Advanced Controls and PHM
GE Aviation Perspective

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Where are we today?

Central FADEC
Separate Monitoring Unit
Lots of cables
Limited flexibility
Where do we want to be?

- Smaller supervisory FADEC
- Engine Area Network
- Distributed Control Modules (DCMs)
- Smart components
- Plug and play flexibility
- Advanced enabling communication strategy
- Intelligent local diagnostics

Reduced Weight and Increased Flexibility Are Drivers
Distributed Control – Spiral Development

Remote **smart sensors**. Only change is that some transducers are moved out of the FADEC to near the sensing station.

- Reduces tubing weight
- Reduces I/O on FADEC and EMU
- Improves dynamic response of loops using the sensors (no delays)
- Initial implementation limited to *benign locations* (lower temps and vibes)

Remote smart sensors on an **engine area network (EAN)** or data-bus. Transducers moved out, sensors provide digital outputs.

- Reduces cable weight
- Simplifies FADEC circuitry and reduces heat load

Remote **self-powered** or bus-powered smart sensors on EAN

- Scavenge (vibration; heat) or battery powered
- Reduces cable weight
- Reduces FADEC power requirements

Remote self-powered **wireless** smart sensors on EAN

- Eliminates wiring between FADEC and sensors

**Smart actuators** that close their own loops on EAN

- Improves dynamic response of actuator loops
- Actuators provide their own diagnostics
Challenges

- Initial benefits will be low, cost high
- Core building block: Distributed Control Module
- High temperature electronics / adv cooling
- Novel powering scheme (A/C power, self-powered)
- Next-gen communication architecture (IEEE 1451?)
- Modular, swappable, reprogrammable
- Certification/qualification (flexible I/O)
Active Engine Control
Active Control - Overview

Active Stability Management
Active Stall/Surge Control
Active Combustion/Emissions Control
Active Noise Control
Active Stability Management

Currently, compressor stall protection provided by Wf/Ps3 schedule
- Must repeatedly stall test engine to develop stall line
- Wf/Ps3 schedule created for worst case stack engine
  - Inherently conservative for 99% of engines
- Give up on acceleration capability to cover worst-case engine
  - For engines that are not EGT margin limited, this gives up Time On Wing (TOW)

Past experience with managing stall margins
- Two op. lines, with a switch to select between them
  - To deal with hot gas ingestion (distortion), for example

Active stability management would replace or augment Wf/Ps3 schedule
- Detect onset of stall (usually using high BW pressure sensors)
- Avoid stall by modulating fuel flow or air flow
- Allow characterization of stall line from small number of accels
Active Stall/Surge Control

**Axial Flow Compressors**

- **Rotating stall:**
  - Non-axisymmetric stalled flow region rotating circumferentially
  - High chance of non-recovery in uncontrolled scenario

- **Surge:**
  - Axisymmetric flow oscillation
  - Classic/mild surge: positive flow only
  - Deep surge: positive + reverse flow
  - Good chance of recovery

What does it mean to actively control stall/surge?

- Sensors to detect airflow properties
- Actuators to induce perturbations in airflow according to control laws
- High-bandwidth, small amplitude control perturbations needed for stabilization
- Two main design intents:
  - Faster/more likely recovery
  - Intentional, continuous operation in stall region
Active Combustion/Emissions Control

Fuel costs demand high efficiency combustion

Environmental regulation and “green” efforts increasingly demand low emissions

Combustors are subject to instabilities
  • More likely in lean-burning combustors (less liner damping yields more pressure wave propagation)
  • Fluctuating combustion heat interacts with acoustic resonance and yields large pressure oscillations
  • Component life and mechanical failure can result

Active combustion control techniques can suppress the high-frequency instabilities

Active combustion control hardware can also help with pattern-factor control, to reduce peak temperatures and emissions
Active Noise Control

Airport/community regulations demand reduced engine noise

Military applications benefit from minimal noise output

Active noise control techniques

- Electro-acoustic or electromechanical noise cancellation
- Feedback or feed-forward control techniques
- Adaptive to noise content, levels, environment
Active Control - Summary

- High bandwidth hardware contributes most to viability of active control techniques.
- In general, modeling and control techniques have been developed and hardware technology is now the enabler (may need more work on models and control strategies once implemented).
- Test rigs and special hardware have demonstrated concepts, but engine-ready hardware is needed.
- On-engine processing/throughput capability is an important consideration for high bandwidth control and model-based methods.
Performance Enhancing Control
NextGen Control Law Architecture

On-line model-based adaptive control & optimization

- Multivariable/distributed control of actuators
- Adaptive control & optimization to account for deterioration varying with flight mode
  - **Address multiple objectives:** Thrust, SFC, TOW
  - **Manage engine constraints:** Safety, Noise, Emissions

<table>
<thead>
<tr>
<th>Key Technology Elements</th>
<th>Benefit</th>
<th>Value</th>
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<tbody>
<tr>
<td>On-line model</td>
<td>Enabler for other technologies</td>
<td>Enabler</td>
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<tr>
<td>Tracking filter</td>
<td>Deterioration estimation to enable controls adaptation</td>
<td>Enabler</td>
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<tr>
<td>Virtual sensing</td>
<td>Sensor redundancy reduction for weight, cost. Improve time limited dispatch</td>
<td>Sensor cost reduction</td>
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<td>Multivariable control</td>
<td>Transient and steady-state performance across flight modes</td>
<td>Take-off, cruise and descent flexibility</td>
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<tr>
<td>Adaptive optimization</td>
<td>Deterioration compensation to improve transient and steady-state performance</td>
<td>Adaptive schedules for TOW, SFC, thrust performance</td>
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<td>Automated software V&amp;V</td>
<td>Improved SW validation/test quality, reduce cost &amp; cycle time. Eliminate code review &amp; unit testing.</td>
<td>Certification cycle time reduction</td>
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PSC and MPC

Selectable optimization mode by pilot or flight control computer
- e.g. minimize SFC at thrust / maximize thrust at EGT / maximize life at rated thrust
- can provide damage mitigation

Accommodates
- engine-engine variations / deterioration / off-design conditions (alt, Mn, Pla, bleed, HPx,...) / unmodeled effects including aircraft effects (drag, store loadings,...)

Point optimization: Performance Seeking Control (PSC) since mid 80s

Next step is path optimization – Model Predictive Control (MPC)

Next steps:
- On-engine / in-flight testing
- Address issues related to “adaptive” control
Prognostics and Health Management

Increasing shift towards “condition-based maintenance”

Moving from traditional diagnostics (reactive) to PHM (predictive, asset management)

JSF program drove PHM into requirements

Benefit justification can be tricky

Larger benefit if PHM is “Designed into” the system

Need to add sensors, but not increase sensor cost
## OSA-CBM Layers

<table>
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<tr>
<th>Layer</th>
<th>Function</th>
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<tr>
<td>Presentation / GUI</td>
<td>Used to display data or system information to the user</td>
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<td>Decision Support</td>
<td>Automated decision making that uses patterns in the signal(s) or feature(s)</td>
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<tr>
<td>Prognostics</td>
<td>Project future health of the system, taking into account estimates of past and future operations profiles</td>
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<tr>
<td>Health Assessment</td>
<td>Determine current health of the system or subcomponents</td>
</tr>
<tr>
<td>Condition Monitoring</td>
<td>Compare features against expected values, or operational limits and output enumerated conditions</td>
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<tr>
<td>Data Manipulation</td>
<td>Mathematical techniques that help extract the desired information from the energy received by the sensor</td>
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<tr>
<td>Data Acquisition</td>
<td>Measure macroscale parameters (e.g. temperature, pressure, vibration)</td>
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Embedded Software
Controls Software Development

**Business Climate**
- Acceptable error rate: zero
- Functional complexity of software increased 10X in a few years
- Demand for faster turn around
- Increasing number of programs
- Less experienced engineers

**Delivering Results**
- Rigorous requirements-based development
- Improved system verification and software robustness
- Focus on common, documented processes via templates, design practices and process instructions
- Better training and guidance
S/W Challenges

Requirements development and validation
Automating software and system verification
Simulation speed
HW/SW Integration
CMMI certification