Advanced Control of Turbomachinery Based Aero-Propulsion Systems

Dr. Sanjay Garg
Chief, Intelligent Control and Autonomy Branch
Ph: (216) 433-2685
FAX: (216) 433-8990
email: sanjay.garg@nasa.gov
http://www.grc.nasa.gov/WWW/cdtb
Caveats

- Focus is on research being done under NASA Aeronautics Research Mission Directorate (ARMD) Programs
  - Applications considered are current and future high bypass turbofans for “larger” commercial aircraft
  - Emphasis is on improving efficiency and safety and reducing emissions
- Presentation is from a “Research” perspective – not engineering and development.

Acknowledgements

Thanks are to:

- All members of the Intelligent Control and Autonomy Branch who are conducting this research and have provided content for this presentation
- NASA ARMD program and project management members who have funded the research
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
Aeronautics Strategic Research Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications
NASA Aeronautics Program Structure
Effective FY15

Aeronautics Research Mission Directorate

------------------------ Mission Programs ------------------------

Advanced Air Vehicles (AAVP)

Airspace Operations and Safety (AOSP)

Integrated Aviation Systems (IASP)

Transformative Aeronautics Concept (TACP)

Advanced Air Transport Technology (AATT) - (GRC)

Airspace Technology Demonstration (ATD) - (ARC)

Environmentally Responsive Aviation (ERA) - (LaRC)

Cross Program Operations (CPO) - (ARMD)

Revolutionary Vertical Lift Technology (RVLT) - (LaRC)

SMART NAS – Testbed for Safe Trajectory Operations (ARC)

UAS Integration in the NAS (AFRC)

Leading Edge Aeronautics Research for NASA (LEARN) - (ARMD)

Commercial Supersonic Technology (CST) - (LaRC)

Safe Autonomous System Operations (SASO) - (ARC)

Flight Demonstration and Capabilities (FDC) - (AFRC)

Transformational Tools and Technologies (TTT) - (GRC)

Advanced Composites (AC) - (LaRC)

Aeronautics Evaluation and Test Capabilities (AETC) - (ARMD)

Convergent Aeronautics Solutions (CAS) - (ARMD)
ICAB Overview

• Mission
  – Research, develop and verify aerospace propulsion dynamic modeling, health management, control design and implementation technologies that provide advancements in performance, safety, environmental compatibility, reliability and durability
  – Facilitate technology insertion into the mainstream aeropropulsion community

• Capabilities
  – 25 engineers and scientists (16 CS, 9 Contractors) - most with advanced degrees and extensive experience in aeropropulsion controls related fields
  – Extensive computer-aided control design and evaluation facilities including real-time and man-in-the-loop simulation facility
  – Strong working relationship with controls technology groups in the aerospace propulsion industry, academia and other agencies
  – Strong collaborative activities with other groups at GRC - Various Branches in the Propulsion Division and with controls groups at NASA ARC, AFRC and LaRC
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
Basic Engine Control Concept

**Objective:** Provide smooth, stable, and stall free operation of the engine via single input (PLA) with no throttle restrictions
  - Reliable and predictable throttle movement to thrust response

**Issues:**
  - Thrust cannot be measured
  - Changes in ambient condition and aircraft maneuvers cause distortion into the fan/compressor
  - Harsh operating environment – high temperatures and large vibrations
  - Safe operation – avoid stall, combustor blow out etc.
  - Need to provide long operating life – 20,000 hours
  - Engine components degrade with usage – need to have reliable performance throughout the operating life
Operational Limits

- **Structural Limits:**
  - Maximum Fan and Core Speeds – N1, N2
  - Maximum Turbine Blade Temperature

- **Safety Limits:**
  - Adequate Stall Margin – Compressor and Fan
  - Lean Burner Blowout – minimum fuel

- **Operational Limit:**
  - Maximum Turbine Inlet Temperature – long life

---

Glenn Research Center
Intelligent Control and Autonomy Branch at Lewis Field
Implementing Limits for Engine Control

- Limits are implemented by limiting fuel flow based on rotor speed
  - Maximum fuel limit protects against surge/stall, over-temp, over-speed and over-pressure
  - Minimum fuel limit protects against combustor blowout
- Actual limit values are generated through simulation and analytical studies
Typical Current Engine Control

• Allows pilot to have full throttle movement throughout the flight envelope
  - There are many controlled variables – we will focus on fuel flow

- FAA regulations provide a maximum rise time and maximum settling time for thrust from idle to max throttle command

Engine control logic is developed using an engine model to provide guaranteed performance (minimum thrust for a throttle setting) throughout the life of the engine.
Some Limitations of Current Engine Control Architecture – Logic

- Not being able to measure the quantities of interest for control (Thrust) / safe operability (Stall Margin, Turbine Inlet Temperature), introduces conservatism in the control design
- To accommodate the unknown effects of engine degradation, and variation on relationship between measured variables and variables to be controlled/limited requires extra margins to be built into the engine design

<table>
<thead>
<tr>
<th>Elements of Stall Margin Uncertainty</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine to Engine Variation</td>
<td>1.0%</td>
</tr>
<tr>
<td>Reynolds Number Effects</td>
<td>1.0%</td>
</tr>
<tr>
<td>Operating Line Deterioration</td>
<td>2.0%</td>
</tr>
<tr>
<td>Stall Line Deterioration</td>
<td>3.0%</td>
</tr>
<tr>
<td>Inlet Distortion</td>
<td>4.0%</td>
</tr>
<tr>
<td>Total Stall Margin Uncertainty</td>
<td>11%</td>
</tr>
</tbody>
</table>
Why Advanced Control Logic?

• The control logic by itself does not impact efficiency. However, Advanced Control Logic can enable design of engines with reduced operability margins - reduce the need for both Transient and Uncertainty stacks in the design Stall Margin
  • Reduction of 3% in Design Stall Margin ~ 1 % TSFC reduction
  • Dynamic Systems Analysis can provide an indication of the performance and operability margin tradeoff available for a given engine design
Some Limitations of Current Engine Control Architecture – Hardware

- Based on the current temperature capability of electronics, the optimal solution for control hardware architecture is a centralized approach – all sensor, actuators are hard wire connected to the ECU (Engine Control Unit) and all signal processing, control calculation, actuator loop closures etc. are done in the ECU
- This centralized control structure severely limits the capability to introduce advanced control technology and new control capabilities

- Rigid Architecture – difficult/expensive to make updates
- Wiring harnesses – weight, connectors
- Fault management
- Obsolescence management
Why Advanced Control Hardware Architecture?

- *Change in control architecture by itself does not change performance.* However, advances in control hardware architecture keep controls from becoming a limiting factor in achievable engine system performance.

**Distributed Architecture:**
A system of asynchronous systems synchronized by a network

**Benefits:**
- Weight reduction
- Life cycle cost reduction
- Improved Availability
- Modularity – easier infusion of new technology
- Advanced Control Applications
  - Wide-Bandwidth Sensing and Actuation
  - Local Loop Closure
  - Information Infused Control
The Role of Advanced Propulsion Controls

**Perception**: The Focus of Propulsion Controls is Operability
- Make the system perform as it was designed
- Not perceived as research, so much as it is engineering

This completely misses the power of controls and electronics, which is *the creation, processing, and use of Information*

*Controls technology cannot advance system performance unless it assumes an active role in system design. Absent this interaction, controls can only optimize operability.*
C-MAPSS40k engine simulation

- Commercial 40,000lb\textsubscript{f} thrust, high-bypass turbofan engine
- Physics-based 0-D Dynamic model
- Realistic engine control system & sensor noise
- Written in MATLAB/Simulink
- Modular design
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
Model-Based Control and Diagnostics Concept

Actuator Commands
- Fuel Flow
- Variable Geometry
- Bleeds

Sensor Validation & Fault Detection

Selected Sensors

Component Performance Estimates

Sensor Estimates

Sensor Measurements

Ground-Based Diagnostics
- Fault Codes
- Maintenance/Inspection Advisories

On-Board Model & Tracking Filter
- Efficiencies
- Flow capacities
- Stability margin
- Thrust

Ground Level

“Personalized” Engine Control

“Personalized” Engine Control

Actuator Positions

Engine Instrumentation
- Pressures
- Fuel flow
- Temperatures
- Rotor Speeds
Modeling Engine Faults and Performance Deterioration*

A general influence coefficient matrix may be derived for any particular gas turbine cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters.

Physical Problems
- Erosion
- Corrosion
- Fouling
- Built up dirt
- FOD
- Worn seals or excessive clearance
- Burned, bowed or missing blades
- Plugged nozzles

Degraded Component Performance
- Flow capacities
- Efficiencies
- Effective nozzle areas
- Expansion coefficients

Changes in Measurable Parameters
- Spool speeds
- Fuel flow
- Temperatures
- Pressures
- Power output

* From “Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines” by Louis A. Urban, 1974

Glenn Research Center
Intelligent Control and Autonomy Branch
at Lewis Field
Optimal Tuner Selection for Kalman Filter-Based Performance Estimation

Background:
- Adaptive on-board engine model
- Applies Kalman filter-based tracking filter

Challenge:
- Underdetermined estimation problem – more unknowns (health parameters) than available sensor measurements

Approach:
- Define tuner vector that is a linear combination of all health parameters and systematically selected to minimize KF mean squared estimation error in the parameters of interest

Results:
- Linear Monte Carlo simulation studies have shown a mean error reduction of approximately 33%

Thrust estimation accuracy comparison (conventional vs. optimal model tuning parameters)
Model Based Engine Control

Goals

• Use an on-board “self-tuning” model of the engine to provide accurate estimates of unmeasured parameters for control design as the engine ages
• Allow for the engine to serve as a backup to the flight control system during emergency scenarios by improving the transient response time of the engines

Approach

• CMAPSS40k simulation as baseline engine
• Integrate engine with Optimal Tuner Kalman Filter to get estimates of unmeasured parameters
• Replace current control architecture with a Thrust controller and Stall Margin limit protection

Results

Thrust Control response over engine life compared to baseline EPR control

Stall Margin limiter over engine life cycle compared to baseline acceleration limiter
MBEC—Benefits Demonstration

Design Stall Margin Reduction
- Trade study showed that with use of MBEC on the C-MAPSS40k engine, the Design Stall Margin can be reduced by 4.7% - 2.9% for transient and 1.8% for engine deterioration

Engine “Redesign”
- An approximate redesign of the engine was conducted by scaling the LPT and HPT performance maps to reduce the corrected mass flow, and move the HPC operating line up for the reduced design Stall Margin

Results
- MBEC provides tight control of Minimum Stall Margin to maintain safe operation throughout engine life while meeting thrust response performance requirement
Run-time Assurance of Advanced Propulsion Control

Overview:
- Investigate vehicle-centric run-time assurance (RTA) of advanced propulsion control algorithms.
- RTA holds the promise of certifying advanced controllers which are difficult to certify using traditional verification practices.
  - Monitor system state during run-time, and when anomalous behavior is detected, revert control to a certified backup controller to assure continued safe operation.

Approach:
- Advance the maturity of the RTA approach by continuing to refine an RTA architecture for NASA’s model-based engine control approach.
- Integrate RTA with NASA’s Conditionally Active Limit Protection architecture to reduce conservatism.

- Continually monitor state of the system
- Compare against validated safe operating envelope
- Upon violation detection, transfer control to Backup System to assure continued safe operation
DART – DGEN Aero-Propulsion Research Turbofan

- Facility based on the DGEN 380 Turbofan Engine developed by Price Induction
  - Dual spool, high bypass geared turbofan rated for 500 lb thrust with FADEC
- Provides an excellent low cost platform to validate advanced control logic schemes through engine test
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
Distributed Engine Control

Technology Challenges:
• High temperature electronics
• Communications based on open system standards
• Control function distribution

Distributed Engine Controls Research at NASA:
• Modeling and Simulation
  o Smart node models
  o Communications
• Dynamic Thermal Modeling
• Advanced Smart Node Development
• Hardware-in-the-Loop – Integration
• Very High Temperature Electronics

Government – Industry Partnership
Distributed Engine Control Working Group
Modeling & Simulation

Commercial Modular Aero Propulsion System Simulation 40k

C-MAPSS40k

- The engine system model is decomposed into a collection of separate elements reflecting characteristics of the hardware
- **Functions, Interfaces, and Data Flow** specific to the control architecture
- **System of Asynchronous Systems**

Decomposition

Modularity

Multi-Rate Modeling
Communication Network Complexity

- Serial data transfer imposes significant effects in terms of delay
- May not be possible to transfer all the data within a single control interval
- Simulation studies conducted to investigate impact of sampling on performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>time constant</th>
<th>Original over sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control interval</td>
<td>419 66.7 0.015</td>
<td>1</td>
</tr>
<tr>
<td>Pressure</td>
<td>25 4.0 0.2513</td>
<td>17</td>
</tr>
<tr>
<td>Temperature</td>
<td>9 1.4 0.6981</td>
<td>47</td>
</tr>
<tr>
<td>Speed</td>
<td>6 1.0 1.0000</td>
<td>67</td>
</tr>
</tbody>
</table>

Sim 2: 150 ms, Tx 375 ms
Hardware in the Loop simulation

Collaborative Simulation Environment for SBIR and component suppliers to develop new technology concepts

Collaborative Hardware Environment to verify high temperature embedded technologies, especially related to “system of asynchronous systems” integration

High-Fidelity Real-Time Modeling

Hardware-in-the-Loop Validation

Rolls-Royce DECSS
Dynamic Thermal Modeling

- Mounting electronics near the engine core requires understanding the environment.
- The reliability of electronics are inversely affected by the peak, duration, and rate of change in temperature.
- Methods and tools developed to model temperatures along the axial engine location for engine operation through the take-off to landing cycle.

Information can be used to determine best place to locate “smart node” components based on temperature capability of electronics:
- Silicon Electronics -55 to 125 °C
- Silicon-On-Insulator (SOI) electronics < 300 °C
- Silicon Carbide (SiC) electronics > 500 °C
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
What and Why of Active Component Control

- The need to provide guaranteed performance, and safe operation throughout the operating envelope and certified on-wing life requires design tradeoffs which result in having to make compromises from the “ideal” performance
- As systems get more complex, achieving these objectives through passive component design becomes more difficult

- Active Component Control, defined as a local loop closure for the component (local sensor and actuator integrated with control logic and processor) provides an opportunity to maintain optimal design performance while providing safe operation
Pattern Factor Control
Objective: actively reduce combustor pattern factor
Status: Concept demonstrated in collaboration with Honeywell Engines under the AST program.

Emission Minimizing Control
Objective: actively reduce NOx production
Status: Fuel actuation concept and hardware developed under AST program. Preliminary low order emission models developed under the HSR program.

Combustion Instability Control
Objective: actively suppress thermo-acoustic driven pressure oscillations
Status: Continuing research under the Intelligent Propulsion System Foundation Technologies project.

Glenn Research Center
Intelligent Control and Autonomy Branch at Lewis Field
Objective: Utilize Active Combustion Control Techniques to suppress combustion instabilities.

Approach: Instability suppression was demonstrated using a high-frequency fuel valve to modulate the main fuel. Fuel valve dynamic characterization rig utilized to predict actuator authority prior to combustion testing.

Results: NASA GRC developed Adaptive Sliding Phasor Averaged Control able to prevent growth of combustion instability in a low emissions advanced combustor prototype with a separate pilot and main fuel stage.

Impact: Active combustion control can suppress combustion dynamics and allow operation of a low emissions combustion concept at conditions that would otherwise be precluded due to unacceptably high pressure oscillations.
Active Combustion Control - Fuel Modulator Development

High Bandwidth fuel flow modulation is essential for suppression of thermo-acoustic instabilities.

Glenn Research Center
Intelligent Control and Autonomy Branch

at Lewis Field
Intelligent Clearance Management

- A significant amount of turbine tip clearance is carried in cruise to avoid rubs during re-accel
  - Current clearance control consists of “cooling” the turbine casing using compressor flow to tighten the clearance during cruise
  - This approach is too slow to account for faster clearance changes during transients

Reducing clearance gap by 10 mils (0.01 inch) results in:
- 10°C (18°F) reduction in exhaust gas temperature (EGT) → increase time-on-wing
- 1% reduction in specific fuel consumption (SFC) → decrease emissions & increase efficiency

Glenn Research Center
Intelligent Control and Autonomy Branch at Lewis Field
Active Turbine Tip Clearance Control (ATTCC)

**Goal:**
- Maintain tight control of clearance between the turbine blade and its casing structure by means of a fast response actuator – reduce the clearance needed in steady-state

**Approach:**
- Develop a generic physics-based dynamic model to predict the turbine tip clearance in the high pressure turbine (HPT) during transients
- Integrate tip clearance model with an engine dynamic simulation and conduct sensitivity analyses to quantify the relationship between actuator performance and engine efficiency gains

- Generic tip clearance model incorporating case cooling flow integrated with the C-MAPSS40k engine simulation
- Predicted tip clearance is representative of the typical “pinch” point during transients

Performance impact at cruise while varying the temperature of the cooling flow
Engine Icing: Simulation, Detection, and Mitigation

The Engine Icing Problem
- Ice crystals have been found to accrete in the engine compression system
- Accretion can lead to engine power-loss:
  - Ice ingestion into combustor causing flameout
  - Compressor surge
  - Engine rollback
- 153 power-loss events identified from 1988-2010

Modeling, Detection & Mitigation
- Use C-MAPSS40k engine simulation
- LPC maps calculated for various blockage levels
- Rollback is caused by the engine controller limiting fuel when certain safety limits are reached
- Existing engine sensors have been shown to be capable of detecting accretion of ice at certain operating points
- Existing actuation can shift engine operating point to:
  - Lower shaft speeds (to prevent limit incursion)
  - Alter airflow conditions (to prevent surge)
  - Change temperatures in compressors (to prevent/melt accretion)
  - Increase shaft speeds (to shed accumulated ice when small)

Engine Simulation Demonstration of Thrust Rollback due to Coupling of Ice Accretion with Engine Control
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
NASA N+3 Engine Configurations

N+3 – Engine in Service in 2035
• NASA emphasis is on developing technologies that will enable such configurations
• Traditional Architecture
  • Advanced” (N+3) Geared Turbofan
    - 40% increase in Nacelle Diameter over current
    - Investigation of Variable Area Fan Nozzle

Controls – Study application of advanced technologies and identify benefits and challenges
• Electric Propulsion
  • Hybrid Electric (hFan)
    - Utilizes on-board energy storage
  • Turbo-electric w/Tail Cone Thruster (STARC-ABL)
    - Draws power of 2 main engines to power BLI ingestion fan at rear of vehicle

STARC-ABL: Single-aisle Turboelectric Aircraft with Aft Boundary Layer propulsion
Tool for Dynamic Modeling and Analysis of HEP Hardware & Control Architectures

- Collaboratively develop the basic subsystem models and interfaces required for an HEP system simulation with sufficient fidelity to perform subsystem hardware requirements and control architecture studies to meet overall system (throttle command to thrust response) dynamic performance requirements and operational life/safety requirements.

**Hardware Architecture Feasibility Analysis**

- **Throttle to Thrust Response**
  - Control of Turbomachinery + PMAD + Propulsor Control to meet FAA dynamic performance requirements
  - Modeling of subsystem interactions

**Control Architecture Feasibility Analysis**

- **Propulsion**

**Overall System – throttle to thrust response**

- **Engine/Alt**
- **PMAD**
- **Driv/Motor**

**Glenn Research Center**
Intelligent Control and Autonomy Branch

at Lewis Field
Thrust 6 – Assured Autonomy for Aviation Transformation
Implication for Propulsion Control

- Autonomous Operation of Air Vehicle Requires Autonomous Operation of the Propulsion System!
- Pilot plays a crucial role in identifying propulsion system malfunction during flight and taking appropriate action to maintain safety of flight

Propulsion Malfunctions and Observed Symptoms

<table>
<thead>
<tr>
<th>Condition</th>
<th>Engine Separation</th>
<th>Severe Damage</th>
<th>Surge</th>
<th>Bird Ingestion/FOD</th>
<th>Seizure</th>
<th>Flameout</th>
<th>Fuel control problems</th>
<th>Fire</th>
<th>Tailpipe fires</th>
<th>Hot Start</th>
<th>icing</th>
<th>Reverse Inadvertent Deploy</th>
<th>Fuel Leak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bang</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire warning</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible flame</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yaw</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High EGT</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N1 change</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2 change</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel flow change</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil indication change</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible cowling damage</td>
<td>X</td>
<td>X</td>
<td></td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoke/odor in cabin bleed air</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPR change</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

X = Symptom very likely
O = Symptom possible
Note: blank fields mean that that symptom is unlikely

Sample Pilot Checklist

1. Inoperative Engine - DETERMINE.
2. Operative Engine - ADJUST as required. Before Securing Inoperative Engine:
3. Fuel Flow - CHECK. If deficient, position auxiliary fuel pump to ON.
4. Fuel Selectors - MAIN TANKS (Feel For Detent).
5. Fuel Quantity - CHECK.
6. Oil Pressure and Oil Temperature - CHECK.
7. Magneto Switches - CHECK ON.
8. Mixture - ADJUST. Lean until manifold pressure begins to increase then enrich as power increases.

If Engine Does Not Start, Secure As Follows:
9. Inoperative Engine - SECURE.
   a. Throttle - CLOSE.
   b. Mixture - IDLE CUT-OFF.
   c. Propeller - FEATHER.
   d. Fuel Selector - OFF (Feel For Detent).
   e. Auxiliary Fuel Pump - OFF.
   f. Magneto Switches - OFF.
   g. Propeller Synchronizer - OFF (Optional System).
   h. Alternator - OFF.

11. Trim Tabs - ADJUST 6° bank toward operative engine with approximately 1/2 ball stick indicated on the turn and bank indicator.
12. Electrical Load - DECREASE to minimum required.
13. As Soon As Practical - LAND.

- Currently, the second biggest cause of propulsion related hull losses is “Propulsion System Malfunction + Inappropriate Crew Response”
Intelligent Propulsion System Architecture
To Enable More Autonomous Vehicle Operation

Goals/Objectives: Develop an engine control architecture that works harmoniously with the flight control, with reduced pilot intervention over time.
- Automatically recognize the vehicle operating mode and configure the engine control scheme to provide optimal performance for that mode with knowledge of the engine condition and capability.
- Preliminary simulation based demonstration will be done for specific elements of the architecture and technology gaps will be identified to achieve overall desired capability.

Progress: Preliminary architecture has been developed building upon previous engine control and diagnostics research. Specific demonstration cases have been studied using the TCM/C-MAPSS40k simulation in piloted simulations.

Glenn Research Center
Intelligent Control and Autonomy Branch at Lewis Field
Outline

• NASA Aeronautics Research Background
• Fundamentals of Aircraft Engine Control
  • Some limitations of current approach to engine control
• Advanced Engine Control Logic
• Distributed Engine Control
• Active Component Control
• A Look into the future
• NASA Developed Tools and Technology Dissemination
• Summary
Engine Simulation Software Packages

The following engine simulation software packages, developed in Matlab/Simulink and useful for propulsion controls and diagnostics research, are available for U.S. citizens from NASA GRC software repository

- **C-MAPSS** – Commercial Modular Aero-Propulsion System Simulation
  - Simulation of a modern commercial 90,000 lb thrust class turbofan engine with representative baseline control logic

- **C-MAPSS40k**
  - High fidelity simulation of a modern 40,000 lb thrust class turbofan engine with realistic baseline control logic

The availability of above software packages has recently been limited to use on U.S. government funded work

- **TTECTrA**
  - Provides the user a preliminary estimate of the transient performance of an engine design without the need to design a full controller

All NASA Publications are available for free download at: [https://www.sti.nasa.gov/](https://www.sti.nasa.gov/)

Additionally, a one hour educational video on “Fundamentals of Aircraft Engine Control” is also available. See [https://www.grc.nasa.gov/WWW/cdtb](https://www.grc.nasa.gov/WWW/cdtb) for more information
T-MATS
Toolbox for the Modeling and Analysis of Thermodynamic Systems

• Open Source MATLAB/Simulink plug-in providing a thermodynamic simulation environment enabling graphics based creation of complex dynamic system models, such as gas turbines

• T-MATS features:
  • Powerful, flexible graphical user interface
  • Modular control system components
  • Integration with Cantera, for calculation of thermodynamics, chemical kinetics, and transport properties of any flow.
• T-MATS/Cantera enables simulation of
  − Combustion reactions
  − Gas turbines that use alternative fuels

• Download for free: https://github.com/nasa/T-MATS/releases

Glenn Research Center
Intelligent Control and Autonomy Branch
at Lewis Field
6th GRC Propulsion Control and Diagnostics Workshop
August 22-24, 2017, Cleveland, OH.

• Workshop Objectives:
  – Disseminate information to the research community about the propulsion control and diagnostics research being done at NASA GRC in support of various projects under the NASA Aeronautics Research Mission Directorate (ARMD) programs.
  – Get feedback on value of the research and validity of technical approach.
  – Identify opportunities for potential collaboration and sharing of tools and methods.

• Workshop Content:
  – Detailed presentations on the GRC PCD research efforts – progress to date and future plans, and tools and simulations available for public use.
  – DoD panel and industry panel to discuss ongoing research in various organizations and future vision for engine control.
  – Poster session with demonstration of GRC developed software packages, and poster presentations by partners and other research community members.
  – One-on-one discussions between NASA researchers and attendees.

• Registration information available at:
  https://www.grc.nasa.gov/WWW/cdtb/workshop2017/location.html

- Participation is limited to U.S. citizens and Permanent Residents representing U.S. organizations.

Glenn Research Center
Intelligent Control and Autonomy Branch at Lewis Field
As turbomachinery based propulsion systems become more complex, advances in controls technology become more critical to achieve the desired efficiency and operability.

- Model Based Engine Control architecture has the potential to enable more efficient engine designs while guaranteeing performance and safe operation over the flight envelope and certified on wing engine life.
- Distributed Engine Control architecture is essential to prevent controls from becoming the limiting factor in the achievable performance of complex propulsion systems.
- Advanced control logic approaches, beyond the current single loop Propulsion+Integral controllers will need to be investigated as additional control effectors are added to the propulsion system – eg. variable area fan nozzles for geared turbofan.

**Biggest benefit is taking into considerations the capabilities provided by advanced control in the early design stage**

- Active component control enables the capability to maintain the desired performance (efficiency, emissions, on wing engine life etc.) without having to make design compromises.
  - Distributed Engine Control architecture is essential for implementing active component control.
- Integrated propulsion/power control/management is essential for efficient and safe operation of “electrified” aircraft.