Advanced Controls and PHM
GE Aviation Perspective

PCD Conference
NASA GRC
Sept. 16, 2015

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Contents

Distributed Control

Distributed Control – Spiral Development Described in 2009. Where are we in 2015?

✓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

DECWG is Driving Implementation

Active Engine Control

The undiscovered country

Active Control – 2009 Vision

Active Stability Management

Active Stall/Surge Control

Active Combustion/Emissions Control

Active Noise Control

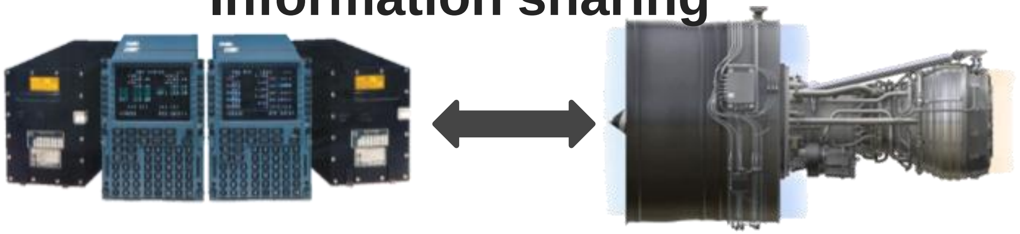
Performance Enhancing Control

FAA CLEEN (FMS-Engine Integration) Three Primary Focus Areas

- Adaptive Engine Control – Uses knowledge of aircraft state and engine health to optimize performance
- Integrated Vehicle Health Management (IVHM) - Uses knowledge of engine health to optimize aircraft performance
- Integrated Flight-Propulsion Control (IFPC) - Synergistic optimization of engine and aircraft

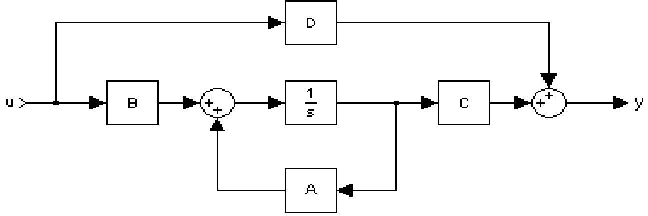
State-awareness is key aspect of FAA CLEEN technology development & maturation

Information sharing



Engine & Avionics

New control concepts and methods



Unified Model

- Guidance & Navigation
- Flight Controls
- Engine Controls

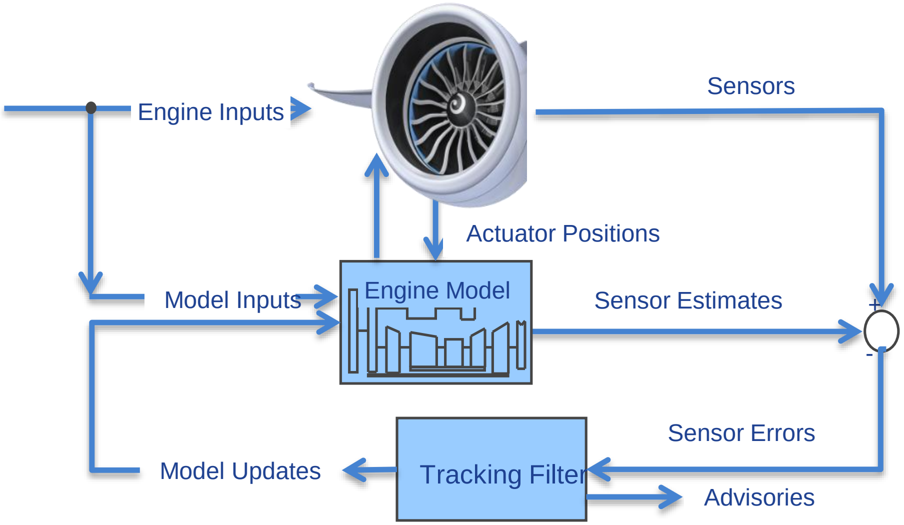
Simulation Controls

Federal Aviation Administration

CLEEN FMS-Engine Integration Technologies

CLEEN Technology	**Fuel Burn Benefit and Application**
Adaptive Control	1%, single and twin aisle configurations, with expected entry into service by 2020+.
IVHM	0.5%, single and twin aisle configurations, with expected entry into service by 2018+.
IFPC	1%, single and twin aisle configurations, with expected entry into service by 2020+.

Adaptive Control:



Benefits:

- Up to 1% reduction in fuel burn

Risks/Mitigations:

- Certification issues
- Special situations such as icing
- Mitigate using normal new product introduction development engine testing

Objectives:

- Develop six different concepts that use awareness of engine state to improve engine performance by adapting design for each engine

Work Statement:

- Modify control logic
- Develop two new sensors
- Perform rig, engine, and flight tests

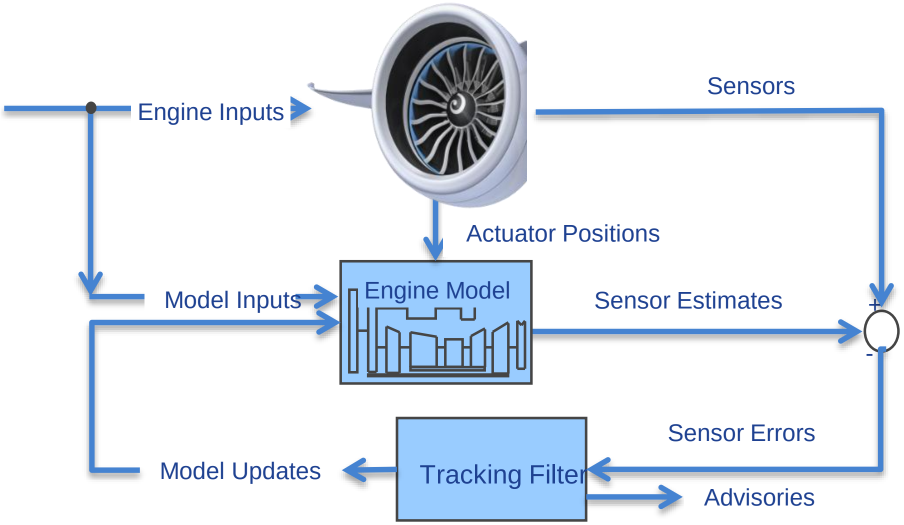
Accomplishments/ Milestones since May 2014:

- Logic design completed: Oct 2014
- Rig testing completed: March 2015
- Ground engine testing completed: August 2015
- Flight testing: Ongoing, will complete in 2015

Status – Adaptive Control

- High-fidelity, physics-based, real-time model
- Parameter estimation algorithm, aka "Tracking Filter"
- Logic to use knowledge of engine state (component health and flight condition) to adaptively tune engine control
- Concept Development and Evaluation (TRL 4)
  - Desktop testing with large number of test vectors
  - Logic tested over full flight envelope, new and deteriorated
- Rig Testing (TRL 5)
  - Logic loaded into FADEC
  - Hardware-in-the-loop testing in controls "dry rig"
- Engine Testing (TRL 6)
  - Ground engine tests to check logic and interfaces
  - Validates concept and provides benefit assessment
- Flight Testing (TRL 7)
  - Currently testing on flying test beds

IVHM (PHM):



Engine Inputs

Sensors

Actuator Positions

Model Inputs

Engine Model

Sensor Estimates

+

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Sensor Errors

Model Updates

Tracking Filter

Advisories

Benefits:

- Up to .5% reduction in fuel burn

Risks/Mitigations:

- Legacy system capabilities – Mitigate using FMS-Engine integration and improved engine hardware as part of PIP

Objectives:

- Develop two concepts that use awareness of engine health to drive advisories
- Once field experience is gained, automate the process via control

Work Statement:

- Modify control logic
- Develop a new sensor
- Perform rig and engine tests

Accomplishments/ Milestones since May 2014:

- Logic design completed: Oct 2014
- Rig testing completed: March 2015

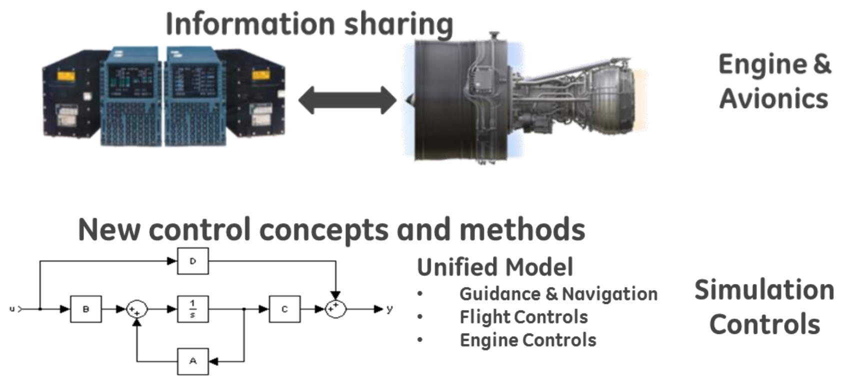
Schedule:

- Ground engine testing – Complete
- Endurance engine testing in 2015

Status – IVHM

- High-fidelity, physics-based, real-time model
- Parameter estimation algorithm, aka “Tracking Filter”
- Logic to estimate engine component health, such as compressor and turbine deterioration
- Concept Development and Evaluation (TRL 4)
  - Logic tested over full flight envelope with simulated component damage, dirty compressor, and deteriorated engine
  - Short-term faults and long-term deterioration
- Rig Testing (TRL 5)
  - Logic loaded into FADEC
  - Hardware-in-the-loop testing in controls “dry rig”
- Engine Testing (TRL 6)
  - Ground engine tests to check logic and interfaces
  - Plan to test on endurance engines as the engine deteriorates
- Flight Testing (TRL 7)
  - Test on flying test beds

Integrated Flight & Propulsion Control:



Benefits:

- Preliminary results yield up to 1% reduced fuel burn
- Reduced fuel yields a proportionate reduction in emissions and noise

Risks/Mitigations:

- Execution time/Innovative numerical methods vs. reduce-order algorithm
- Model accuracy/Experimental validation by actual flight data

Objectives:

Develop five technologies that exploit awareness of the engine performance to achieve more optimal vehicle control (improve fuel economy)

Work Statement:

- Integrate the FMS with the FADECs
- Reformulate the vehicle performance optimization problem
- Demonstrate the prototype system achieves TRL 6

Accomplishments :

- Benefits validate via computer simulation (TRL 4)
- Monte Carlo completed
- Initial testing of prototype FMS complete
- Laboratory demonstration of TRL 6 completed

Status – IFPC

- High-accuracy 6 DOF vehicle and engine models used to assess benefits and demonstrate prototype system in laboratory (TRL 6)
- Concept Development and Evaluation (TRL 4)
  - Optimal control theory applied to achieve more optimal vehicle and engine performance — 3 technologies
  - Concepts proved by computer simulation — 3 technologies
  - Monte Carlo study underway to quantify benefits
- Prototype System Development (TRL 5/6)
  - Requirements and design specifications complete
  - Model-based design and machine-generated code complete
  - Experimental software integrated with airworthy hardware
  - Test plan and procedures complete
  - Test procedure validation completed
- Laboratory demonstration of prototype FMS (TRL 6) completed recently

Performance Optimization on Military Engines

Applying Active Control, IVHM, and IFPC to military engines

- Planning flight control integration
  - Enables mode-selectable optimization
- High-fidelity, physics-based, real-time models with improved convergence rate
  - Working in Collaboration with the Ohio State University to develop more computationally efficient embedded models
- Parameter estimation algorithm, aka “Tracking Filter”
  - Scaling to accommodate additional cycle elements
- Sensor and actuator development
  - Developing and testing new sensor technologies and new sensor types
- Distributed control architecture
  - Enabling local loop closure
- Thermal management
  - Improving heat rejection through fuel system
  - Integrating bypass stream heat exchangers

PHM

Prognostics and Health Management

Increasing shift towards “condition-based maintenance”

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

Benefit justification can be tricky

Larger benefit if PHM is “designed into” the system

Need to add sensors, but not increase sensor cost

PHM “buckets” and trends

1. Sensors
    - New sensors for vibes, blade health, etc.
    - Low-cost sensors

2. Data storage and transmission
    - Much larger amounts of data being stored on board aircraft
    - Need efficient ways to offload data

3. Algorithms
    - Need to process large amounts of data
    - Balance between on-board and off-board processing

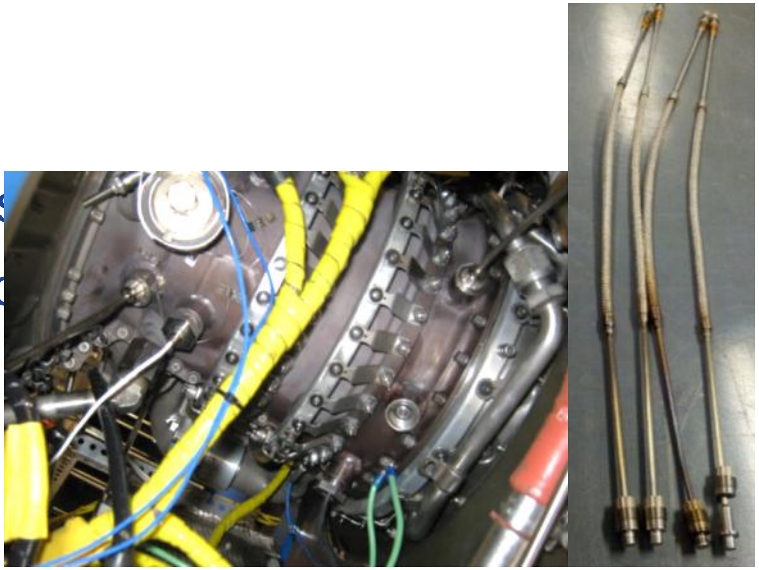
4. Personalized engine/component health
    - Higher fidelity models with increase in compute capability
    - Parameter estimation algorithms still important, but emphasis shifting to implementation issues

Big Data and Ground-Based Infrastructure Are Key

imagination at work

Advanced Sensors

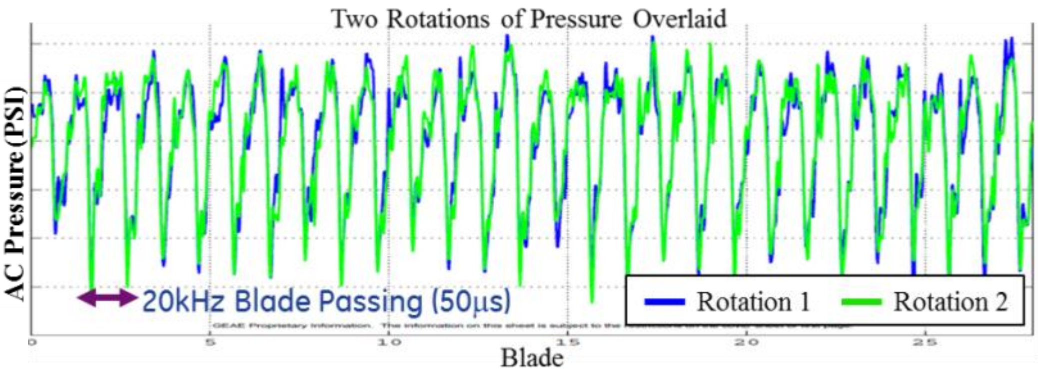
Compressor Active Stability Management (CASM) Sensor



CASM sensor being developed with Oxsens

Directly detect ***impending*** stalls for all GE c as land and marine

- 3 high bandwidth sensors tested >25hrs 2013
- Multiple stalls achieved in 2014 testing
- TRL-6 compressor rig 2015, 100Hrs 85 stalls



- Dry Rig Testing Completed
- Multi-engine test plan in 2015-201

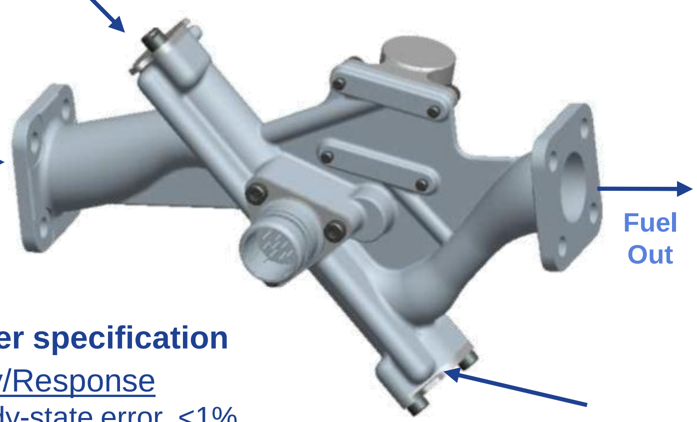
GE Cross-Business Synergies

- Algorithm Optimization
- Benefits Testing
- Endurance & MRL Demonstrations

CASM Hardware TRL-6 in 2015

Ultrasonic Fuel Flow Meter

Ultrasound fuel flow transmitter design



Transmitter specification

Accuracy/Response

Low steady-state error, <1%

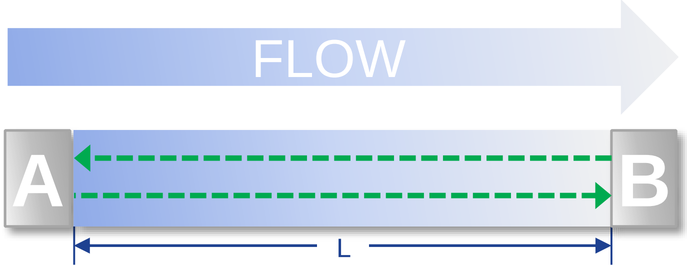
Dynamic response > 10 Hz

Operating range

- Fuel temp range: -65F to 290F
- Extreme fuel temp: 325F
- Ambient air temp range: -65F to 350F
- Extreme air temp: 375C

Basic concept

Flow velocity can be measured using two U/S transducers acting as Tx and Rx.



- - - T_{up} transit time for upstream signal

- - - T_{dn} transit time for downstream signal

L : Path Length

Program goal and milestone

- The goal of this program is better accuracy & faster response time in fuel flow measurement.
- **The technology development program will achieve TRL-6 by end of 2015**.