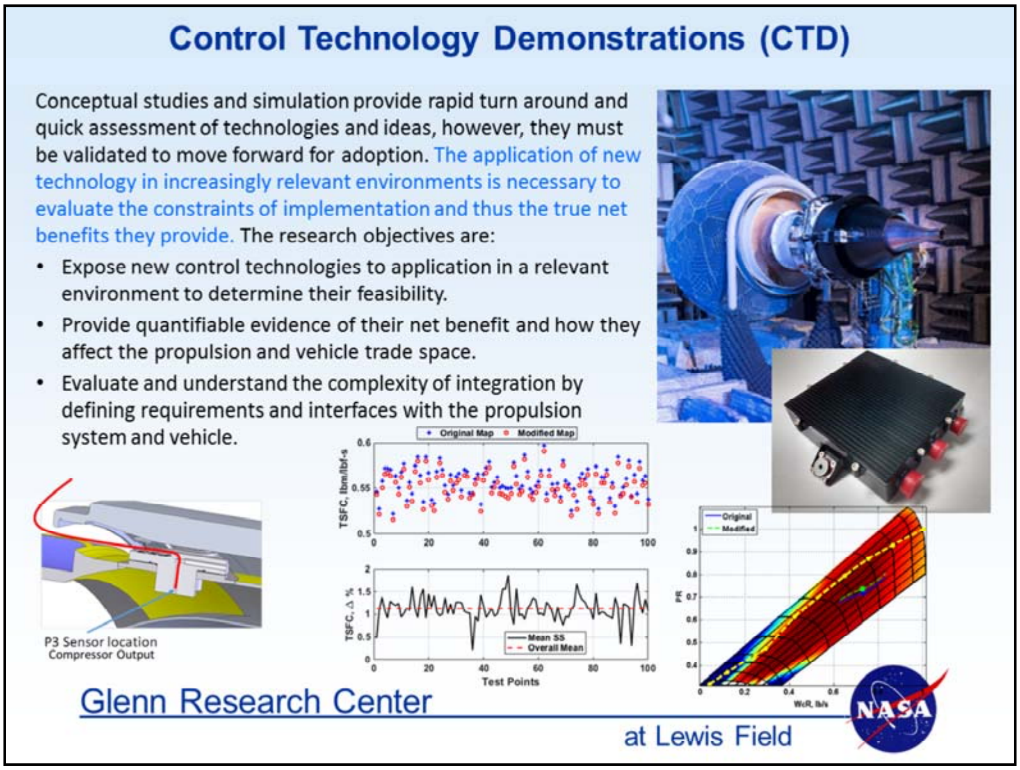


Distributed Engine Control Technologies (Contd.)

Distributed engine control is made more effective by the use of high temperature electronics. Glenn Research Center is a world leader in very high temperature silicon carbide electronics operating at 500°C and above. The DECWG™ industry consortium is also developing specialized processing electronics for engine applications above 200°C. Together these technologies are opening up new capabilities in propulsion control, enabling the distributed architecture.

Progress in very high temperature small-signal silicon carbide electronics has been advanced from simple amplifier circuits containing a few transistors to large scale integration (LSI) integrated circuits (IC) using thousands of transistors. Among the devices being fabricated are high frequency ring oscillators, analog-to-digital converters, and even microprocessors.

Among the milestones are demonstrations of very high temperature sensors and the high temperature processing components that enable the realization of the engine-embedded modules of distributed engine control architecture. These can be coupled to simulations of the performance and thermal models of the engine environment.



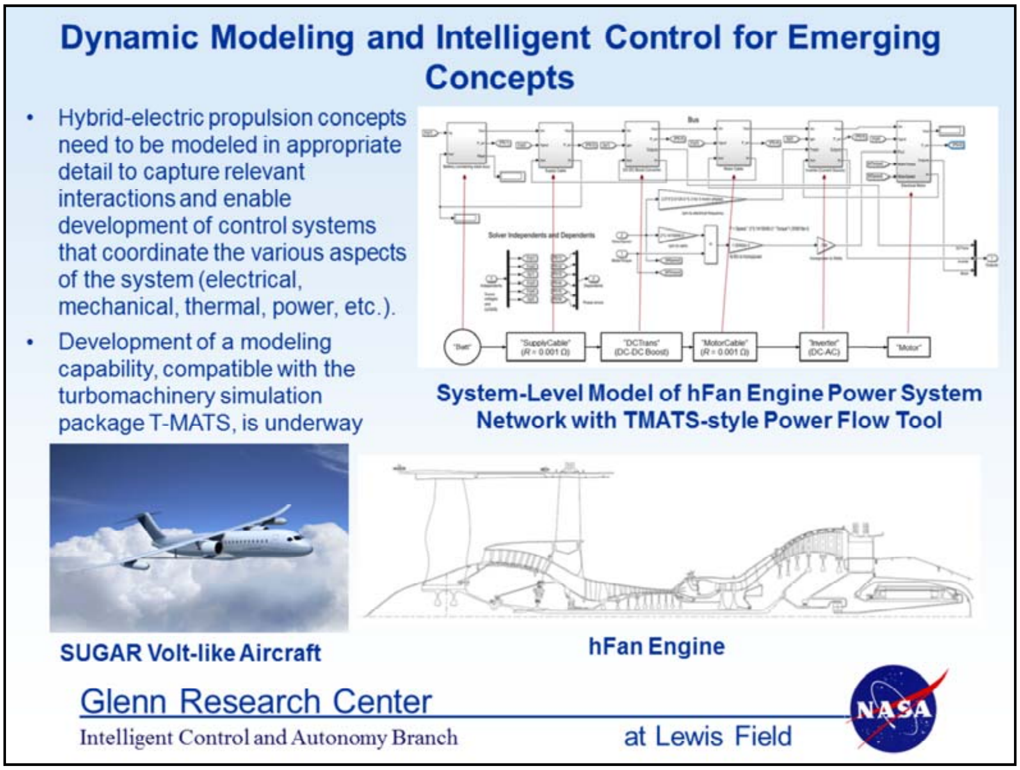
Control Technology Demonstrations (CTD)

Under the Control Technology Demonstration (CTD) task of the TTT project, ICAB is working towards maturing and demonstrating several control technologies in relevant environments. A test facility called DART (DGEN Aero-Propulsion Research Turbofan) has recently been established at GRC with the DGEN 380 Turbofan engine. The DGEN 380 is a dual spool, high bypass geared turbofan rated for 500 lb thrust and is equipped with a FADEC (Full Authority Digital Engine Control). It provides an excellent low cost platform to validate advanced control logic schemes through engine test.

Near term plans are to install and test several new sensor technologies. These high temperature sensors improve measurement accuracy and also have the capability for wide-bandwidth, which enables additional insight into the dynamic operation of the engine. When coupled with high temperature signal processing capability, they enable new information to be extracted from the engine system for improved performance and safety while off-loading the processing burden in the engine controller.

Also slated are a series of tests that employ model based control and other advanced control algorithms that improve engine performance through the use of an on-board, real-time engine model that accurately predicts the exact state of the engine dynamics over its life cycle. Use of this technology can be fed back into the engine design during development to perform system trades that safely reduce excess design margin so that it can be applied to reducing fuel burn, weight, and cost. Work has been done to develop a dynamic model of the DGEN engine which is currently being used to design a model based engine control for implementation and testing in DART in late 2019.

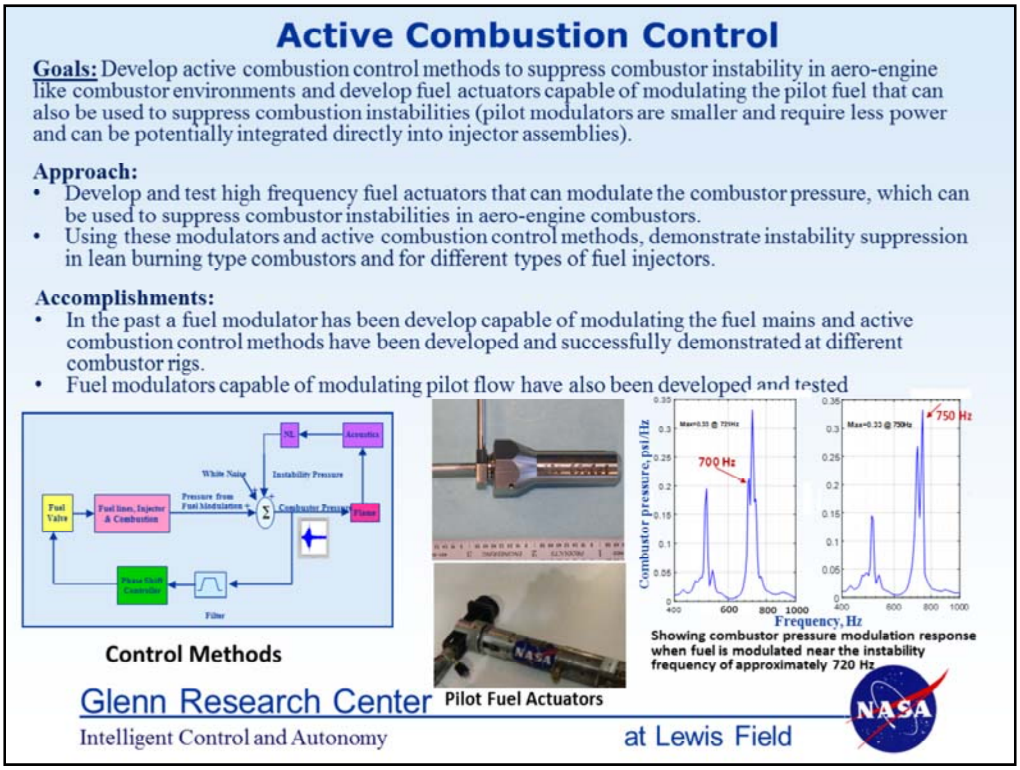
Ref: Connolly, J., Csank, J., Chicatelli, A., and Franco, K., "Propulsion Controls Modeling for a Small Turbofan Engine," AIAA 2017 Joint Propulsion Conference, Atlanta, GA, July 10-12, 2017.



Dynamic Modeling and Intelligent Control for Emerging Concepts

Hybrid/turbo electric or fully electric propulsion systems are being explored by researchers with the aim of improving fuel efficiency, emissions, and noise levels. As newer concepts are developed, it is important to create propulsion system level simulations that take into account the increasingly complex electrical system. However, much of the very high frequency behavior of the electrical system is irrelevant when considering the dynamics of the overall system. Therefore, these propulsion concepts need to be modeled in appropriate detail to capture relevant interactions and enable development of control systems that coordinate the various aspects of the system (electrical, mechanical, thermal, power, etc.). The ability to model these electrified propulsion systems at the appropriate time scale to capture the relevant interactions is necessary for coordination of the disparate parts; it allows the development of requirements for the integrated system. The approach taken here is to develop a modeling toolbox for electrical system components compatible with the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS), NASA's Open Source graphical building block language for the creation of turbomachinery models. Creating this capability within a graphical framework will enable rapid prototyping of simulated concept engines in a natural environment for control system design. The preliminary work in this area has already resulted in a Power Flow (an analysis method for power grids) Modeling capability compatible with T-MATS being developed and validated. This new tool has been used to build dynamic models of several hybrid electric propulsion concepts, including the NASA hFan (Parallel Hybrid Electric Turbofan, for SUGAR Volt-like aircraft) power system.

Ref: Chapman, J.W., and Litt, J. S., "An Approach for Utilizing Power Flow Modeling for Simulations of Hybrid Electric Propulsion Systems," 2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), Cincinnati, Ohio, 12-13 July 2018.



Active Combustion Control – Fuel Modulator Development

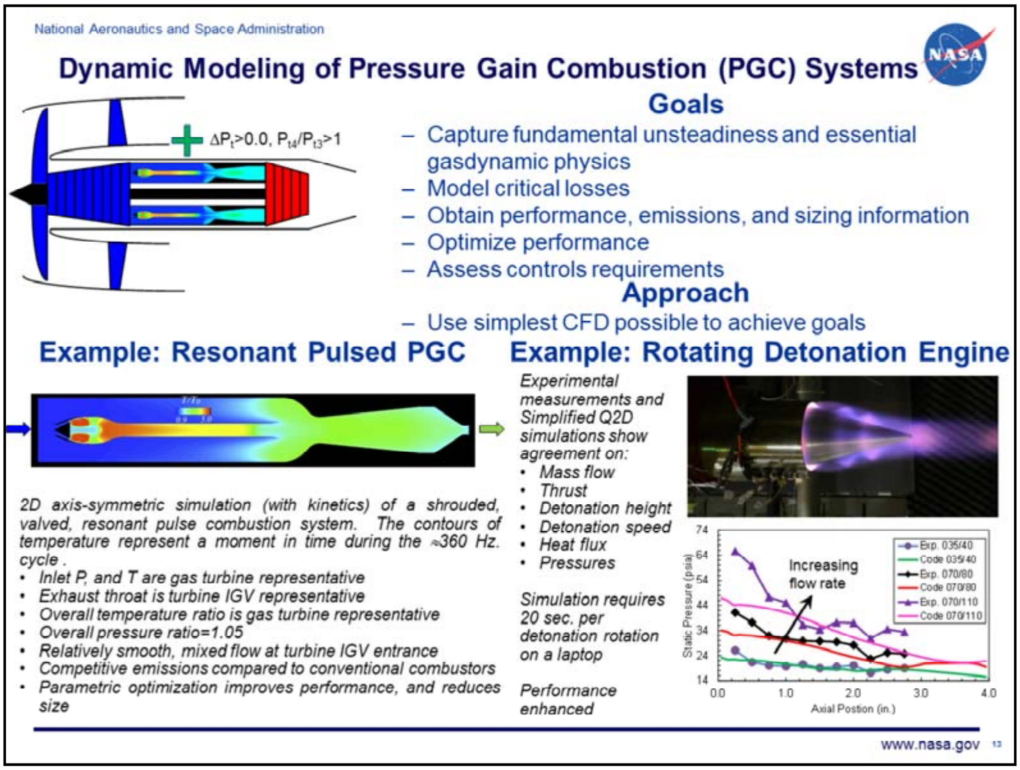
Lean burning combustors are advantageous for the reduction of emissions, like NOx and particulates, to meet NASA goals. However, these combustors are prone to combustor instabilities, and mitigation of these instabilities is an enabling technology for lean burning combustors. Academia, NASA, and Industry have worked to find ways to mitigate these instabilities either passively or by active combustion control. Active combustion control offers a more encompassing solution for this problem as it can potentially cover the whole operating envelope of the engine.

In the past, active combustion instability suppression using the Adaptive Sliding Phasor Average Control (ASPAC) method has been successfully demonstrated by NASA at different combustor test cells operating at engine pressures, temperatures, and flows, and with different injectors. A critical component in the control loop is a high-frequency fuel valve used to perturb the combustor fuel flow. For these demonstrations, a high frequency fuel modulator was developed and used to modulate the fuel mains.

For the current effort, smaller size modulators have been developed capable of modulating the pilot fuel. These modulators require less power and potentially they can be integrated directly into the injector assemblies, which can also simplify their thermal management. Pilot fuel modulators have been recently tested at NASA GRC, and it has been demonstrated that such a modulator can sufficiently perturb the combustor pressure to be used for active combustion control. These tests for the fuel modulators are currently ongoing, and in the near future the plan is to demonstrate active combustion control using only pilot fuel.

The figures show a simulation diagram for the ASPAC method, two of the pilot fuel modulators that are currently being tested, and the spectral densities of combustor pressure for fuel modulation applied at discrete frequencies, near the instability frequency of approximately 720 Hz.

Ref: Kopasakis, G., Thomas, R., Saus, J. R., Chang, C. T., “Combustor Pressure Response to Pilot Fuel Modulation for Active Combustion Control,” AIAA Joint Propulsion Conference, July 9-11, 2018, Cincinnati, OH.



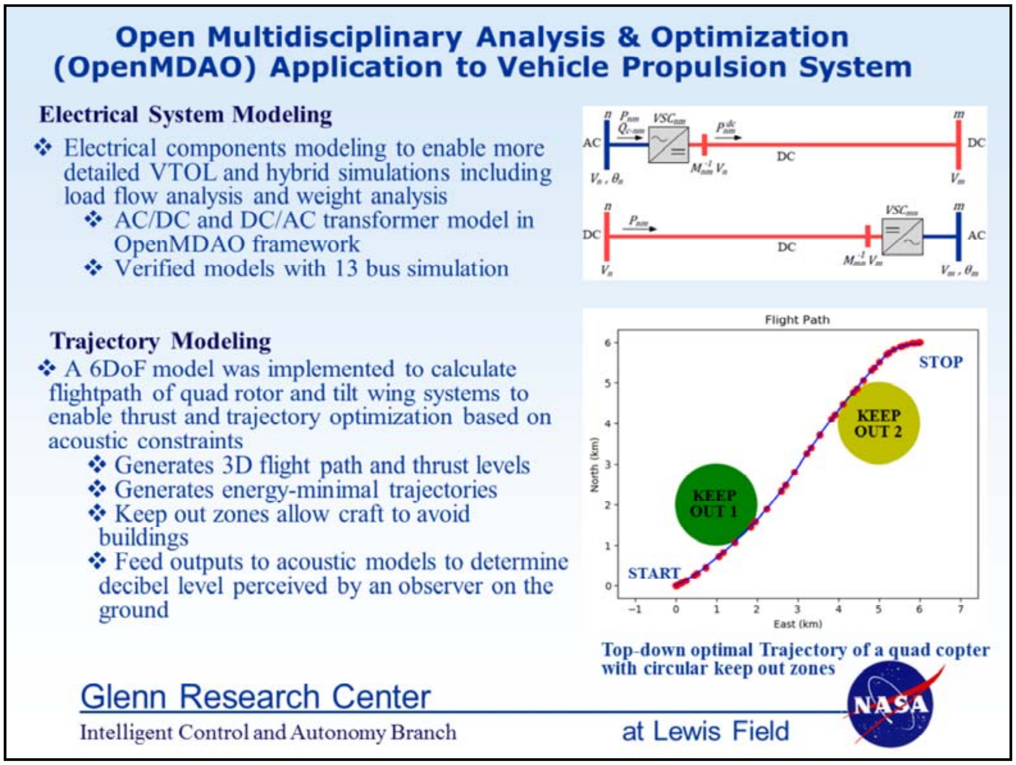
Dynamic Modeling of Pressure Gain Combustion (PGC) Systems

Pressure gain combustion (PGC) is under investigation for the full range of air breathing flight applications. Of particular interest is the potential application to gas turbines. Here, the pressure rise (as opposed to a conventional combustor pressure loss) yields higher engine thermal efficiency and specific power. All PGC systems are fundamentally unsteady. They achieve limit-cycle, not steady state, operation. Furthermore, they are fluidically (though not mechanically) complex. As such, there is a certain level of fidelity that models require in order to capture the physics and provide utility as design and optimization tools. The current PGC modeling effort is focused on providing such fidelity, but not more than is necessary. This effort has led to the use of simplified CFD approaches, two of which are illustrated above.

The left side shows output from a 2D axi-symmetric simulation of a so-called resonant pulse combustor. These are among the simplest of the PGC systems. They provide the least amount of pressure gain, but their simplicity, robust operation, relatively smooth effluent, and low emissions potential are attractive. They have also been successfully integrated and operated in gas turbine systems. The right side compares simulated and measured results from a rotating detonation engine (RDE). These PGC devices produce some of the highest pressure gains, but also produce high heat loads, substantial flow non-uniformities, and valving challenges. The flow in an RDE is nominally axial, however, the detonation travels circumferentially and continuously.

Conventional measurements are extremely difficult to make in PGC devices. The unsteadiness, heat loads, and frequency requirements render most sensing elements useless, or non-functional. Validated CFD tools such as those described here can therefore provide insights where instrumentation cannot. They can also help explain anomalous bulk experimental results that can be measured such as thrust and flow rate.

Ref: Paxson, D., “Examination of Wave Speed in Rotating Detonation Engines Using Simplified Computational Fluid Dynamics,” 2018 AIAA SciTech Forum, Jan. 8-11, Kissimmee, Florida.

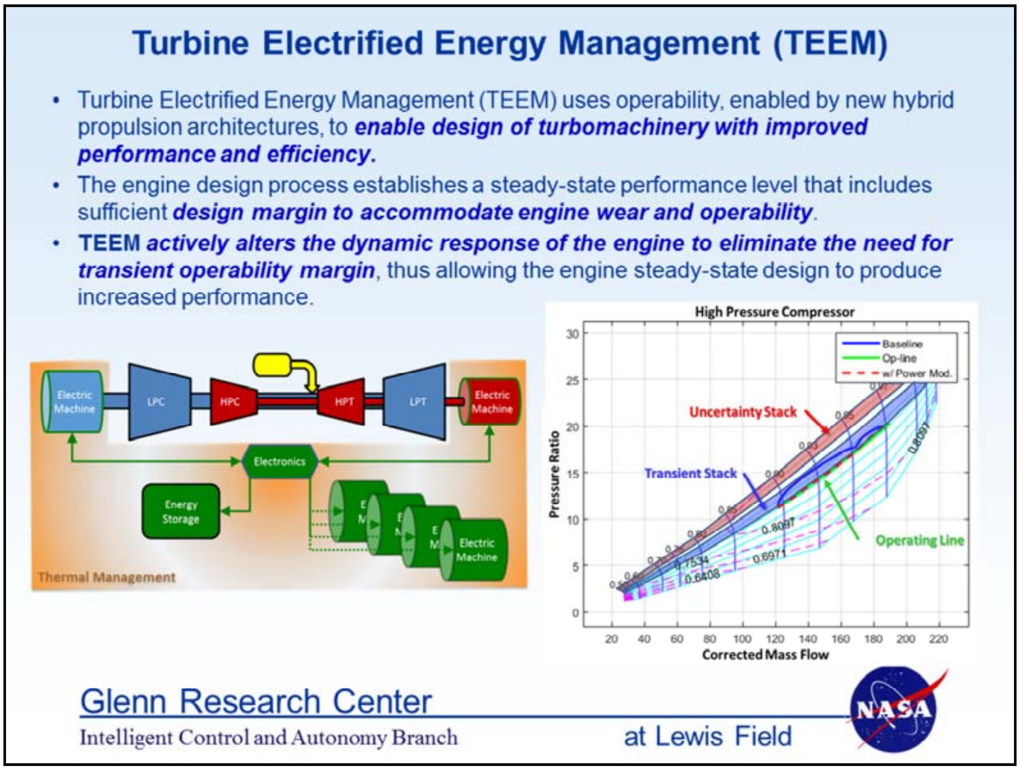


Open Multidisciplinary Analysis and Optimization (OpenMDAO) Application to Vehicle Propulsion System

The OpenMDAO project is currently working to develop an integrated design capability for hybrid electric Urban Air Mobility vehicles, including aerodynamics, propulsion, structures, thermal, trajectory, and acoustics models. ICAB work for OpenMDAO involves two aspects: electrical subsystem modeling to enhance the propulsion subsystem models; and transient trajectory modeling using a pseudo spectral optimal control scheme.

The electrical subsystem model is being developed to simulate complex power distribution grids for hybrid electric aircraft. This will allow for thermal and weight considerations to be integrated into the overall optimization. The models are being built using a load-flow based analysis scheme. The models have been validated against a 13 bus power distribution grid published in the literature.

A six degree of freedom (6 DoF) model for quad rotor motion, based on work by Randal Beard at Brigham Young University, was implemented in the OpenMDAO framework. This allows us to use optimal control approaches to determine aircraft thrust and moment demand. The current simulation in the second graph shows a top down view of the trajectory of an electric unmanned quad rotor configuration for 200lb package delivery as described in “Concept Vehicles for VTOL Air Taxi Operations”. This is an impulse minimization trajectory (the system is trying to create as little thrust as possible to travel from the start area at [0,0] to the end area at [6,6], a point located 8.5 km away from the start). Two keep out zones are placed in the trajectory path to simulate buildings or local air fields. The control system solves the optimal control problem using the Legendre-Gauss-Radau pseudospectral method. The vehicle travels North and East and successfully avoids the keep out zones. The next step with this work is to connect the trajectory component to the acoustic model that determines the amount of noise created by the craft for a given orientation, thrust level, and prop blade configuration. Additional optimizations can then be run using constraints for maximum allowable noise for a ground observer.

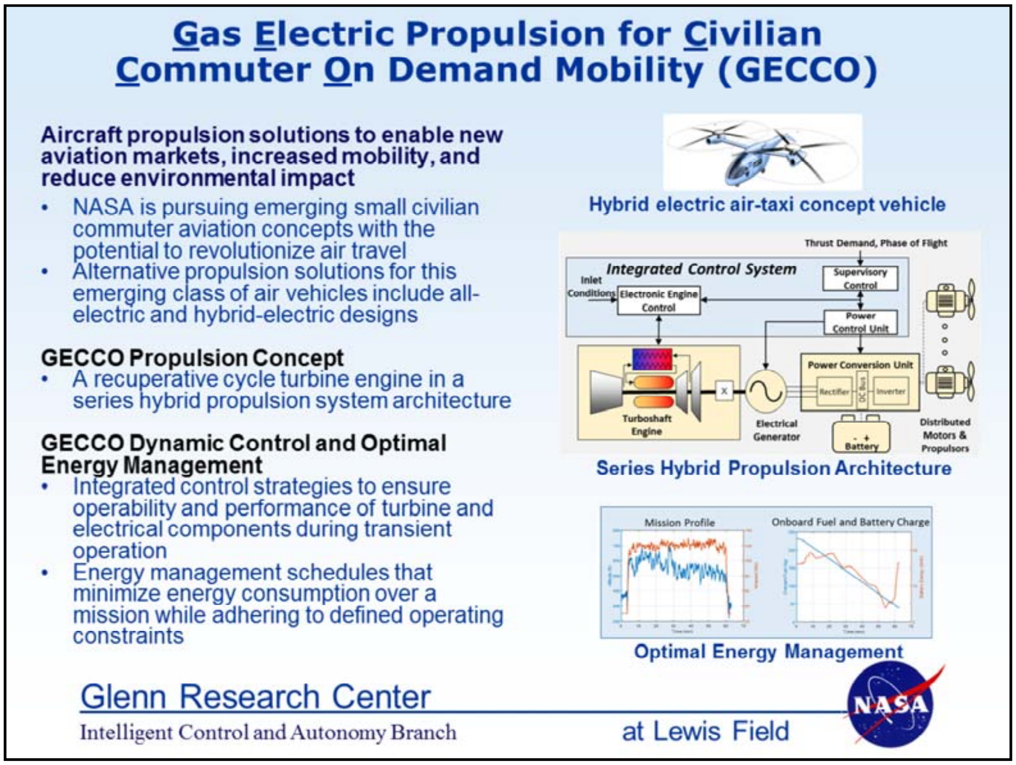


Turbine Electrified Energy Management (TEEM)

NASA is investing in Electrified Aircraft Propulsion (EAP) research in an effort to achieve the goals to increase fuel efficiency, reduce emissions, and reduce noise levels for commercial transport aircraft. The addition of electrical machines to the propulsion system is expected to have a significant impact on commercial aircraft efficiency, mainly through increasing the effective bypass ratio of the propulsion system, and energizing low momentum airflow around the aircraft that otherwise contributes to drag. However, less consideration has been given to how the presence of electrical machines could be utilized to improve the performance of the gas turbine system for thrust or power production on the aircraft. In response, an energy management operability concept, referred to as Turbine Electrified Energy Management (TEEM), has been proposed. The concept is a transient control technology that supplements the main fuel control to suppress the natural off-design dynamics associated with changes in operating state. Using electric machines on the engine shaft(s) to add or extract power, the engine can be made to operate on the steady-state operating line during transients, thus greatly reducing the need to maintain transient stall margin stack in the compressors. The concept acts upon the relationship between the low pressure spool speed (N1), high pressure spool speed (N2) and fuel flow (WF), which needs to be maintained to transition the engine power along the steady-state operating line.

The TEEM concept and several of its benefits have been demonstrated through an open-loop example using a model of the hFan propulsion system. The hFan is a parallel hybrid electric turbofan with a 1380 hp electric motor connected to the low pressure spool designed to augment thrust. Concept feasibility has been supported through simulation demonstrating that significant benefits can be achieved with modestly sized motors on each of the engine shafts with a modestly sized energy storage element. Observations from the study revealed that independent control of the shaft speeds could achieve the stated goals of TEEM.

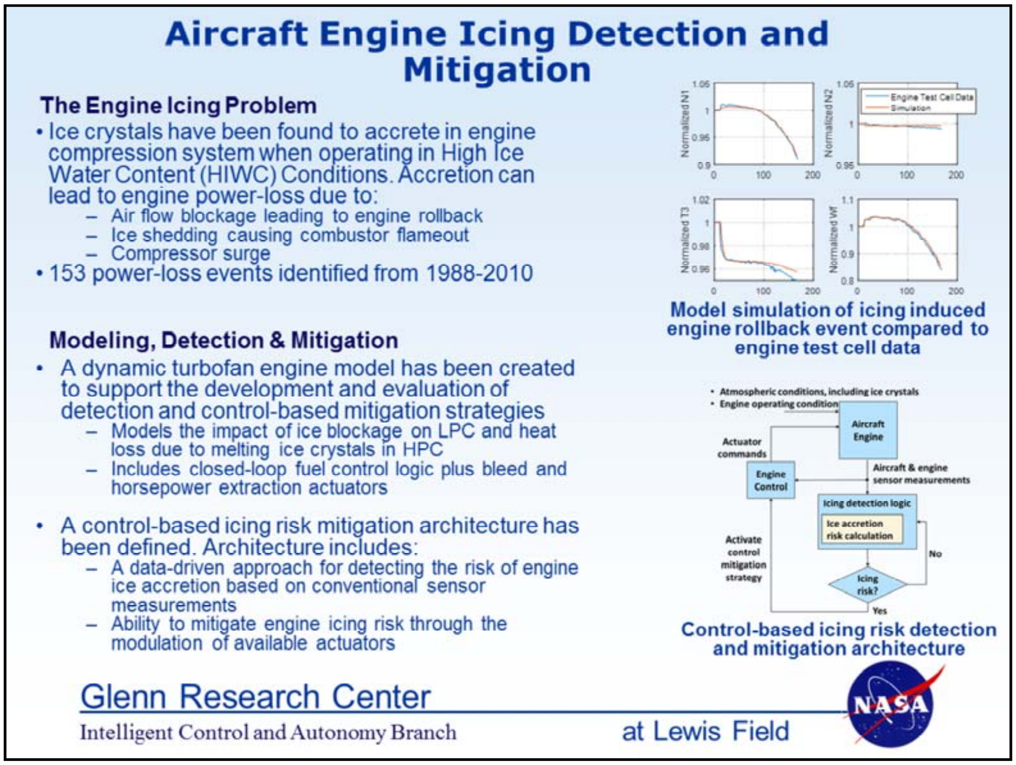
Ref: Culley, D.E., Kratz, J. L., Thomas, G.L., “Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs,” AIAA Joint Propulsion Conference, July 9-11, 2018, Cincinnati, OH.



Gas Electric Propulsion for Civilian Commuter On Demand Mobility (GECCO)

NASA is conducting research in the area of urban air taxi operations, also known as On Demand Mobility (ODM) applications, or urban air mobility. This includes small vertical take-off and landing (VTOL) aircraft with distributed propulsion systems designed to transport people and goods over short ranges. The demand for this emerging aviation market is largely driven by increasing ground-vehicle commute times in densely populated areas. These unique vehicles permit the consideration of non-traditional propulsion concepts. On the smaller range of the power scale required for these vehicles, all-electric propulsion solutions are being considered. However, as range and payload requirements increase hybrid-electric designs, which combine gas turbine and electrical propulsion concepts, are more practical. Recently, NASA has initiated research in the development of a small, efficient, propulsion systems for ODM applications. This effort is titled Gas Electric Propulsion for Civilian Commuter ODM (GECCO). It entails a recuperative cycle turbine engine, using a lightweight, multi-functional heat exchanger, in a series hybrid-electric propulsion system architecture. The series hybrid architecture includes a turboshaft engine, an electrical generator, battery energy storage, and distributed motors and propulsors.

As part of the GECCO effort, NASA is considering the dynamic control and energy management aspects of series hybrid electric propulsion designs. The resulting propulsion system architecture has a high degree of coupling between the turboshaft, the electrical system, and electrically driven propulsors. Changes in individual subsystems will directly impact the operation of other subsystems, and thus an integrated control strategy is required to ensure the operability and performance of each subsystem. The applied integrated control strategy will limit rapid loading or unloading of the torque applied to the turboshaft power turbine shaft to avoid surge or combustor blowout limits. The GECCO activity will also explore the application of optimal energy management strategies developed in the automotive industry for hybrid electric propulsion designs. These techniques apply analytical and numeric optimization methods to produce energy management schedules that minimize fuel burn over a given mission while adhering to defined operating constraints (e.g., ensuring minimum onboard fuel reserves, turbine maximum continuous power limits, battery maximum discharge rates, battery state-of-charge, etc.)

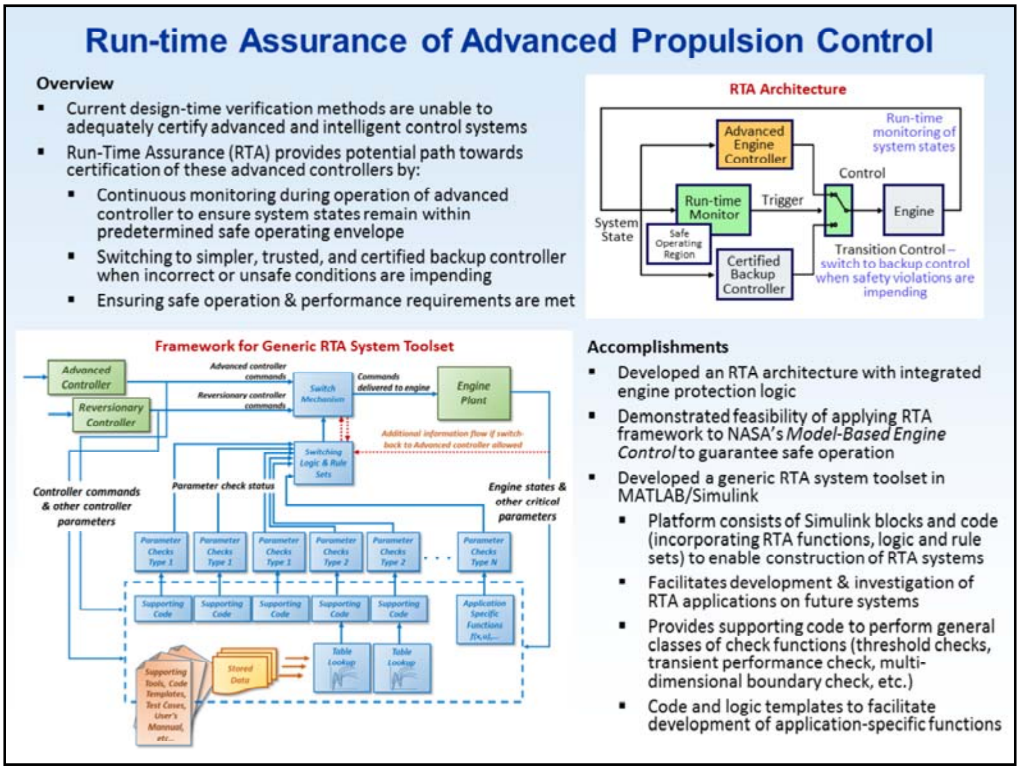


Aircraft Engine Icing Detection and Mitigation

Aircraft flying in regions of high ice crystal concentrations are susceptible to the buildup of ice within the compression system of their gas turbine engines. This ice buildup can restrict engine airflow and cause an un-commanded loss of thrust, also known as engine rollback, which poses a potential safety hazard. The aviation community is conducting research to understand this phenomena, and to identify avoidance and mitigation strategies to address the concern. To support this research, a dynamic turbofan engine model has been created to support the development and evaluation of engine icing detection and control-based mitigation strategies. This model captures the dynamic engine response due to high ice water ingestion and the buildup of ice blockage in the engine's low pressure compressor. It includes a fuel control system allowing engine closed-loop control effects during engine icing events to be emulated. The model also includes bleed air valve and horsepower extraction actuators that, when modulated, change overall engine operating performance. This system-level model has been developed and compared against test data acquired from non-production (experimental) version of the Honeywell ALF502-R5 turbofan engine that underwent engine icing studies in an altitude test facility at NASA GRC.

A control-based architecture providing an integrated strategy for the detection and mitigation of the engine ice accretion risk has been proposed. If an engine icing event is detected or an elevated risk of engine icing is identified, a control mitigation action will be taken to move the engine to an operating point of lower risk for ice accretion. The detection logic monitors conventionally available engine sensor measurements to detect operating conditions and engine thermodynamic performance changes indicative of ice accretion risk. The detection logic's ability to detect engine operating conditions at risk of ice accretion has been demonstrated using engine test cell data. In their present form, the architecture and dynamic engine model can facilitate follow-on work to assess the feasibility and effectiveness of control-based icing risk mitigation strategies.

Ref: Simon, D.L., Rinehart, A. W., Jones, S., M., "A Dynamic Model for the Evaluation of Aircraft Engine Icing Detection and Control-Based Mitigation Strategies," ASME-GT2017-65128, ASME Turbo Expo 2017, June 26-30, 2017, Charlotte, NC.



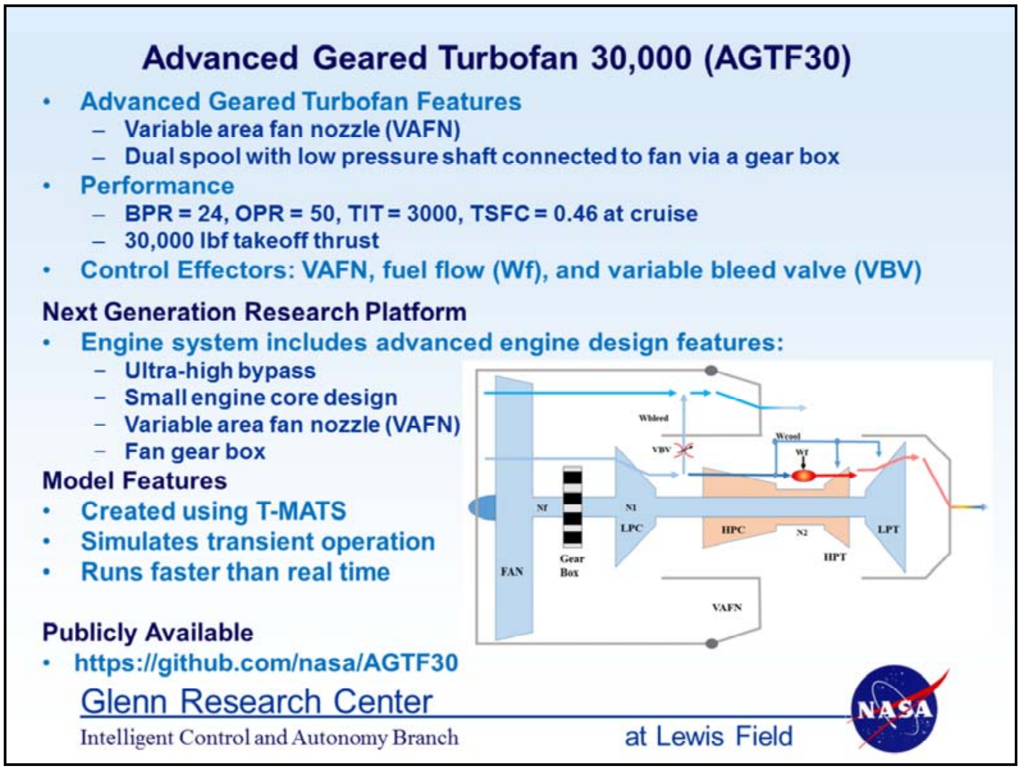
Run-time Assurance of Advanced Propulsion Control

Safety and operational requirements for modern aircraft systems call for increasingly advanced control capabilities. Before these advanced algorithms can be deployed, it must be assured that they never instigate instabilities that can impact the safety of the aircraft. Certification of such systems will require thorough verification and validation (V&V) to achieve high confidence in their safety. As these algorithms become progressively complex, it is anticipated that certification will become prohibitively costly and, ultimately, infeasible using current V&V practices. One potential means to addressing this shortfall in V&V capability is the use of run-time methods in an enabling role.

An approach called Run-Time Assurance (RTA) has been developed that holds the promise of certifying these advanced controllers by continuously monitoring the state of the feedback system during operation. The framework achieves safety assurance by ensuring that system states remain within predetermined safe operating limits. In the event that anomalous behavior is detected, control is automatically reverted to a simple certified backup controller that assures continued safe operation of the system, albeit at a reduced performance level.

A research study has successfully demonstrated the RTA framework's ability to guarantee the safe closed-loop operation of an experimental, NASA-developed model-based engine controller (MBEC) comprising an advanced Kalman filter parameter estimator and thrust-estimate controller. Results illustrate the potential benefits of using RTA to protect engine operation and point towards a possible run-time approach to enabling the in-flight operation of advanced controllers. An outcome of this research is the development of a generic RTA system toolset for use in the MATLAB/Simulink environment. This platform consists of Simulink blocks and code, which incorporate the necessary RTA functions, logic, and rule sets to facilitate the construction of RTA systems. This capability allows researchers to easily develop, test and investigate the application of the RTA approach to future advanced control systems.

Ref: Schierman, J., Neal, D., Wong, E., Chicatelli, A., "Runtime Assurance Protection for Advanced Turbofan Engine Control," AIAA 2018 Guidance, Navigation, and Control Conference, Kissimmee, FL, January 8-12, 2018.



Advanced Geared Turbofan 30,000 (AGTF30)

The AGTF30 model represents a hypothetical 30,000 lbf thrust class geared turbofan engine that includes a variable area fan nozzle, a gearbox connecting the low pressure shaft to the fan shaft, and a relatively small engine core. It is representative of the types of ultra-high bypass ratio engine concepts developed under NASA sponsored N+3 studies with Engine In Service date of 2035. AGTF30 was developed using the GRC-developed Toolbox for the Modeling and Analysis of Thermodynamic Systems, which is based on MATLAB/Simulink. The AGTF30 is a full envelope simulation that may be run steady-state or dynamically, using a set of input files. It has the capability to generate linear models in the form of state-space equations, which allows researchers to design, implement, and test control algorithms and concepts directly in the MATLAB/Simulink environment. The AGTF30 is free, open-source software available online at the NASA GIT repository: https://github.com/nasa/AGTF30.

A full envelope baseline control design was developed for the AGTF30 to enable investigation of advanced control approaches. This closed-loop model is being used extensively in the various research tasks described in this paper.

Ref: Chapman, J. W., and Litt, J. S., "Control Design for an Advanced Geared Turbofan Engine," AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA, July 10-12, 2017.

6th GRC Propulsion Control and Diagnostics Workshop

The 6th GRC PCD (Propulsion Control and Diagnostics) Workshop was held on Aug. 22-24, 2017 at the Ohio Aerospace Institute, Cleveland, OH. The objectives of the workshop were to: Disseminate information to the research community about the propulsion control and diagnostics research being done by the ICAB in support of various projects under the NASA Aeronautics Research Mission Directorate (ARMD) programs; get feedback from peers on the value of the research and validity of the technical approach; and identify opportunities for potential collaboration and sharing of tools and methods.

The workshop consisted of: detailed presentation on ongoing research in aircraft engine control and diagnostics covering progress to date, future plans, and tools and simulations available for public use; DoD (Air Force, Army and Navy) panel and industry panel to discuss ongoing research in various organizations and future vision for engine control; poster session with demonstration of GRC developed software packages for engine simulation, control design and evaluation, and poster presentations by our partners and select research community members; and one-on-one discussions between NASA researchers and attendees to answer any questions and identify potential collaboration opportunities. Additionally, a tour of the controls research facilities was provided for the attendees. There were about 30 attendees from academia, industry and government with a large portion being from the industry. The feedback from the attendees was extremely positive in terms of the workshop meeting the sated objectives and the opportunity it provides for networking within the aero-propulsion control and diagnostics research community.

The presentations from the workshop are available as a published NASA CP (Conference Proceedings). Below is a sample of overall feedback provided by some of the attendees:

- The workshop provided informative sessions on NASA research and avenues for collaboration.
- Always good conversations. The topics appeared to be more useful to me, than several other conferences that I have been to.
- Requesting the participants for their feedback and comments created an interactive experience
- Excellent! Really appreciated being here and would love to come again!

Concluding Remarks

The Intelligent Control and Autonomy Branch (ICAB) at NASA GRC (Glenn Research Center) is working in strong partnership with industry, academia and other government agencies to develop the propulsion control and health management technologies that will help meet NASA's Aeronautics Research Mission goals. 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. We also actively pursue opportunities to disseminate information on our technology development efforts to the aerospace research community by presenting papers at technical conferences, holding the GRC Propulsion Control and Diagnostics Workshop on a bi-annual basis, and making available various software tools for enabling advanced research in propulsion control and diagnostics.

Acknowledgement

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