Propulsion Control Technology Development Needs to Address NASA Aeronautics Research Mission Goals for Thrusts 3a and 4

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The Commercial Aero-Propulsion Control Working Group (CAPCWG), consisting of propulsion control technology leads from The Boeing Company, GE Aviation, Honeywell, Pratt & Whitney, Rolls-Royce, and NASA (National Aeronautics and Space Administration) Glenn Research Center, has been working together over the past year to identify propulsion control technology areas of common interest that we believe are critical to achieving the challenging NASA Aeronautics Research goals for Thrust 3a: Ultra-Efficient Commercial Vehicles - Subsonic Transports, and Thrust 4: Transition to Alternative Propulsion and Energy. This paper describes the various propulsion control technology development areas identified by CAPCWG as most critical for NASA to invest in. For Thrust 3a these are: i) Integrated On-Board Model Based Engine Control and Health Management; ii) Flexible and Modular Networked Control Hardware and Software Architecture; iii) Intelligent Air/Fuel Control for Low Emissions Combustion;

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and iv) Active Clearance Control. For Thrust 4a, the focus is on Hybrid Electric Propulsion (HEP) for single aisle commercial aircraft. The specific technology development areas include: i) Integrated Power and Propulsion System Dynamic Modeling for Control; ii) Control Architectures for HEP; iii) HEP Control Verification and Validation; and iv) Engine/Airplane Control Integration. For each of the technology areas, the discussion includes: problem to be solved and how it relates to NASA goals, and the challenges to be addressed in reducing risk.

I. Introduction

A dvancements in control technologies have played an important role in enabling improvements in aircraft engine performance and safety. Reference [1] provides a historical perspective of propulsion control technology development in the United States. NASA (National Aeronautics and Space Administration) has played a significant role in advancing propulsion control technology through research at Glenn Research Center (GRC) [2]. Although NASA aeronautics programs continue to support propulsion control research [3], there are challenges associated in articulating as to how investment in advancing control technologies directly addresses NASA goals. Traditionally control technology is seen as enabling for airplane/engine operation but not directly critical to achieving NASA goals of improving aircraft efficiency and reducing the environmental impact of aviation. To fully understand and address this perceived disconnect, the controls technology leads from the four major engine manufacturers in the United States and NASA GRC, and the propulsion technology lead from Boeing decided to form the Commercial Aero-Propulsion Control Working Group (CAPCWG). The charter of CAPCWG states that: "CAPCWG will focus on identifying technology development needs which support the goals and objectives of NASA Aeronautics Research Mission Directorate (ARMD) Programs. It will provide a forum for communicating and advocating the technology development needs to government organization leadership in civil aviation." The first activity that CAPCWG has taken on is to identify the propulsion control challenges that need to be solved to add the most value towards meeting the goals of NASA Aeronautics Research Strategic Thrusts 3a and 4, which are: Ultra-Efficient Commercial Vehicles - Subsonic Transports, and Transition to Alternative Propulsion and Energy, respectively.

In the NASA roadmap for Thrust 3a [4], the research theme "Ultra-efficient Propulsion – Research and development of technologies to enable new propulsion systems with high levels of thermal, transmission, and propulsive efficiency, reduced harmful emissions, and innovative approaches to noise reduction," is relevant for propulsion control. The focus on this theme is to develop technologies that will enable Ultra High Bypass engines for introduction into service in 2035. There is ongoing low TRL (Technology Readiness Level) work in many propulsion control areas that is relevant to this theme. These research areas include advanced control law architectures such as Model Based Engine Control [5], future engine control hardware architectures such as Distributed Engine Control [6], and various applications of active component control such as: active combustion control to enable full flight envelope operation of low emission combustors; and active turbine tip clearance control to enable efficient operation of high bypass engines with small size cores [7]. CAPCWG members reviewed the current propulsion control research efforts, and based on common interests between industry and NASA goals, identified four technical areas where NASA investment is needed to advance technology to a high enough TRL that it can be picked up by industry for incorporation into their future generation propulsion systems. These are: i) Integrated On-Board Model Based Engine Control and Health Management; ii) Flexible and Modular Networked Control Hardware and Software Architecture; iii) Intelligent Air/Fuel Control for Low Emissions Combustion; and iv) Active Clearance Control. The next section describes these technologies and the challenges that need to be addressed in more detail.

In the NASA roadmap for Thrust 4 [8], two research themes are relevant for propulsion controls. These are: i) Hybrid Electric Components & Technology; and ii) Modeling, Simulation, Testing. NASA is investing in hybrid electric propulsion (HEP) concepts for a wide class of air vehicles, from innovative Vertical Take Off and Landing (VTOL) vehicles for Urban Air Mobility to large commercial class transport aircraft. A number of system level studies have been performed in the latter area to analyze various HEP concepts. Ref. [9] provides an overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transports. So far, the NASA investment has focused on looking at optimization of energy usage for various HEP concepts, and development of electric component technologies. Only recently has NASA started considering the issues of modeling and understanding the interaction between

turbomachinery operability and electrical power extraction or power input. Considering the challenges associated with safe, optimal performance and operability of HEP systems, specifically turbomachinery and power generation system coupling issues during the transient phase of the propulsion system operation, the CAPCWG has identified the following four key technology areas for consideration for development by NASA: i) Integrated Power and Propulsion System Dynamic Modeling for Control; ii) Control Architectures for HEP; iii) HEP Control Verification and Validation; and iv) Engine/Airplane Control Integration. Section III describes in more detail these technologies and the challenges that need to be addressed.

II. Propulsion Control Technologies for Thrust 3a

The four technology areas identified by CAPCWG as important for NASA investment to meet the goals of Thrust 3a are described in this section.

A. Integrated On-Board Model Based Engine Control and Health Management

The traditional engine control approach is to use data from physical sensors for feedback control to ensure performance and safety of the engine. Performance relates to how well and efficiently thrust is delivered in response to power lever position, whereas safety involves ensuring the engine's mechanical integrity while maintaining operability via a stall and blowout free operation. This has to be accomplished over the complete operating envelope and certified on-wing operating life of the engine. The variables of interest, such as thrust for performance, and compressor stall margin and turbine inlet temperature for safe operation, cannot be measured directly. The engine control therefore uses sensed variables such as shaft speed or pressure ratio, which correlate to thrust, and measurable pressures and temperatures, which correlate to other variables of interest, for safe operation. Because of the uncertainty associated with this "indirect" control approach, there is necessarily significant conservatism in the control design since the control logic must ensure safe operation and that performance requirements are met in the worst-case conditions – end of life engine operating in the most challenging external conditions. 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 at its current condition. 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. Model Based Control (MBC) involves the execution of an explicit model in the controller, as shown in Fig. 1 wherein the model is updated using data from sensed variables combined with appropriate estimation techniques. MBC involves using the parameters from the model to influence engine control in real time. Model Based Diagnostics (MBD) is similar, except that there is no feedback from the model to the engine control (the arrow pointing upwards) and the model is used only for anomaly detection and health assessment. When combined with prognostics and life usage monitoring or usage based lifing, it becomes Model Based Prognostics and Health Management (MBPHM). Model Based Control and PHM (MBCPHM) is used in the rest of the paper to mean both.
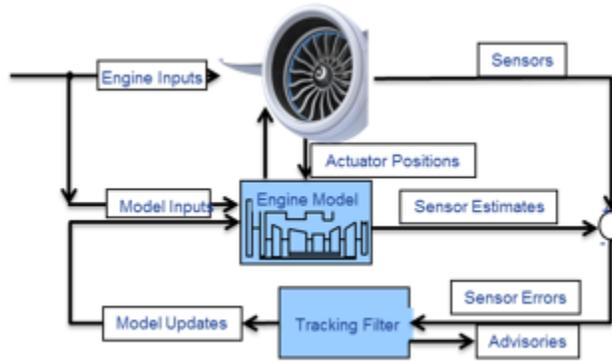
Fig. 1. Model Based Control and Prognostics and Health Management (MBCPHM) uses an on-board model of the engine to estimate parameters of interest

There are many types of model based control, including models used in the feedback loop as shown in Fig. 1 or in the feedforward loop; models used to estimate feedback parameters that cannot be sensed easily (thrust, High Pressure Turbine (HPT) tip clearance) or models used to calculate controller gains in real time (Dynamic Inversion). See References [5,10,11] for some example studies on MBC. The advantages of MBCPHM over conventional sensor based only systems include:

- Virtual sensors, either for use as backup to existing control sensors or as estimators of difficult to sense parameters such as thrust and turbine inlet temperature, T41.
- Maintenance action recommendation based on health assessment – also known as condition based maintenance, as opposed to the current approach of schedule based maintenance.
- Anomaly detection, also referred to as fault detection and isolation. This includes sensor fault detection or fault detection based on performance shifts. This can also include fault accommodation, such as utilization of a model based estimate for a variable used in control when a control sensor fails.
- Cumulative damage models (CDM) and usage based lifing (UBL)
- Shop visit workscoping
- Performance improvement by reducing uncertainty margins. For example, a model based control system allows for a "state-aware" control instead of one designed for the worst-case condition. State awareness includes awareness of engine health state (e.g., new vs. deteriorated engine), state of the aircraft (flight condition) and state of the environment.

The last benefit listed above is the main potential contribution of MBCPHM to the Thrust 3a goal of "Ultra Efficient Propulsion." As stated earlier, there is significant conservatism built into the engine design – such as design stall and temperature margins, to ensure safe operation of the engine during transients and with aging because the current control design approach uses available measurements for control. The capability enabled by MBCPHM to "personalize" the control of an engine to its specific current condition opens up the possibility of designing more efficient engines with reduced design margins. System studies [5] have indicated that a reduction in design stall margin of 3% can reduce specific fuel consumption by 0.5%. Preliminary investigations of MBCPHM design [5] have shown that reduction in design stall margins of 3% or greater is feasible if current engines were to be designed with model based control in mind for implementation in the product. With the next generation ultra-high bypass engine designs with highly loaded fans and compact cores, the potential benefits of designing the engines taking into consideration the capabilities offered by MBCPHM can even be greater.

The "cost" for MBCPHM is an increase in data throughput capability required and software complexity. The latter results in increased cost of software development and testing at the bench, integration lab, and flight test levels. In a few cases, MBCPHM requires the addition of sensors, but in most cases it works with the existing sensor suite. Fortunately, processor capability has been increasing dramatically and modern FADECs (Full Authority Digital Engine Control) are a lot more capable than in the past. The penalty for not taking advantage of MBCPHM is that we leave engine performance on the table and operating costs will remain high.

Note that as propulsion systems get more complex due to the use of increased variable geometries on the engine to improve performance, or due to an increase in system-level complexity such as the use of multiple propulsors on hybrid-electric system, MBCPHM becomes more attractive. While the individual propulsion system may be simpler, fuel/energy storage is more complicated, or at least less mature. While jet fuel is flammable, current systems are good at carrying fuel around without ignition, and delivering it to the engine to be appropriately burned. For electrical energy storage and distribution, there is concern in the industry about battery volatility. A lot of the complexity for health monitoring, system isolation, and system control moves from the engine to the energy storage and distribution systems. There is perhaps some opportunity to learn from automotive systems. MBCPHM will also be an enabler for a more autonomous propulsion system of the type emphasized in NASA's Thrust 6, Assured Autonomy for Aviation Transformation [12]. The key elements of MBCPHM, challenges in development and application of MBCPHM, and suggested role for NASA in addressing these challenges are discussed next.

1. *Elements of MBCPHM*
    The key elements of an MBCPHM system, as shown in Fig. 2, are:
    - Engine Model
    - Tracking filter
    - Optimizer or supervisory controller
    - Interface logic
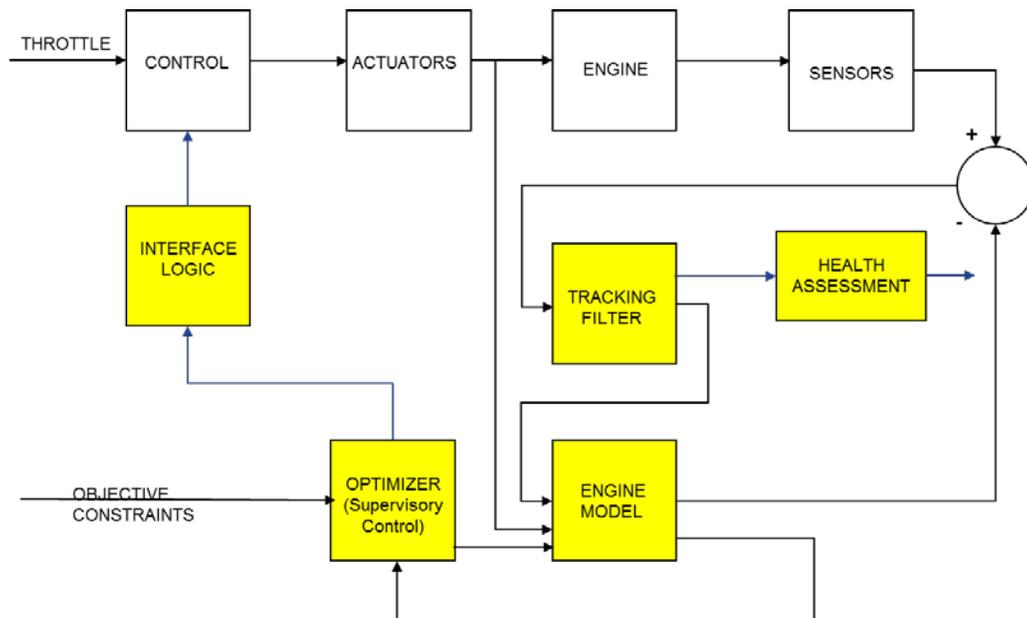   - Health Assessment

Fig. 2. Key elements of a MBCPHM system

The model can be a simple model, such as a map model or linear engine model (LEM) – map models are typically estimators of the form Y = f(X1, X2) and are implemented using simple curve fits or table-lookup schemes, whereas LEMs are state-space models typically used in regulator design. A collection of linear models, called a Piecewise Linear Model (PLM) is often used as a full flight envelope model that can execute very rapidly [13]. Models can also be regression based, from multi-parameter polynomial fits to neural networks, sometimes referred to as response surface fits. Finally, models can be physics-based, either simplified or high fidelity depending on processor capability.

A tracking filter is a parameter estimator, used to "personalize" the model to match a specific engine's characteristics. Without a tracking filter, a model is typically representative of an average new engine. A tracking filter tunes the model to account for variation in new engines due to manufacturing tolerances, and for subsequent deterioration of the engine in the field. A tracking filter is what enables a model to become a digital twin. Tracking filter design techniques include the Kalman filter and its variants, and observers of

various kinds [14]. Other techniques include use of extended solvers of the type used to enforce continuity and mass and energy balance in cycle models, and machine learning techniques [13].

A supervisory controller (Optimizer) enables the integration of the model and tracking filter into the rest of the control and to make intelligent use of the model to perform the control and PHM functions described in the introduction to this section. A classic example is Performance Seeking Control (PSC), used to optimize engine performance at a specific flight condition [15,16]. Other examples include path optimization via Model Predictive Control [17], and the yet-to-be-developed supervisory controllers required for hybrid-electric systems, autonomous systems, and unmanned aerial vehicles (UAVs).

The interface logic helps integrate the supervisory control with the nominal engine control. Examples include logic to limit and check changes to reference calculated by the PSC and to enter them as trims to the nominal control in a smooth and safe manner.

The health assessment block takes the output of the tracking filter to calculate useful information such as compressor or turbine health indices, which in turn can drive maintenance action or removal and replacement of gas path components.

2. *Challenges and Potential Solutions*

There are many reasons why MBCPHM systems, although studied for over thirty years, are only now beginning to make it into product. Three main challenges are listed below and discussed in this subsection:

- Computational power
- Robustness and accuracy of the model
- Software verification and validation (V&V), that is, certification of 'adaptive' control logic

MBCPHM requires computing power. Legacy systems had elements of MBCPHM, but the models were often limited to map models and LEMs. With the recent increases in processor power, as well as the use of multicore and multiprocessors and even distributed control systems, the emphasis has shifted from "can we do it?" to "what is the best architecture?" For instance, the EEC (Electronic Engine Control) on GE's LEAP engine used on the Airbus A320Neo and Boeing 737Max aircraft uses a dual core processor. It also includes a digital twin running in real time.

Model accuracy requirements are increasing as the potential uses expand. A model used as a backup sensor for a reversionary control mode may require a certain level of accuracy but a model parameter used for the primary control parameter or for PSC may need a higher level of accuracy. There is a strong correlation between accuracy and model complexity or throughput. Also, while nominal accuracy may be good, accuracy for off-nominal or faulted conditions may be poor. This leads to the concept of model robustness. Model robustness refers to how reliable the model outputs are, especially for off-nominal conditions. Off-nominal conditions include portions of the flight envelope that are not key design points where model-matching is usually performed, large changes in variable geometry (e.g., modeling of large off-stator effects on compressor maps), rain or ice ingestion, inlet distortion, and engine or sensor faults. Solutions to the robustness issue include adding features to the model, adding logic to assess model health, use of less accurate but more robust models to augment a high-fidelity model, and extensive testing.

Two significant concerns with MBC are software V&V and certification. If some nondeterministic or learning software is in play, how do we know that the system is learning correctly? Strictly speaking, even a learning algorithm or a fuzzy controller is deterministic, in that given the same set of inputs, it will calculate the same set of outputs. However, the concern is whether there is a possibility that the control will gradually wander off into some undesirable state. There are software tools to make sure that requirements are properly implemented and test vectors are comprehensive enough to cover all paths. However, from an engineering perspective, there are two possible ways to ensure robustness:

a. Testing, testing, testing. Lots of tests, run over extended periods, with all known variations in inputs to cover the full range and rates of change.
b. Since the concern is whether the control will wander off, why not limit how far it can? The basic idea is to define a baseline control system or model of expected behavior and to define bounds around that behavior, essentially defining a channel in which the engine is allowed to operate. The bounds are loose enough to allow for optimization, but tight enough to ensure operability and safety of the engine. This "backbone with bounds" or "operating channel" technique also allows for certification, since certification tests can include testing to the bounds. These bounds could be opened up in special cases such as fault or damage accommodation.

3. Role of NASA in MBCPHM Technology Development

Given the challenges for MBCPHM described above, a key question is how to align time for entry into service with NASA's roadmaps and those of the Air Force, Navy, and Army. That is, when does the technology development need to be completed for various vehicle entry points? Given that some MBCPHM technologies are ready for introduction now whereas some others will take five to ten years to mature, what can the government do to promote and mature these technologies? Yes, the government agencies can provide funding, but they can also provide direction. Industry's role is to show the connection between these technologies and reduction in energy, emissions, and noise. Industry is also responsible for implementing these technologies on real engines and performing the required ground engine and flight testing. The FAA and other international regulatory authorities will play their usual role in ensuring system safety, but can also partner with industry to promote these technologies. Last but not the least, academia and NASA can work to develop new technologies to solve the problems listed above, such as: the development of methods to improve the accuracy and robustness of on-board model designs; studying the potential benefits and challenges of incorporating model based control on engine configurations (N+3) that NASA envisions for entry into service in the 2035 time frame; and development of methods for efficient V&V of model based control designs. NASA's investment in these areas will help reduce the risk for industry to fully incorporate MBCPHM in future production engines.

B. Flexible, Modular, and Networked Control Hardware and Software Architectures

As aircraft engines have developed over time, the number of functions, internal systems, and external/customer deliverables has increased. Along with that increase in complexity, the engine control system has also grown substantially, in both hardware and software scope, to provide control for these functions and systems. The requirements for these multiple systems vary greatly. For example, engine safety functions such as overspeed protection require fast response times and low computational overhead, whereas engine health monitoring and predictive maintenance functions allow for slower response times but can require high computational overhead. These very different requirements lend themselves to correspondingly different hardware and software solutions. However, aircraft engine control systems have been traditionally federated into as few units as possible, and this constrains the allowable design trade space. As a result, compromises are made with control system sub-component selections—in terms of performance and/or reliability—and subsequently with the performance of the engine as a whole to meet certification and customer requirements. The negative impact of this is realized in the design and integration phase in that the electrical/electronic, hydraulic, pneumatic, and mechanical aspects of a control system must be made more complex to maintain the single/dual box control system architecture. Additionally, the impact is felt in the maintenance and overhaul phase in that these large LRUs (line replaceable units) of the control system must be pulled off engine when any of the many functions they provide are faulty. Future control systems will be optimized in these design, integration, and maintenance areas by physical distribution across the engine and aircraft of the many systems and functions of the engine controller. However, technical challenges remain with this type of architecture to fully mature it for incorporation into a product engine.

Contemporary aircraft engine control systems use legacy pedigree where possible in their designs. This is largely driven by the very high cost of certifying new technologies or design approaches in safety-critical hardware and software. For decades, EECs (electronic engine controllers) have been certified in relatively consistent environmental conditions using proven system architectures and design approaches to meet regulatory requirements for, as examples, in-flight fault tolerance, robustness against electromagnetic interference, and robustness against solar radiation. This approach lends itself well to predicting certification costs and to reducing the risk of a given design successfully making it through the many testing and validation gates in the certification process. However, the reliance on what is known and proven has prevented the organic evolution of the control system hardware architecture design to what is optimal. Increasingly, aircraft engine control systems are monitoring more sensors, driving more valves and actuators, and executing more complex algorithms within that traditional architecture and design approach. The motivation for this is to get the benefit of increased functionality while keeping certification risks and costs at a minimum, but this approach can only go so far before limitations such as physical space or computational horsepower make it no longer viable. As engine control systems are asked to monitor and actuate more systems, the physical space they consume naturally becomes larger. As engine control systems are asked to compute more, especially for functions such as engine health monitoring and cybersecurity, the components that can do this and survive harsh environments become fewer and more

expensive. Additionally, for each new function or system, more electrical harnessing and pneumatic or hydraulic piping must be routed across the engine to a federated controller, which drives up complexity, cost, and weight.

There are many ways that the growing problems of the traditional engine control system architecture can be addressed, and one of the more promising approaches is to distribute the engine control system around the engine and aircraft based on the specific requirements of each function of the controller [18]. The benefits of this approach are many, including but not limited to: more localized computation for a given function (lower weight, higher performance), physical space claim relief, and less intrusive maintenance due to smaller, distributed LRUs. Localized computation allows for a faster responding system due to the more compact system architecture for that function. Additionally, it removes the weight associated with electrical, pneumatic, hydraulic, and/or mechanical lines that would be needed in a centralized solution. An example of a control architecture with distributed functionality is shown in Fig. 3. In such an architecture there are "smart nodes" placed along the engine casing as close as possible to the sensing element or actuator (shown as small green boxes in Fig. 3). These smart nodes locally perform actions such as signal processing, Digital to Analog or Analog to Digital conversion, component fault diagnostics, control loop closures for actuators etc., and provide the needed data to the control computer, for processing of control laws, through a digital network.
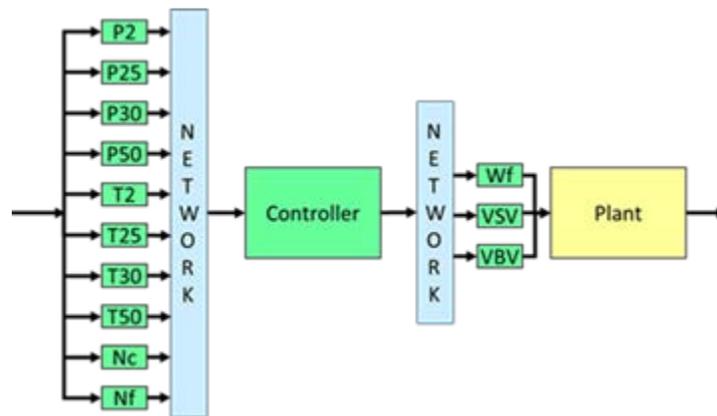

Fig. 3. An example networked control architecture

The distribution of the control system around the engine, nacelle, or aircraft reduces the issue of physical space claim in any one location. If a failure occurs in one of the distributed nodes in this architecture, only that one faulty node needs to be inspected or removed/replaced, rather than having to pull an entire EEC, as is done in a traditional, federated architecture. Smart nodes can even perform self-diagnostics to help with fault isolation. Lastly, a control system architecture that is distributed into multiple, modular nodes is better positioned for low cost future improvements. For example, if processing core improvements are made in industry for higher reliability or cybersecurity protections, and this leads to in-field retrofits of existing applications, then specific nodes of the distributed engine control system can be selected for this retrofit as a cost/benefit analysis determines is warranted.

1. Technology Development Challenges and NASA Role

Distributed control system architectures have been researched by NASA and industry over the past number of years, and much learning and corresponding advances in technologies have been made because of that research [19,20]. However, technical challenges remain to fully bring them to market, and NASA can continue to help with these challenges for the benefit of the entire aerospace industry. Although it is extremely challenging to relate investment in advancing control hardware architecture directly to achievement of NASA goals of increased efficiency and reduced environmental impact of propulsion systems, it is important to note that NASA investment is warranted because advances in the control architecture are critical to realizing the potential gains of other technologies that NASA is investing in. This is especially true for the N+3 engine configurations of ultra-high bypass with compact cores, which will result in significant challenges to implement the control system using the current federated architecture. NASA has a strong history of investing in advancement of control architectures. NASA, in partnership

with Air Force Research Lab (AFRL) and industry played a very important role in the transitioning of engine control from hydro-mechanical to the current FADEC [21]. As summarized in Ref. [20], AFRL is working extensively with industry through the Distributed Engine Control Working Group (DECWG) to advance technologies to enable implementation of networked control architectures in future military engines. It will be of benefit to the commercial propulsion industry for NASA to leverage the AFRL and industry partnership to focus advancement of those technologies that are specifically relevant to the NASA envisioned N+3 engine configurations.

Research in high temperature electronics will enable the placement of distributed electronic nodes into more locations on engine. Without that design freedom, the full ability to optimize the control system design will be limited. Research in developing tools to simulate different control architectures to study the impact that electronics temperature capability has on the architecture and vice versa, and establishing facilities for doing control hardware-in-the-loop testing of components of a flexible modular architecture developed by various entities are legitimate government functions. A strong government role in these areas ensures that advances in control components are available to all the industry members. Research in diagnostics for distributed nodes will greatly reduce the certification risks around the new failure modes introduced with a distributed system, as well as better inform maintenance activities. This research is critical because distributed control systems will have to show the same robustness to failure modes as the legacy, federated architectures. Research in fiber optics will be important for advancing this technology. Fiber optic harnessing has the potential to reduce the weight impact of additional electrical harnessing needed in a distributed architecture. It can even provide weight savings relative to legacy architectures, especially if it is expanded to the harnessing that connects the aircraft to the engine(s). NASA can continue to support industry by advancing these technologies to show that they are functionally viable, are robust enough to survive certification requirements, and provide the benefit necessary to replace incumbent designs. The costs and timeframes of completing these efforts are high and long enough that it is difficult for industry to fully support them on their own, and NASA has the unique ability to move them forward for the benefit of all.

C. Intelligent Air/Fuel Control for Low Emissions Combustion

In the drive to improve fuel efficiency and reduce community noise and pollution impacts, NASA is investing in generation "N+3" engines that will have higher bypass ratios with compact cores. These engines will feature lean burning combustor technologies that are advantageous for emissions reductions and offer opportunities for increased efficiencies. These low-emissions gas turbine combustors [22], with an example shown in Fig. 4, use fuel staging (see Fig. 5) to provide the optimal combination of emissions, efficiency and operability on a variety of fuels. Staging is the process of sequencing the fuel injection through local injection zones, to tailor the fuel-air mixture ratio over a large engine operating (airflow) range.

Fig. 4. NASA/PW/UTRC Axially-Controlled Stoichiometry Low-Emissions Combustor showing multiple fuel ports
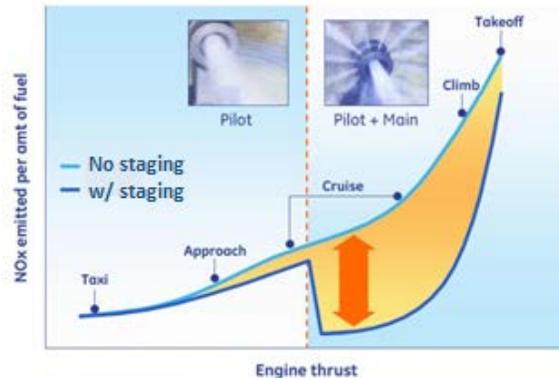
Fig. 5. Nitrogen Oxides (NOx) emissions reduction for a combustor where fuel staging is utilized compared to one with no staging

Fuel-staged combustors have multiple fuel injection systems, some of which may be turned off for portions of the operating envelope. While this presents problems in terms of the thermal management of the fuel (i.e., coking) and operability, it also presents opportunities. In particular, it provides free parameters in the control of the combustor. The total fuel and air flows to the combustor are constrained by the operating point of the engine. Fuel staging allows the total fuel flow to be apportioned to the different stages, providing the flexibility to distribute fuel to meet a series of operability and performance metrics.

Much emphasis has been placed recently on pollutant emissions. These include Nitrogen Oxides (NOx), Carbon Monoxide (CO), and particulate matter. All three of these pollutants demonstrate a strong sensitivity to local fuel/air ratios, either directly (for particulates) or indirectly due to the relationship between fuel/air ratio and gas temperature [23]. Figure 6 shows such a relation of combustor temperature to NOx and CO emissions, which is also associated with fuel/air ratio.
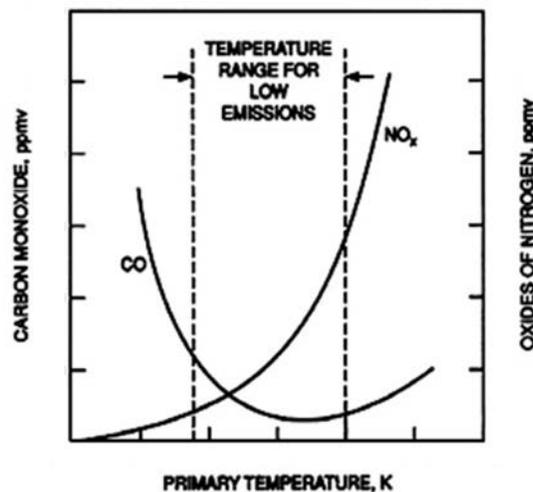

Fig. 6 NOx and CO emissions in relation to combustor temperature - shows a notional operating range for lower emissions

1. Technology Challenges

Pollutant emissions, though, are only one metric of combustor performance. Operability metrics are also constraining. These include: i) ignition; ii) lean blowout; and iii) combustion instability. Lighting the combustor, either at ground start or altitude relight, requires that fuel be well atomized and delivered to the region of the igniter reliably. Lean blowout is largely a transient issue. As an engine decelerates from high power to low power, the fuel/air ratio in the combustor decreases. Depending on the rate of that deceleration, the instantaneous fuel/air ratio in the combustor (or in one zone of it) can dip below quasi-steady values. It is important to ensure that part or all of the combustor does not blow out in these situations, so adequate margin must be maintained.

Combustion instabilities are a complicated physical problem that involves coupling between the combustor acoustics and the unsteady heat release of the combustion process. The resulting high pressure oscillations can cause vibratory or thermal damage to the combustor, and also result in audible combustor tones. Low-emissions or lean burning combustors have historically demonstrated a higher propensity to exhibit these problems over portions of their operating envelope [24]. Much work has been done on the active control of combustion instabilities, Ref. [25,26]. So far, this work involved modulating the fuel mains to generate a combustor pressure that opposes that of the instability. Lately, work at NASA focused on developing smaller fuel modulators capable of regulating the pilot flow, and to use that to suppress the instability. The advantages of pilot fuel modulators are their smaller size, which may allow to integrate them directly into the injector assemblies, and their reduced power requirements. Figure 7 shows test results with such a modulator that can generate a combustor pressure response when modulating near the instability frequency of approximately 720 Hz, thereby showing promise for use in active combustion control.
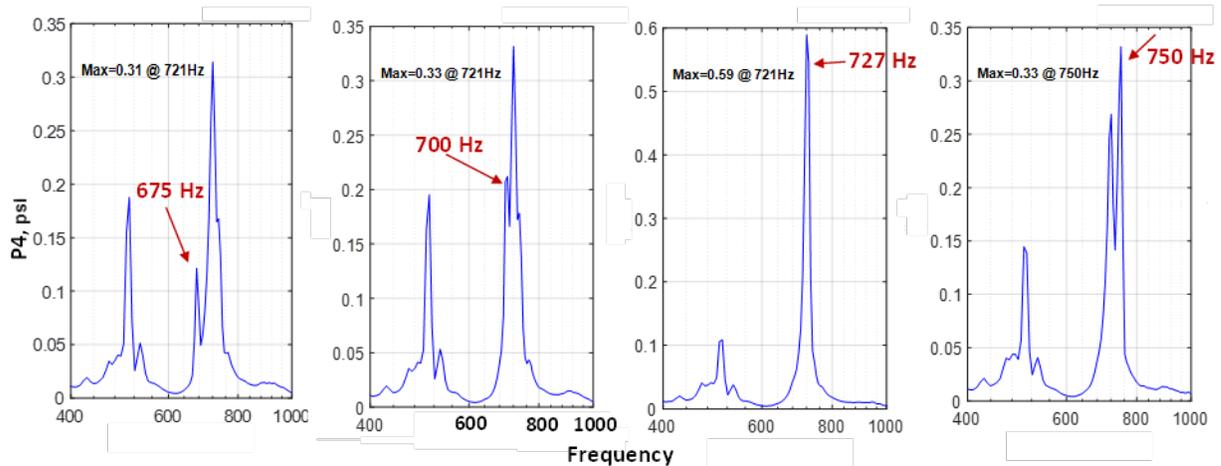

Fig. 7. Spectral densities of combustor pressure response due to approximately 25% fuel modulation applied at different frequencies. The approximately 500 Hz instability shown is a secondary instability existing in the particular combustor rig

Redistribution of fuel within the zones of the combustor has shown promise in some combustion instability applications [27], and would be directly enabled by the technologies discussed here. Again, all three operability metrics defined earlier are directly influenced by the local fuel/air ratio in different regions of the combustor. Additional metrics affecting durability, such as pattern factor (i.e., exit temperature distribution) are also influenced by fuel distribution. The temperature margin kept in the combustor due to pattern factor is approximately 25% of average combustor temperature rise, and thus, significant improvements in fuel efficiency can be realized by sensing and controlling local zone temperatures via distributed fuel actuators to reduce pattern factor.

In the near future, alternate fuels will become a reality. While these fuels are nominally equivalent to Jet-A (a.k.a. "drop-in" fuels), there will be some variability in key properties [28] that can affect the operability or performance of the combustor. Future systems must be robust to these variations and be able to adapt to them.

It becomes apparent that the ability to control the local distribution of fuel and air is critical to our ability to optimize the combustion process to meet all of the above performance metrics. The advent of fuel-staged combustors gives us leverage to do so. Typical fuel-staged combustors use a "pilot zone" to manage low-power operation. Much like a pilot in a home furnace, this is used to light the combustor, keep it lit during transients, and minimize CO emissions at low power. The pilot stage typically operates at all conditions. A second zone is engaged for high power operation, and therefore is generally designed to minimize NOx emissions, particulate emissions and pattern factor (all high-temperature issues). Depending on combustor architecture, some designs employ a third fuel stage to transition between pilot and the high power zone.

Current designs use setpoint operation to determine how fuel flows are split between the different stages at different operating points. These setpoints are often determined empirically to provide the best

compromise solution for the series of metrics described earlier. Improvements to this setpoint strategy can be achieved using embedded sensing, actuation, and control. These strategies may be even more important when the variables of alternate fuels are introduced. Actuation is nominally a matter of valving. Current designs have valves that split flow between stages. Further authority over the fuel/air ratio at different individual fuel injectors could be enabled by local valves at each fuel injector. Cost and reliability are key here, as fuel injectors are line-replaceable units. Valve architecture and installation will likely be dependent on individual combustor or fuel injector design. Sensing is perhaps the most difficult aspect of controlling local fuel/air ratio. The ability to directly and reliably measure local fuel/air ratio *in situ* is not currently in hand. Sensing the performance metrics (emissions, lean blowout precursors, instability precursors, gas temperature) may be a more direct route to controlling those metrics via fuel/air ratio, but these also represent a more complicated sensing problem. One sensor may not be effective in quantifying each of the relevant metrics. Cost will also be an issue. Implementation of local sensing in or near fuel nozzles may be required, leading to high part count and complexity. Minimizing cost while creating value with the control may involve limiting the control system to certain critical metrics that cannot be achieved with setpoint control.

Lastly, a supervisory control must balance local control with system level constraints. The overall fuel flow is set by the engine operation, so the combustor control can only decide how to distribute it. This may require that quantitative tradeoffs between different performance metrics are embedded within the control architecture to enable it to decide which needs are most critical at a given point. For example, keeping the combustor lit during a transient event will most likely be more important than managing NOx emissions during that same event.

2. Role of NASA in Combustion Control Technology Development

Combustors that meet NASA N+3 goals are currently being developed (~TRL3), but nominally without embedded active control technology. Some elements (e.g., valving) of the control schemes described above are at equivalent TRL, but engine-ready sensing technology is much less mature, likely TRL1-2. Key investments in: combustion control sensing and/or enabling technologies to provide accurate estimates of variables that are difficult to measure directly but are needed for control; the overall control architecture geared to meet specific requirements at specific operating conditions and to provide robust performance across the whole operating envelope; flight capable robust actuators that can be integrated into the compact core concepts; and rig level testing of the integrated concepts to mature technologies to TRL 6 are required for these technologies to be considered for inclusion in the 2035 engine in service concepts. The industry is inherently averse to investing in high risk technologies associated with active control, and will make compromises on the emissions goals to achieve what is achievable through passive approaches to combustor design. NASA's investment in appropriate maturation of control component technologies and demonstration of integrated control feasibility are essential to reduce technology development risk and encourage industry to incorporate these advanced concepts to be able to meet the challenging emission goals in operational engines.

D. Active Clearance Control

Active maintenance of tight clearances in aircraft turbine engines reduces gaspath leakage between the tips of the rotating blades and the surrounding air seal structure. Gaspath leakages due to excessive tip clearance can have a profound impact on the compressor and turbine performance, especially the turbine. The ability to reduce clearances offers significant improvements in engine performance and operation economy, in metrics such as lower fuel consumption rates, reduced emissions, lower noise, and decreased life cycle cost via extended engine service life. Previous studies [29,30] have shown benefits on the order of a 1% specific fuel consumption decrease for 10 mils (0.01 inches) of turbine blade tip clearance reduction.

The rotating core of a gas turbine engine experiences significant variations in centrifugal force and temperature throughout the flight profile, resulting in relative expansion and contraction of the gap between the rotor casing and tips of the spinning core blades. The gaps must be designed sufficiently wide to avoid rubbing of blade tips into the surrounding seal material, especially during engine throttle transient operation, when the relative gap naturally changes. But care must be taken to avoid excessively wide gaps that would allow flowpath air to leak over the tips of the blades without passing between them, negatively impacting engine performance and thus lowering fuel efficiency. The tip clearance gap varies dynamically

throughout a flight as illustrated in Fig. 8 and therefore it would be advantageous to implement control of this gap.
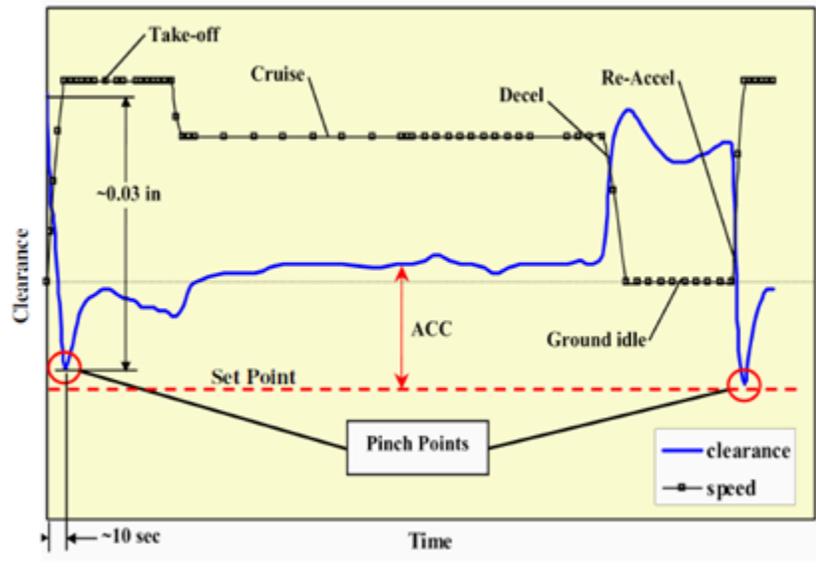

Fig. 8. Example of tip clearance variation over the course of a flight (from Ref. [30]). The solid blue line shows the clearance variation over the course of a flight. The dashed red line is the desired clearance throughout the flight, potentially achieved through the use of Active Clearance Control

During steady engine operating conditions, especially during aircraft cruise flight segments; tip-to-case gaps can be actively reduced, improving the operating efficiency of each module by reducing the amount of air leakage through the clearance gap. The resulting improvement in efficiency provides significant benefits in cruise fuel burn, range, and payload capability - especially for long-range aircraft. NASA reports [30] that for large transport engines, turbine tip clearance modulation of approximately 0.02 to 0.05 inches at a rate of 0.01 inches per second would prevent unnecessary gaspath leakage during cruise and significantly improve engine efficiency.

Current technology in many mid and large-sized commercial transport aircraft gas turbine engines uses real-time modulation of turbine case cooling to tighten running turbine blade tip clearances during the stable cruise segment of flight. This system directs cooling air onto the high-pressure turbine (HPT) and low-pressure turbine (LPT) cases during certain flight segments to cool and shrink case diameters, thereby reducing running clearances of the turbine blades. Disadvantages to an active clearance control system are added weight and complexity of sensors, actuators, control logic, and wiring harnesses. Today's Active Case Cooling systems can require on the order of a minute for full modulation of the clearances due to the slow thermal response of the turbine cases (large thermal mass and weak convective coupling to cooling air). Active case cooling typically must be turned off during most of the ascent and descent segments of flight. The physics of thermal modulation does not permit actuation at a sufficiently fast response rate to move the case out of the way during engine transient operation.

Most active clearance control systems in use on today's aircraft are "open loop"; that is, they don't use a direct measurement of clearance as a feedback input into the engine control laws. Initial active clearance control laws roughly estimated clearance from engine throttle setting and flight condition. Over time, the estimation algorithms have become more sophisticated, using a dozen or more engine and aircraft measurements to synthesize a clearance. However, significant margins must be factored into the active clearance control algorithms due to uncertainty of actual running clearances on each engine. A means to accurately measure and actively provide closed-loop control of turbine tip clearance throughout the aircraft flight envelope would help improve engine gas path performance.

1. Advanced Active Clearance Control Technology Challenges

In a 2011 NASA Glenn Technical Memorandum titled "Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts" [31], three key enablers of a Next Generation Active Turbine Clearance Control System were identified. The first enabler was a "fast-acting blade tip seal effector providing the

dynamic range and responsiveness desired." This would allow clearance control to be active throughout the entire flight profile, rather than just at the cruise condition. The Memorandum suggested that in addition to making improvements to the current thermal case modulation methods, "new concepts could use Shape Memory Alloy material to change case shape at different segments of flight, such as cruise and takeoff." There has been recent progress in "Blade Tip Blowing" techniques that might be applied. Recent advancements in power electronics and electric actuation opens the door to some compact means of modulating clearances that weren't available at the time of the study.

Another key enabler is a means to more directly estimate if not measure blade tip clearances in real time to enable closed loop feedback control through advanced sensing and dynamic modeling. Reference [31] mentions the need for "materials used for sensing elements and packaging that can withstand the high temperatures in the core of the engines." There have been many advances, especially in recent years, in methods for real-time measurements in hot environments. This is particularly true for those using optical and microwave methods that physically separate sensing element from the digital signal processing element, which can be located in a more benign operating environment.

One other key enabler is the means to integrate the direct measurement of clearance with fast response actuation into closed-loop fast-response active clearance control. This requires the ability to build dynamic models of the clearance phenomenon, coupled with control laws running in a computer aided control design and evaluation environment, such as MATLAB/Simulink. Such a capability allows researchers to explore and increase understanding of how to implement the clearance control law algorithms and how those control laws would interact with the control system hardware. Such efforts have been conducted in the past at NASA, including the recent study in Ref. [32]. Figure 9 shows an example result of the tight turbine tip clearance achievable with higher bandwidth casing actuation based active clearance control.
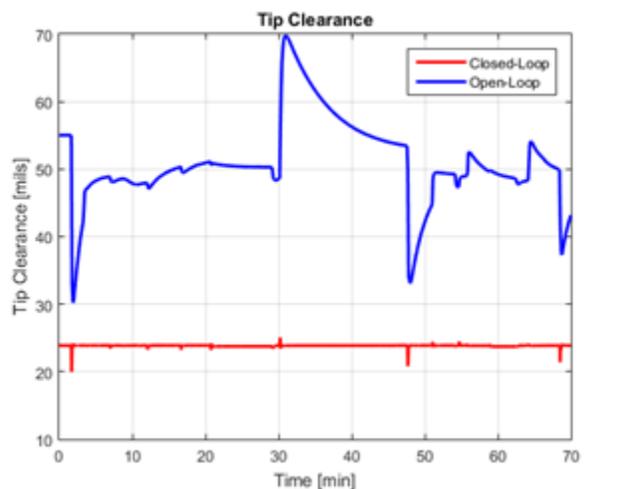

Fig. 9. Model predictions of turbine tip clearance variations for an open-loop case cooling approach and a closed-loop active clearance control actuation approach (from Ref. [32])

Reference [31] concludes that "it is feasible that active clearance control will be developed sufficiently by 2035 to be incorporated into the N+3 era aircraft." Taking advantage of recent progress in supporting technologies, a focused effort by industry, in partnership with NASA, should be able to realize a fast-response Advanced Active Clearance Control even sooner than N+3.

2. NASA Role in Advancing Active Clearance Control Technology
NASA's Energy Efficient Engine (E3) Program made investments in technologies to improve baseline GE CF6-50C and P&W JT9D-7A engines. Active clearance control was used on a compressor to control tip clearances as the blades expand and contract, and reports were that "active clearance controls is now gaining status doing the same job on the turbine stages of several modern engines." The NASA E3 started work on Active Clearance Control in 1978 - now 40 years ago! Why should NASA and industry now partner in another round of investment in Advanced Active Clearance Control? There are several drivers, based on NASA's projections of near-future commercial aviation trends:

- With ongoing advances in technology, gas turbine engine cores are getting smaller. This results in lower weight and smaller diameter, which in turn reduces nacelle drag. Blade tip clearance gaps now become a larger percentage of the smaller core diameters, and thus have a greater percentage impact on engine efficiency. There is greater incentive to tighten clearances on smaller engine cores than there has been on larger cores.
- NASA has identified a trend towards more (lots more) smaller aircraft operating in the US airspace. There has been a significant increase in the number of new and updated single aisle aircraft starting to enter into service. These studies are showing that the trend is expected to continue towards a proliferation of even smaller "short hop" aircraft. These aircraft would have limited operating time at cruise conditions, where slow-response thermally-actuated active clearance control systems have been utilized. Faster methods to tighten clearance that could be used throughout the entire flight profile are needed.

Investment in technologies to enable tight control of clearances, both for compressor and turbine, will directly contribute towards the NASA goal of enabling insertion of ultra-efficient propulsion systems in service in 2035. NASA investment in developing high risk elements of the technology such as:

- dynamic models of clearance changes during engine transients;
- means of either accurately measuring tip clearance with advanced sensors or estimating it with advanced algorithms using available sensor data; and
- prototypes of means of fast actuation of the compressor/turbine casing, combined with rig level integrated demonstration

will be instrumental in industry picking up this technology for insertion into future production engines.

III. Thrust 4 - Transition to Alternative Propulsion and Energy

NASA ARMD's strategic thrust 4 focuses on the propulsion and energy technology needs for large transport aircraft and emerging small aircraft markets [33]. A variety of new technologies are required to support this vision, including advances in aircraft/propulsion integration, improvements in gas turbine engines, development of hybrid/turboelectric propulsion systems, and advances in sustainable alternative jet fuels. In addition, electrified aircraft propulsion has been identified as a key enabler for low-cost, environmentally friendly, small aircraft for new emerging markets. Figure 10 shows the six potential electric propulsion architectures that rely on different electrical components for producing propulsive thrust [34,35]. These include:

- All electric: Use batteries as the sole source of propulsion power. Here, battery power supplies the electricity used to run motor driven fans. The batteries are charged when the aircraft is on the ground or are replaced in between flights.
- Hybrid electric: Combines battery and gas turbine sources of power for propulsion. Hybrid electric architectures can be either series or parallel in nature:
  - Series Hybrid: All propulsive thrust is supplied through fans that are electrically driven by battery power, power generated by a gas turbine, or a combination of these two power sources. All power output supplied by the gas turbine is used to drive an electrical generator. This generated power is then used to either drive the fan or charge the battery. Series hybrid designs are well-suited for distributed propulsion concepts as multiple motors/fans can be included in such designs.
  - Parallel Hybrid: A battery driven motor and a gas turbine are both mounted on a common shaft and used to drive the propulsor (fan). In this configuration, either or both the gas turbine and battery can provide propulsive thrust at any given time.
  - Series/Parallel Partial Hybrid: This has one or more fans that can be mechanically driven by a gas turbine, plus others that are electrically driven. These electrically driven fans can be powered by batteries or by turbine-driven generators.
- Turboelectric: Turboelectric designs do not rely on batteries to generate propulsive thrust, and may be either fully or partially turboelectric in their design:
  - Full turboelectric: All power produced by the gas turbine is used to drive an electrical generator that produces electricity used to drive motor driven fans.

o   Partial turboelectric: The gas turbine serves dual roles for thrust generation. It mechanically drives a fan, plus it supplies power to an electric generator, the electrical power output of which is then supplied to electrically driven fans.
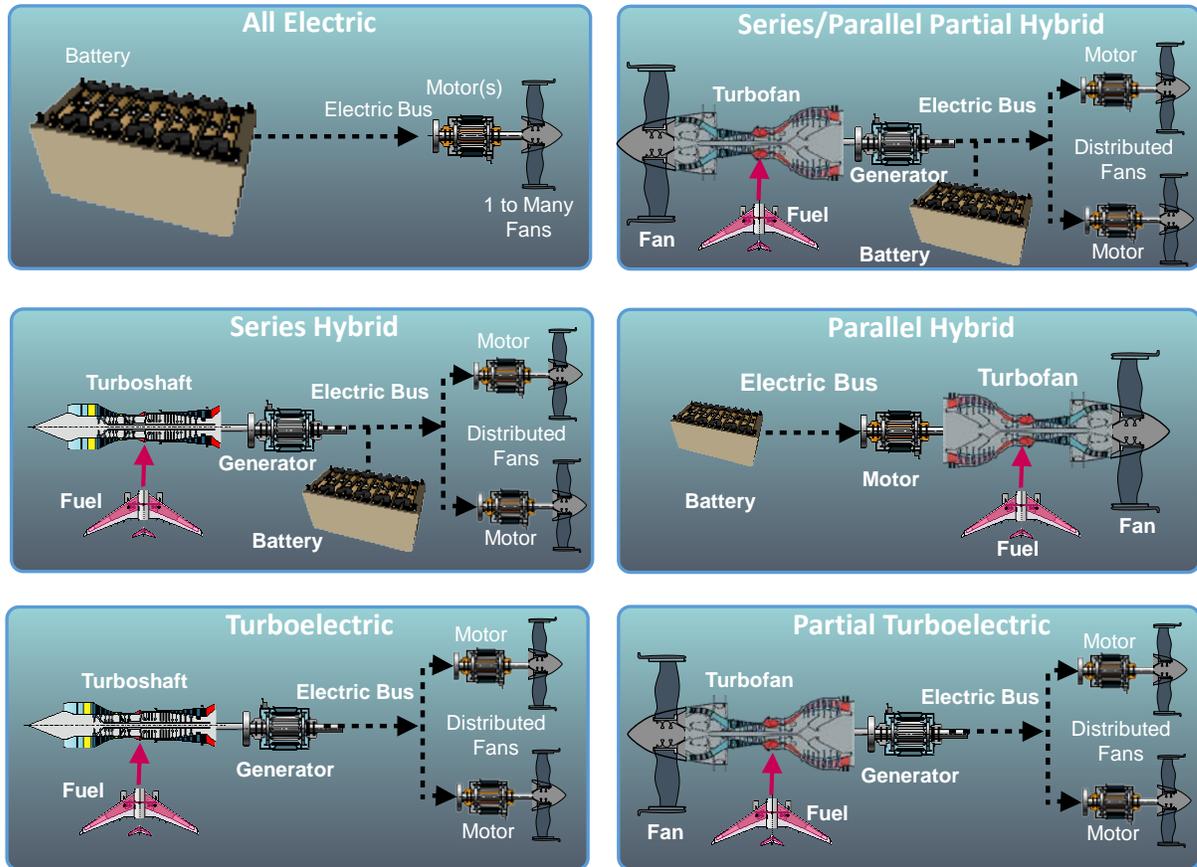

Fig. 10. Electric propulsion architectures

NASA and industry are investing in electrified aircraft propulsion for large subsonic transports to improve efficiency, emissions, and noise [9]. A few of the electrified aircraft propulsion vehicle concepts that have been proposed are shown in Fig. 11. These include:

- Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL): STARC-ABL is a partial turboelectric propulsion design consisting of two wing-mounted turbofan engines plus an electrically driven boundary layer ingesting tailcone thruster. The turbofan produces thrust directly in addition to driving generators used to produce electricity to drive the tailcone thruster.
- N3-X: A fully turboelectric design with a fully distributed propulsion system based on superconducting electric machines and power distribution.
- Boeing SUGAR (Subsonic Ultra Green Aircraft Research) Volt: This uses a parallel hybrid electric drive concept to augment the cruise portion of a flight by driving the fan with battery-powered motors. This configuration is also referred to as hFan.

STARC-ABL – Partial Turboelectric
Source: NASA

N3-X –Turboelectric
Source: NASA

Boeing SUGAR Volt – Parallel Hybrid
Source: Boeing

Fig. 11. Large subsonic transport electrified aircraft propulsion concepts

The remainder of this section will present and discuss controls-related technology needs and challenges related to the electrified aircraft propulsion vision of NASA ARMD Strategic Thrust 4. This includes needs in the areas of integrated dynamic modeling and control, control architectures, verification and validation, and engine/airplane integration.

A. Integrated Power and Propulsion System (IPPS) Dynamic Modeling for Control Design

In traditional aircraft engine applications, two or more engines provide not only the propulsive thrust, but also bleed air for the aircraft's environmental control system (ECS) and electric power to the aircraft for everything from avionics to actuation of flight control surfaces to cabin lighting and entertainment systems. Typically, the electric power supplied by the engine is a small fraction of the total power it produces. The engines also have heat exchangers to cool oil used in gearboxes and bearings, and for managing the temperature of fuel used to drive engine-mounted servo-actuators.

Newer applications such as aircraft driven by hybrid electric propulsion (HEP) have substantially higher power requirements, necessitating the use of new architectures such as variable cycle engines and large generators coupled with the turbomachinery. These and other enhancements also require more complex systems for managing thermal loads. Figure 12 shows a typical integrated power and propulsion system (IPPS).
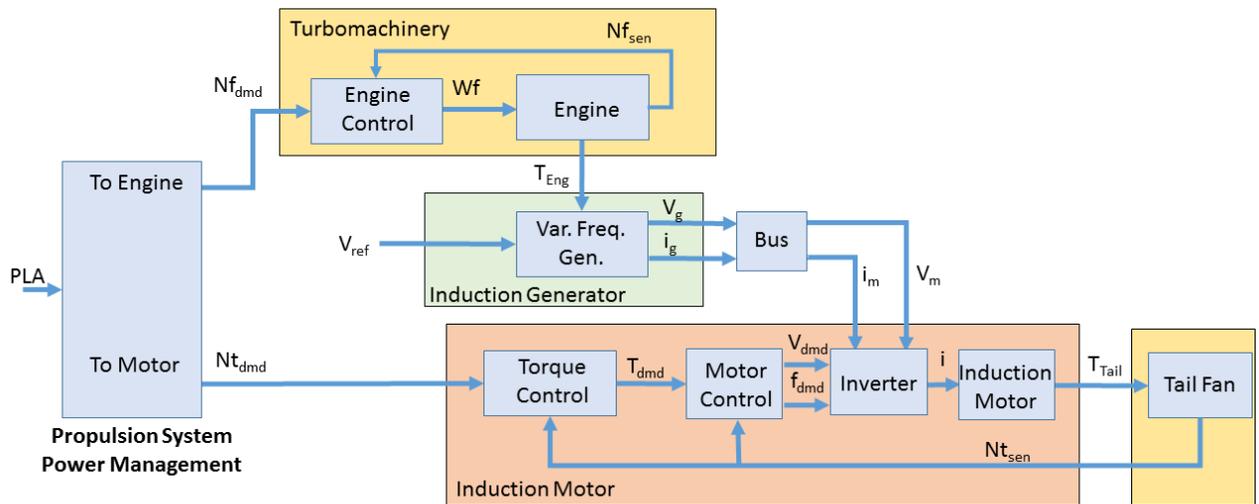

Fig. 12. Example high level control architecture for a turboelectric propulsion system showing the interaction between subsystems

Large changes in power extraction, in the form of load drops and load accepts, can impact engine operability, i.e., can cause the combustor to flameout or the compressor to stall. Also, distributed propulsion introduces computational delays that can impact control stability. In systems with a supervisory controller, the way each engine is operated, the manner in which power is distributed to each propulsor, and the ability to provide a prediction of potential large changes in engine operation, all play a critical role in

the smooth transition of power and thermal loads, which impacts engine operability and aircraft performance and stability. Therefore, having representative dynamic models of the key engine, power, thermal, and control elements is critical to study different architectures and to test for performance and stability of the system in simulation before implementation using real hardware. The elements of the IPPS model and challenges associated with developing such models are discussed in the following.

1. *Elements of IPPS Model for Control*

    An IPPS model and control will include the following
    - Component models
    - Engine models
    - Propulsor models
    - Thermal system models (pumps, heat exchangers, lube systems, actuation, aircraft electronics, etc.)
    - Power management and distribution
    - Thermal management
    - Control system (sub-system control, supervisory control, location of control)
    - Network, communication architecture, interfaces

    The model of the IPPS system is designed to capture the interaction between electrical and mechanical components, between heat sources and heat sinks, and between engine and control.

    Various modeling tools are available, but the leading contenders are the existing tools, i.e., the Numerical Propulsion System Simulation (NPSS) and MATLAB/Simulink. NPSS is a modeling environment developed by a consortium of NASA and leading aerospace companies. Jet engine companies use NPSS to create their highest fidelity engine models, which they use to design turbomachinery and to provide performance models for internal and external use. NPSS models are physics-based, nonlinear models that can be steady-state or dynamic and can include simplified or full control logic. MATLAB and Simulink are industry standard for the development and testing of control logic, although final testing is often done in the NPSS environment. Newer modeling environments include pyCycle [36] and OpenMDAO [37]. While models can be desktop models or embedded real-time models, this paper will discuss desktop models used in defining architectures and studying the interaction between the various components or sub-systems of the IPPS model. A good starting point for desktop studies is the MATLAB/Simulink based NASA-developed open-source thermodynamic simulation package Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) [38] combined with a compatible Power Flow modeling tool [39]. Figure 13 shows an example model developed using tools of this type [40].
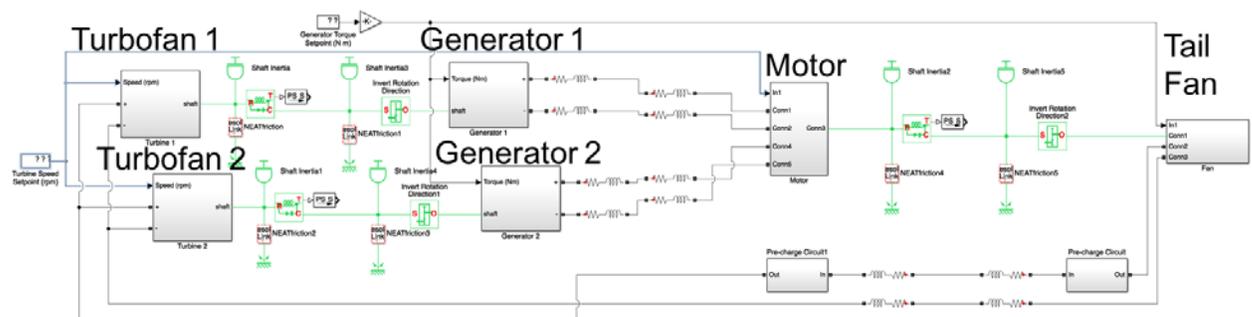

Fig. 13. Diagram of a model of the STARC-ABL using MATLAB/Simulink based power and turbomachinery modeling blocks

2. *Challenges*

There are several challenges in the design and implementation of IPPS models. These include:
- Model accuracy and throughput: What are the fidelity vs. time scale tradeoffs to capture interaction accurately enough for control design without requiring excessive simulation time?

When are simple dynamic elements such as first order lags sufficient, and which nonlinearities and delays is it important to model?

- Interaction between elements: Are all the electrical, mechanical, fluid, and thermal elements modeled? What about the control system? How are the interactions between the components shown?
- Load drops and accepts: These impact engine operability. The size of load change and the rate at which the load changes are important, as is the modeling of any energy storage and discharge elements.
- Supervisory control: An IPPS system is by its very nature an integrated system consisting of multiple sub-systems, or a system of systems. While it may be possible to design a single large integrated control system, there are good technical reasons and several organizational ones that make it desirable to have a more distributed architecture – one in which each sub-system has its own controller, and a supervisory controller directs the interaction between the subsystems. Perhaps a practical system is a hybrid, somewhere between a centralized and a fully distributed system.
- Integration with airframe: While a decentralized system with a supervisory control provides for separation and decentralized control, the reality is that an IPPS system requires tighter integration with the aircraft. After all, it is the aircraft or pilot that determines changes in power level, and can assist by providing information about objectives and current and future operating conditions. This is discussed in some more detail later in the paper.
- Additional Partners: With a conventional aircraft, engines belong to the engine company and the airframe and flight controls belong to the airframer. With an IPPS system, there is potential for additional electrical component vendors and for systems integrators. The roles of these new partners in the overall aircraft integration will need to be defined in a way that is acceptable to the current major players.
- Prognostics and Health Management (PHM): An IPPS system requires a more sophisticated prognostics and health management system, both because there are more components and because there is greater interaction between elements. Integrating the traditional PHM with the power system health management will pose additional challenges.
- Integrated dynamic models for trade studies, especially power system trades.
- Battery modeling and state-of-charge estimation.

3. NASA Role in IPPS Dynamic Modeling for Control Design

It is important for NASA to take the lead in developing generic tools for dynamic modeling of integrated propulsion and power systems just like NASA took the lead in developing NPSS and T-MATS. The NASA developed tools can be publicly available and will enable a broad set of researchers to address the key challenges listed above.

B. Control Architectures for Hybrid Electric Propulsion

Aircraft engine control systems are designed to ensure safe, reliable, and efficient dynamic operation of the engine throughout the vehicle's operating envelope. Conventional engine control architectures tend to be centralized in their design, with the control logic for each engine implemented in a dedicated control computer, or FADEC unit. HEP control systems are expected to be more distributed in their design, requiring the coordinated control of turbomachinery and electrical subsystems. Figure 14 shows a side-by-side comparison of a conventional engine control architecture and the control architecture envisioned for a HEP system.

In the conventional architecture, the FADEC receives thrust commands from a flight control computer and commands the engine to deliver a requested amount of thrust. Engine closed-loop control logic implemented within the FADEC is designed to process engine sensed feedback measurements and then calculate and supply updated commands to the engine's actuators. Limit logic along with acceleration and deceleration schedules are applied within the control logic to ensure that engine operability and stability are maintained during transients. The amount of bleed air and horsepower extracted from conventional engine designs tend to be relatively small, and the control is designed to be robust to these power extraction levels. In multi-engine aircraft, each engine is independently controlled and operated. The amount of data sharing or transfer between engine control systems tends to be limited or nonexistent, and if data transfer is

performed, steps are taken to identify or mitigate any potential common mode faults that could affect the operation of more than one engine.

HEP system control architectures will be vehicle and configuration specific, but in general HEP control systems are envisioned to be more distributed with a high degree of coupling or sharing of information between subsystems. In addition to a gas turbine controller (FADEC), a controller for the electrical components of the HEP system will also be required. The electrical component controller will communicate with power electronics to control the operation of electrical components. This includes controlling the amount of generator power offtake from the gas turbine engine, and the delivery of power to one or more electric motors driving distributed fans. For designs that include a battery, the electrical component controller will also be responsible for controlling the rate of battery charge or discharge. In hybrid electric designs, the amount of gas turbine power offtake is expected to be a significant percentage of the engine's total power output. As such, any changes in the amount of engine power offtake must be done in a coordinated fashion. To supply this coordination, the HEP control architecture shown in Fig. 14 proposes the inclusion of a supervisory controller. The supervisory controller receives thrust demands from the aircraft, and then coordinates the operation of the gas turbine engines and electrical components to produce this requested amount of thrust.
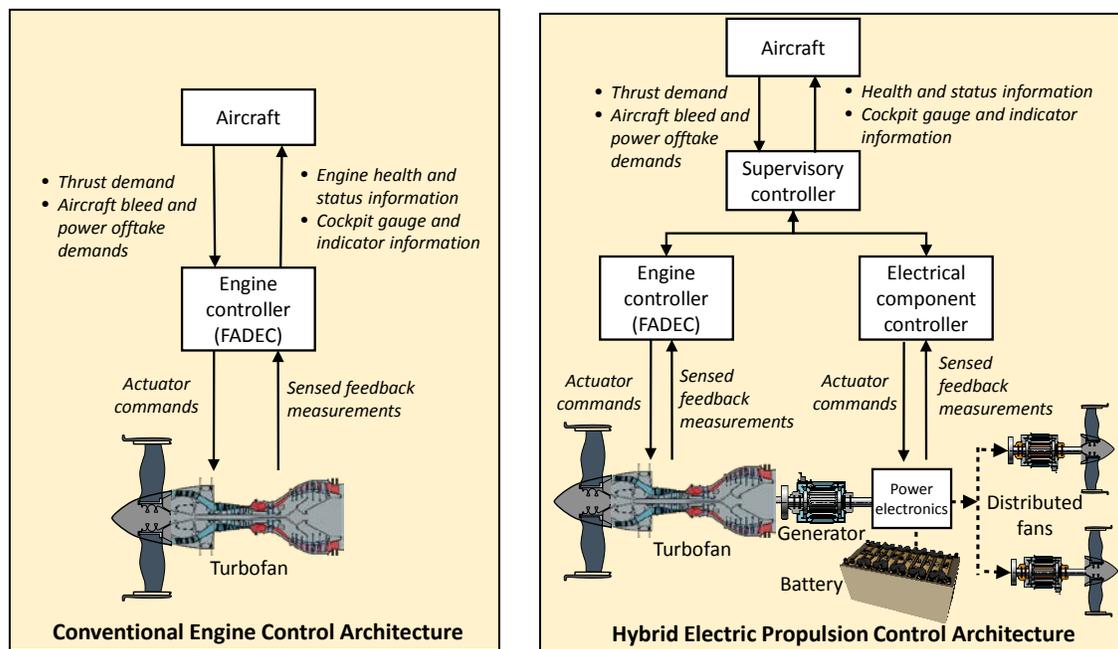

Fig. 14. Conventional and hybrid electric propulsion control architectures

While HEP systems present significant control design challenges, it is important to recognize that the coupled nature of these systems also presents controls opportunities to improve efficiency and operability. The controls challenges and opportunities afforded by these designs are further discussed in the subsections below.

1. Dynamic control to ensure system operability and stability

Conventional aircraft engine control systems are designed to provide reliable engine operation during transients. The primary engine control command is fuel flow, which is regulated to produce the desired engine response in terms of fan speed, engine pressure ratio (EPR), or some other sensed feedback variable representative of thrust. Acceleration and deceleration schedules are applied to maintain operability margins during transients and guard against compressor stalls or combustor blowout. Limit logic is also applied to protect against engine over-speed or over-temperature events. In addition to fuel flow, conventional aircraft engine control systems are also tasked with scheduling the operation of variable geometry such as stability bleed valves and variable stator vanes included in the engine's compression

system. All aircraft engines must meet a certification requirement to respond transiently from flight idle to 95% maximum power in no more than 5 seconds.

For HEP systems, the high amount of gas turbine power offtake required for electrical generation adds complexity to the control system design. If not limited, the amount of power offtake requested by electrical generators could potentially compromise gas turbine engine operability. Therefore, control logic within the electrical system controller must be included to limit the overall amount, and rate-of-change, of engine power offtake. In addition to gas turbine engine operating limits, the electrical components and motor driven fans are also expected to have critical operating limits that must be maintained. This includes the torque loads and speeds at which fans and mechanical components driven by electrical power can operate. It may also include electrical component limits such as the total power delivered through cables, battery state of charge, and battery maximum charge/discharge rates.

Although dynamic control challenges for HEP systems do exist, there are also potential benefits that can be gained through control. Engine power offtake can be considered as an additional actuator that can be used to control engine operation, especially in cases where power is extracted from both the high and low rotor spools simultaneously. In such cases it may be possible to adjust spool speeds in a coordinated fashion to enhance overall operability. The capability to either add power to or extract power from engine spools provides further control flexibility. With power addition/extraction it may be possible to consider alternative engine designs that may allow elimination of compressor stages or actuators currently required for operability and stability.

2. Optimal energy and thermal management

Conventional aircraft engine designs are optimized to provide maximum efficiency at the cruise operating point of the aircraft. Hybrid electric propulsion designs will also be expected to deliver maximum efficiency at a cruise design point. However, the coupled nature of HEP systems offers the potential to implement control schedules that further optimize the operation of the system. This may include optimal energy management strategies that seek to minimize overall fuel burn and battery energy consumption for a given mission while adhering to operational constraints. This may entail seeking to simultaneously operate the engine near its point of minimum thrust specific fuel consumption (TSFC) while operating electrical components such as generators and motors at speeds and torques close to their regions of maximum efficiency. Thermal management considerations will be a key factor and must be accounted for in scheduling engine and electrical component operation. The control system should also be robust to normal performance variations expected within the system due to manufacturing tolerances or degradation experienced by the components over time with use. The supervisory control is expected to control the coupled operation of gas turbine and electrical components in a coordinated fashion.

3. Fault and hazard detection and mitigation

The design process of an aircraft propulsion system includes a failure mode, effects and criticality analysis (FMECA) conducted to identify all potential system failures or hazards, and design enhancements taken to ensure that those events are properly mitigated. The engine control system plays an important role in this process as a significant amount of the engine's control logic is devoted to fault detection, isolation, and accommodation functionality. This includes reversionary control modes that are activated in the event of certain fault types to allow the engine to continue to operate and produce thrust. A HEP system must also be designed to ensure that any potential propulsion system failures occur gracefully with proper mitigation. Many aspects of fault tolerant design extend beyond the control system, for example, designing components of the appropriate size and redundancy to accommodate potential faults. However, the control system is still expected to play a large role in fault accommodation. These are expected to be failsafe designs, where system actuators revert to a failsafe operating condition in the event of a failure, and reversionary control modes account for contingencies such as one-engine-inoperative or failures of electrical system components. The supervisory controller is expected to play a key role in failure/hazard accommodation. It will receive health and status information from engine and electrical system controllers, and then command the system changes necessary to mitigate identified faults. For purely turbine engine driven aircraft, the overall system is designed for the aircraft to be safely operable with one engine shut down due to any failures. For a HEP system where an electrically driven propulsor is receiving power generated from more than one turbine engine, the issue of how to handle one turbine engine failure needs to be addressed through appropriate control architecture design.

4. Control architectures to facilitate certification and aircraft engine integration

Conventional aircraft engines, including their control system, are largely self-contained designs. Traditionally, the engine manufacturer has maintained ownership of the design, as well as the responsibility of having the engine certified for operation. Due to their distributed nature and often unique integration into the aircraft, HEP control architectures will present new certification and aircraft integration challenges. HEP system verification and validation, and aircraft integration are covered later in this paper. However, any HEP control system architecture should be designed taking ease of certification and aircraft integration considerations into account.

5. NASA Role in helping define "optimal" control architecture for HEP systems

As the above discussion shows, there are many issues to be addressed in coming up with an "optimal" control architecture for a given HEP system configuration. NASA has taken the lead in defining a couple of the HEP configurations for single aisle commercial aircraft – these are STARC-ABL and hFan. Using these configurations as a baseline, NASA can play an important role in developing tools and methodologies which can be used to arrive at the "optimal" control architectures for these configurations. Such tools and methods will be useful to the industry and other research partners in coming up with their own "optimal" control architectures for their specific HEP system designs.

C. Hybrid Electric Propulsion Control Verification and Validation (V&V)

Modern propulsion systems are increasingly evolving to include more electric propulsion. This has come to fruition in the automotive industry and is making its way into the aerospace industry as well. HEP is a first step in this shift towards more electric propulsion as it is a means of using electric generators to supplement traditional gas turbines—rather than replace them entirely—which results in less stringent safety/regulatory requirements levied upon the design. Viewed entirely as a backup system, the electric portion of a hybrid-electric design is seemingly a non-impact to existing gas turbine architectures. However, any additional complexity to a system results in additional failure modes that need to be considered. These additional failure modes will lead to additional fault detection and accommodation (FD&A) strategies for the engine control system. Similarly to every function of the engine controller, these failure modes and their FD&A strategies need to be verified in all of the varying operating conditions of the target aircraft. Additionally, the integration of an electric generator to the system will impact the behavior of the engine for many normal/non-failure mode conditions, and this will impact the engine control approach generally and not just from an FD&A perspective. The overarching strategy of how to verify hybrid-electric functions for an engine control system and apply that strategy to existing certification regulations is a new area of research that will need much attention in the coming years.

1. Challenges of HEP System V&V

HEP is a generational change for the aerospace industry, so there is not a baseline or existing approach to compare to other than the traditional gas turbine engine. V&V approaches for traditional gas turbine engines are understood and have been proven over many decades. Although HEP systems are new, they will not impact the fundamental aspects of these approaches since the way to prove a design can be certified is largely not constrained by the design itself. However, new design analysis tools and testing plans and environments will likely be needed to show the details of the hybrid-electric design can meet certification requirements. These tools and testing environments include, but are not limited to: vibration analysis, solar radiation effects, thermal analysis, and functional/dynamic modeling. Additionally, impacts of the hybrid system on the certification strategy for the entire propulsion system need to be assessed. It is likely that the electric portion of a hybrid system will make some aspects of certification easier due to the increased capability of the engine, but it is also likely that other aspects make certification more difficult due to common mode failures with and overall performance impact on the gas turbine portion. On the increased capability side, the existence of an electric generator could mitigate the detrimental effect of compressor surge or combustor flameout to the point of no longer making those events hazardous. On the common mode failure side, the electric generator could have single point failure modes that disable the generator, the gas turbine, and potentially the aircraft itself. Also, as discussed earlier, for purely turbine driven aircraft, the engines are certified as an individual entity and the certification requirements are well defined. For a HEP system, especially any architecture other than a series hybrid system where there is a one to one connection between a turbine engine and an electrically driven propulsor, it is not clear as to whether certifying the turbine engine system and the electrical power system separately will be sufficient.

In such cases the certification will need to be done at the fully integrated power and propulsion system level.

2. NASA Role in HEP System V&V

Given HEP is such a new field of study for the aerospace industry, it is very important for NASA to research the high risk and new technological aspects of the field. V&V of the hybrid-electric system is one of those high risk areas. As mentioned, some of those risks are associated with new failure modes of the electric system, impact to functionality of the gas turbine, and new design tools and testing environments needed to prove the design meets certification requirements. These risks should have viable mitigations, but they are risks now due to the newness of this field and thus being "known-unknowns." Along with these risks, there are opportunities as well since the additional functionality of a hybrid-electric system may make the certification basis for an engine easier to justify. With respect to each of those detailed areas of risk and opportunity, the overarching goal of the research would be to provide guidelines for how to apply existing regulations and advisories from the FAA (Federal Aviation Administration) to hybrid-electric systems, and what new requirements needs to be developed for certification.

D. Engine/Airplane Control Integration

The engine/airframe integration of electric and HEP systems presents new considerations and challenges to the technical team. This section of the paper provides some general discussion on topics of interest to integrate HEP or electric propulsion control systems onto a commercial airframe. These discussions are based on a sampling of study vehicles that NASA and other groups have proposed.

For the propulsion controls group at an Airplane OEM (Original Equipment Manufacturer), the traditional objective is to integrate the propulsion system with other aircraft systems, the flight crew, and the maintenance crew. That trio of tasks is growing, for example, as the team now supports data integration with advanced health monitoring and fleet metrics. Moreover, research may focus on improving use of information, simplifying tasks required of flight crews and maintenance crews, and adding novel features to improve efficiencies. Novel features include, for example, integrated flight and propulsion control capability that provide new airplane design space.

Electric and HEP control systems propose the challenge of integrating greater complexity while reducing flight crew training and flight crew workload. The flight deck objective is to provide high-level information about the operating status of the propulsion system, and to provide actionable recommendations regarding propulsion system malfunctions. Moreover, commercial aircraft are already increasing the level of integration of propulsion systems with various aircraft systems. Architectural philosophies will need to be developed. For example, does the propulsion system have electrical power storage separate from the aircraft electrical system, or are they integrated? The answer will be derived from a requirements analysis of safety, size-weight-cost, and operational requirements. Issues that need to be addressed for various aspects of aircraft operation are discussed in the following.

1. Flight deck displays

The long-term goal for the flight deck of commercial transport will continue to be reducing crew training requirements and crew workload tasks in flight. The objective for the flight deck of a hybrid-electric aircraft should be to make the complexity of the propulsion system a non-factor for the flight crew. This will open up new opportunities for smart software systems to provide information about the state of the propulsion system, and make decisions as appropriate to continued safe and efficient flight.

One objective will be to reduce propulsion system information on the flight deck. Perhaps indications can be limited to information about the current thrust levels, maximum thrust available, and an "engine health score." Moreover, the objective is to utilize minimal, high level, instructions to the flight crew to accommodate propulsion malfunctions, such as, "reduce thrust", "shut down engine", "attempt engine restart / do not attempt engine restart," etc. Of course, this requires an integration of PHM algorithms with the propulsion control laws, and creation of new PHM algorithms to accommodate the real-time needs of the aircraft. To accomplish this objective, the integrated propulsion/power system control software will be tasked with greater decision making to recommend specific crew action. This will require novel, intelligent algorithms that are understandable, testable, and certifiable.

2. Flight deck controls

Generally, the propulsion control system will need to be smart enough to configure the propulsion system to respond to airplane-level commands. Conceptually, the airplane should be able to provide commands to start or shutdown the engine and/or the power system driving a specific propulsor, and provide fully-modulated forward and reverse thrust. The propulsion control system should be able to configure available resources to meet the demands of the aircraft and flight crew, while making the interfaces as simple and ergonomic as practical.

For a more conventional-looking aircraft, replacing two or three gas burning engines with a similar number of electric motors, maintaining independent thrust levers for each thrust source remains viable. However, for a concept with six motors per wing, as an example, the ergonomics and mechanical size of independent thrust levers becomes unwieldy. In the case of partial turboelectric HEP systems such as the NASA STARC-ABL configuration, where the turbine engines provide both direct thrust through a shaft driven fan and generate power for an electrically driven propulsor, the control architecture used to drive the electric propulsor will determine whether the flight crew needs to be provided a separate control effector (thrust lever) for it. Thus a configuration including an "aircraft executive" software function becomes attractive, wherein the flight crew would provide commands of "more thrust / less thrust" with a single lever, and software would determine how best to accommodate the flight deck request. Moreover, propulsion system malfunction accommodation is simplified and prevents incorrect crew action.

3. Thrust Management

For an airplane configuration incorporating multiple, redundant engines, the management of thrust requirements and redundancy could be disruptive. New design space may open up for integrated flight and propulsion controls, redundancy management, and total thrust requirements. On current, two-engine jet aircraft, one engine out leads to a huge loss of thrust. With six or twelve propulsors, one propulsor out may be a less critical event. Of course the metrics of maintenance costs, weight, and probability of failure all increase for a propulsion system with increased number of engines/propulsors. Careful consideration of the advantages and disadvantages of an aircraft configuration need to be weighed against the requirements and objectives of an aircraft's purpose.

4. Malfunction Interpretation

A failure in the gas turbine or fuel system, or a failure in the electric motor or battery systems may cause a loss of thrust, or a loss of range, or create a threat to the airplane. It should be the responsibility of the control system to detect and interpret these malfunctions in those terms. Instead of raw data provided to the flight crew for interpretation, the propulsion system should provide information in terms of immediate crew action required, crew action recommended, and whether crew should reconsider flight plan and/or final destination.

Electric propulsion and HEP systems create a new engineering discipline. Current engine design engineers have expertise in materials, thermal analysis, aerodynamics, and mechanical systems. The new paradigm requires the propulsion engineering discipline to add electric motors, power systems, and electrical power storage to the knowledge base. Similarly, integrated flight and propulsion control systems and algorithms would benefit from an engineer with knowledge in airplane control, propulsion control, propulsion systems, actuation, basics of power component management and control, and malfunction detection and accommodation.

IV. Conclusion

This paper presented the perspective of the Commercial Aero-Propulsion Control Working Group (CAPCWG) on the propulsion control technology development needs to meet the goals of relevant research themes under the NASA (National Aeronautics and Space Administration) Aeronautics Research Strategic Thrusts 3a and 4. The CAPCWG identified four control technology development areas for "Ultra-Efficient Propulsion" research theme for Thrust 3a, and another four control technology development areas for the combined research themes "Hybrid Electric Components & Technology", and "Modeling, Simulation, Testing" under Thrust 4. Each of the technology areas was briefly described, technology development challenges were listed, and the role that NASA needs to play in technology development was identified. NASA focus on the Ultra-Efficient Propulsion research theme is to develop technologies that will enable ultra-high bypass (UHB) engines with compact cores to meet challenging efficiency, emissions, and noise

goals. The four control technology development areas for this theme are extensions of the work that NASA has supported in the past but with an emphasis on addressing the challenges specific to incorporation on UHB engines. For the Thrust 4 research themes, NASA focus is on developing Hybrid Electric Propulsion (HEP) system technologies for single aisle commercial aircraft. This is a new concept from the propulsion control perspective and the four technology needs identified address the challenges associated with integrated control of propulsion and power systems to ensure that the HEP system meets the requirements for performance and operability. Issues with integration of the HEP system with the aircraft are considered in developing the overall control architecture for the HEP systems.

Acknowledgements

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