National Aeronautics and Space Administration

Distributed Engine Control

Proposed 5 Year Plan:
System Benefits and Implementation Challenges

Industry Representatives
Distributed Engine Control Working Group

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A Subset of the Panel Discussion on

Transition in Gas Turbine Engine Control System Architecture: Modular, Distributed, Embedded

Originally presented at the

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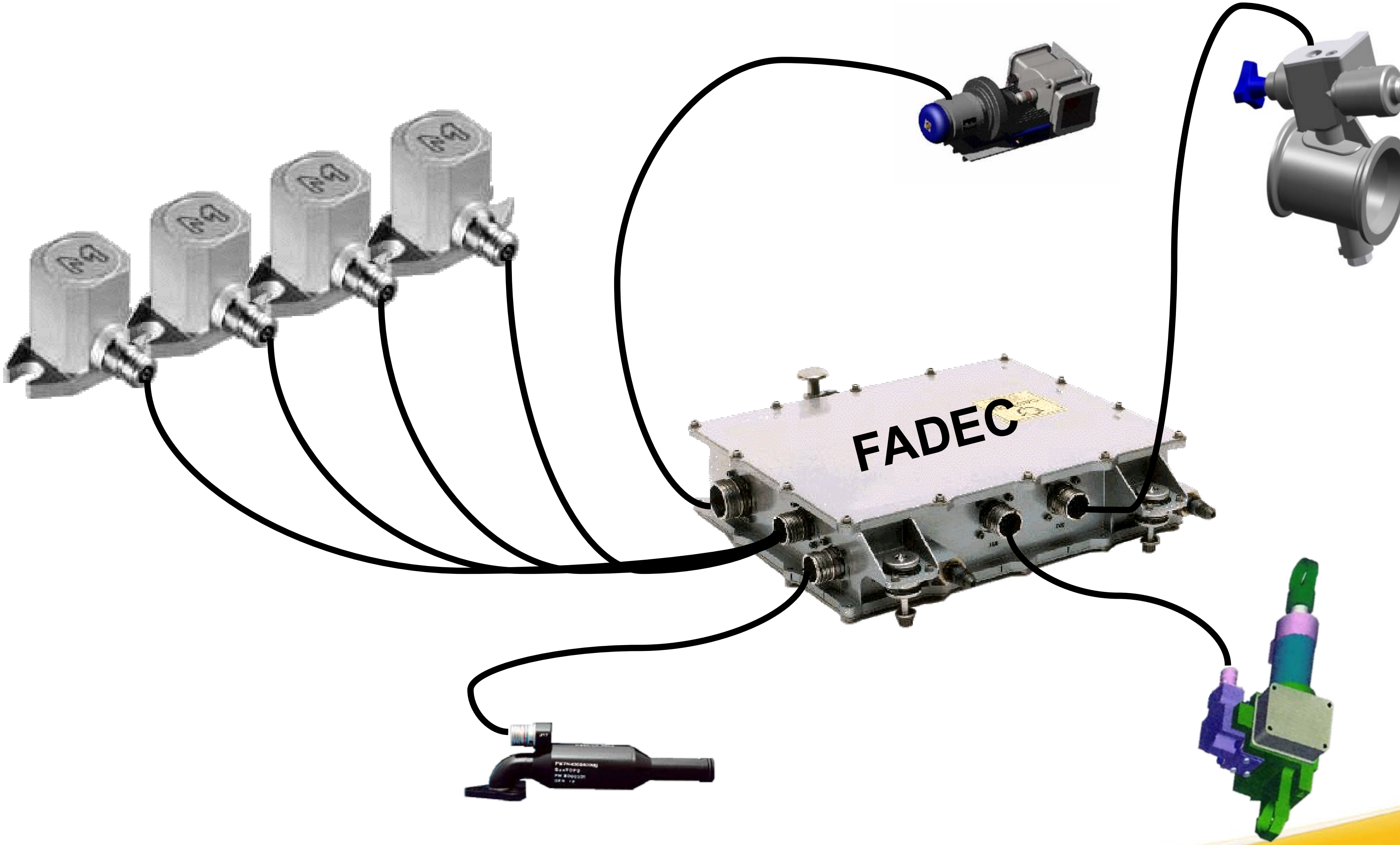
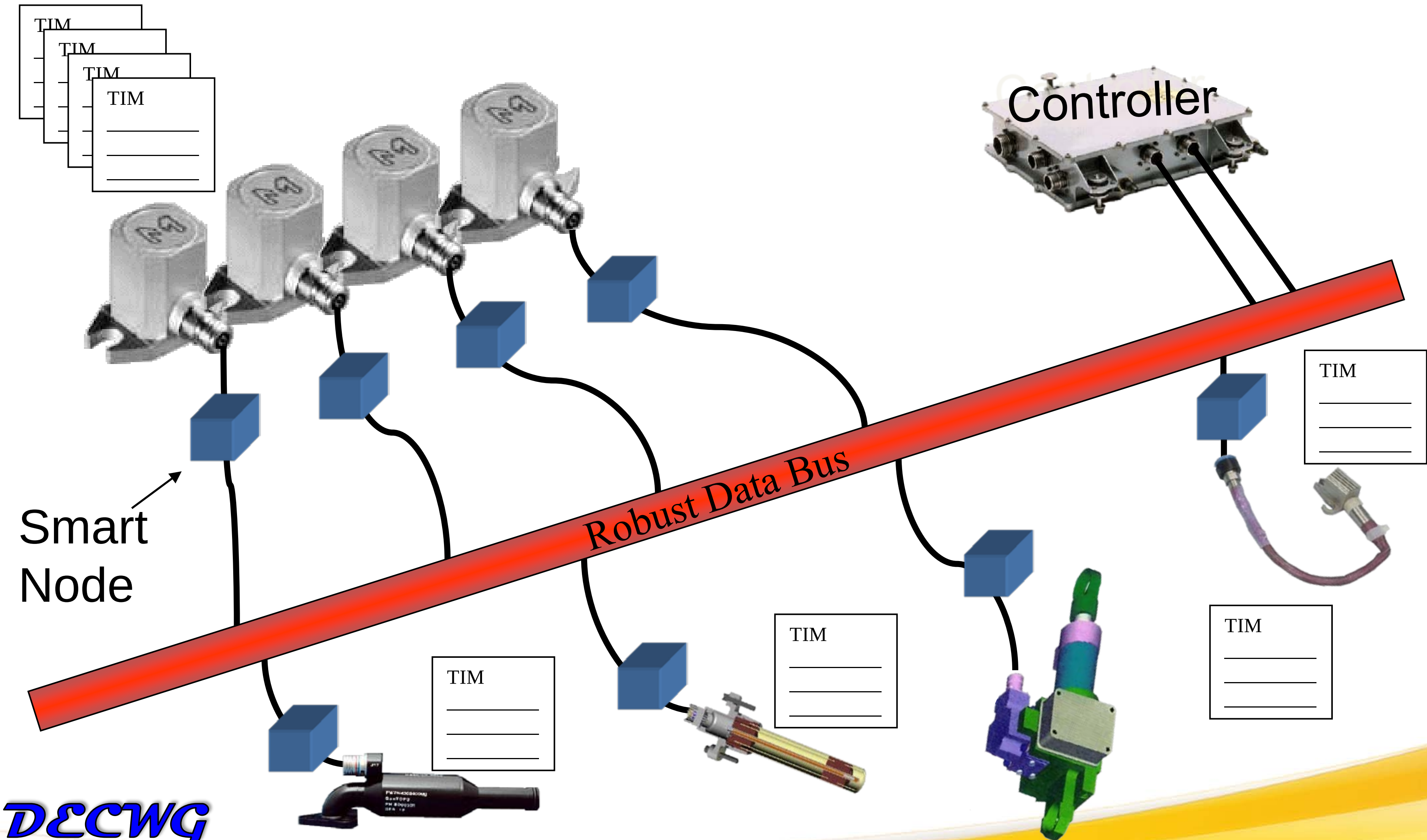
Outline

- Vision & Need for Future Turbine Engine Control
- Implementation & Technical Challenges
- Summary & Future Plans

Traditional Centralized Architecture



Example of Distributed Architecture



Vision and Need for Future Turbine Engine Control

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Technical Requirements for Distributed Controls

Physical Drivers for New Control System Designs

- Thermal Environment
- Externals Packaging
- Rapid Reconfiguration / Upgradability
- Generic Physical/Functional Interface
- Environmental Requirements
- Certification Impact
- Integration Testing
- Financial Responsibility

Focus on Near-Term Applications

- Concentrate on commercial applications with production volumes
- Design for maximum leveraging though multiple applications

Technical Requirements for Distributed Controls

Thermal Environment

- Design electronics to withstand existing hardware thermal conditions
- Recognize limitations of typical industry materials
- Aluminums (300F/149C), Elastomers (350F/177F)

Externals Packaging

- Need to integrate electronics onto or within existing hardware
- Minimize unique hardware
- Adding new/extra mounting hardware drives cost, weight in the wrong direction

Technical Requirements for Distributed Controls

Rapid Reconfiguration / Upgradability

- Should be able to specify same part number DCM for multiple applications
- Design DCM internal gains such that they can be varied without hardware changes

Generic Physical/Functional Interface

- Similar to the way EHSV interfaces are controlled today (ARP490)
- Bolt/connector interfaces should be standardized
- Standard functionality, memory, loop closure, communication bit structure, etc.

Technical Requirements for Distributed Controls

Environmental Requirements

- Design for existing ambient temperatures and vibration environments
- Don't drive cost/complexity into the DCM to withstand unrealistic margins
- Focus on actual engine environments, not D0160/810 generic requirements

Certification Impact, Changes to Testing

- Allow certification at modular level
- Require system level certification using black box approach to testing
- Allow flexible system expansion/contraction without recert. required

Technical Requirements for Distributed Controls

Integration testing

- System integration testing paradigms will shift
- System integration tasks will shift one layer down the food chain
  - AS/OS boundaries may drive testing location, integration responsibilities

Financial responsibility

- Need to keep focused on cost of products, don't design and build beyond our minimum needs (with reasonable margins)
- System costs need to make the case for this new technology
  - Individual component costs are flexible
- Design + Development + Certification + Procurement + Life Cycle Cost = Net Savings for our Customers

Economic Drivers for New FADEC Designs

FADECs Have Unique Electronics Hardware Requirements

Issues

- High Temperature Capable Electronics for FADECs Are Specialty Items
- ~20 Years FADEC Production Runs vs. Rapid Consumer Electronics Turnover
- FADEC Electronics Often Nearing Obsolescence At Entry Into Service
- "Out-of-Plan" FADEC Obsolescence Turns Are Major Budget Challenge

Implications for Future FADECs

- Improved Methods for Enabling Electronics to Tolerate Engine Environment
- Use of Common FADEC Electronics Components Supply Base
- Exploration of Boutique Manufacturing Supporting Small Quantity Electronics

Need Broadly Applicable High Temperature Electronics Supply Base

Economic Drivers for New FADEC Designs

Not Realizing Cost Benefits from Reuse / Upgradability

Issues

- Point-Designs Typically Increase Initial Cost and Reduce Production Costs
- Upgrades Can Cost As Much As Original FADEC Implementation
- FADECs Are Not Designed with Reuse in Mind – No "Pay-It-Forward"

Implications for Future FADECs

- Need to Consider Life Cycle Business Case in Design
- Partitioned Architectures Limiting Necessary Re-Validation
- Modular and Reconfigurable FADEC Components / Architectures

Point-Design FADECs Don't Support Reuse / Upgradability

Economic Drivers for New FADEC Designs

FADEC Implementation Time Pacing Engine Development

Issues

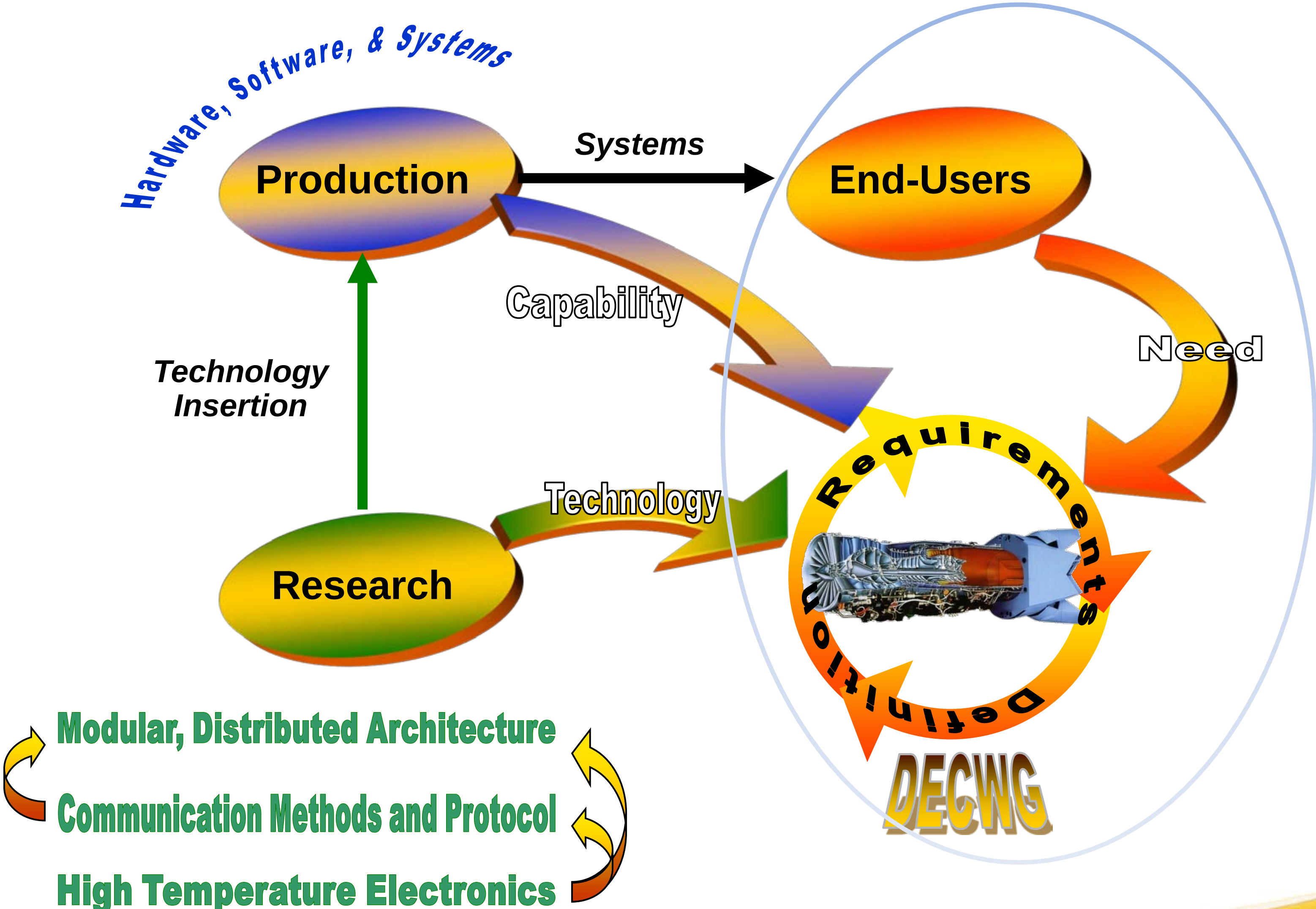
- FADEC Definition Usually Lags Engine Definition in Preliminary Design
- Long Development and Validation Times Consumed by for FADECs
- Weight / Cost Reduction Campaigns Drive FADEC Iterations

Implications for Future FADECs

- Move Away From Point-Design FADECs
- Leverage Common FADEC Components / Modules
- Safety First / Understand Trades Cost and Weight Trades

Modular FADEC Designs Favor Rapid Implementation

The Process for Distributed Controls



Objective: Modular, Open, Distributed Engine Control

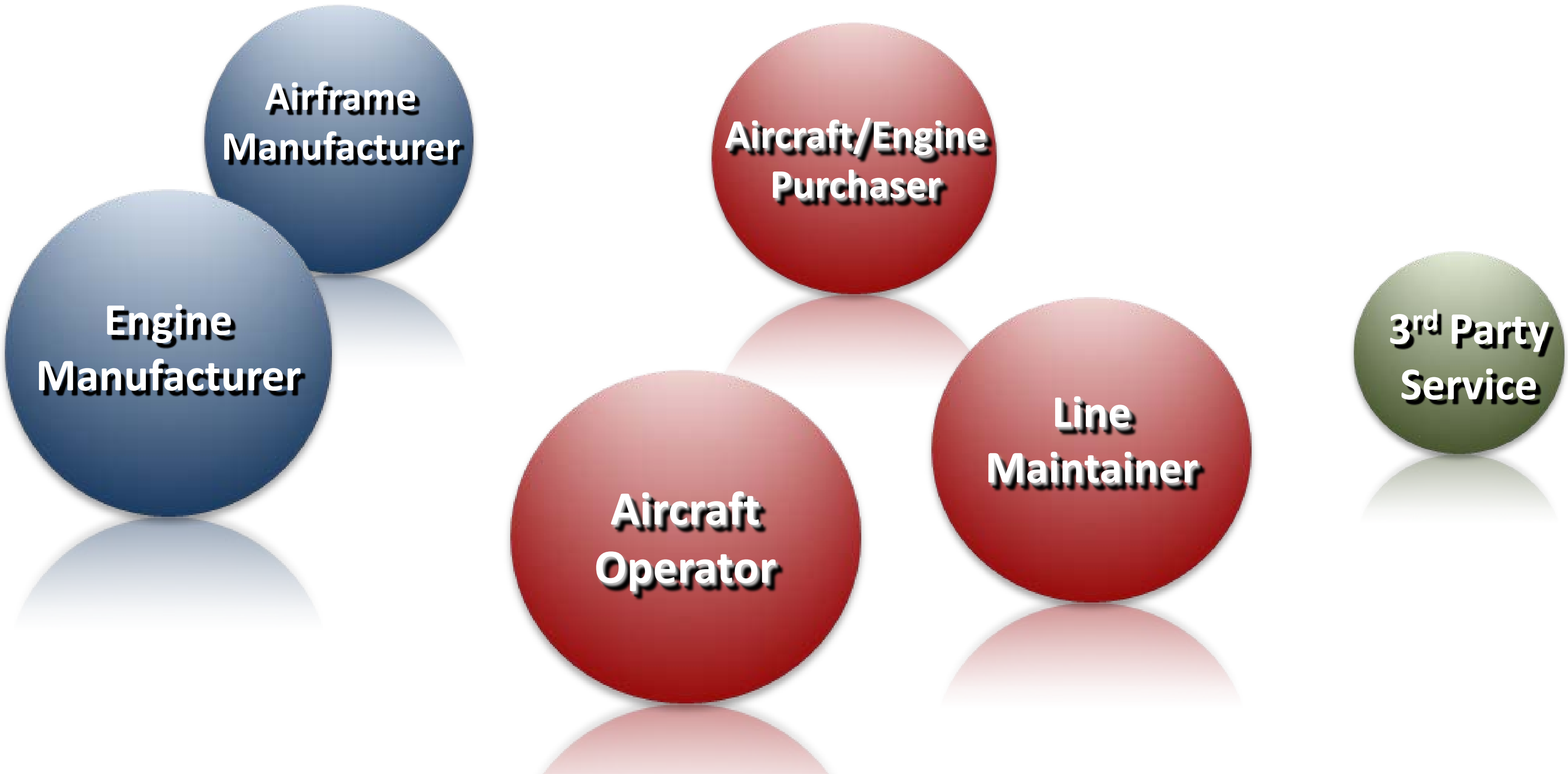
Technology Benefits

- **Increased Performance**
  - Reduction in engine weight due to digital signaling, lower wire/connector count, reduced cooling need
  - 5% increase in thrust-to-weight ratio
- **Improved Mission Success**
  - System availability improvement due to automated fault isolation, reduced maintenance time, modular LRU
  - 10% increase in system availability
- **Lower Life Cycle Cost**
  - Reduced cycle time for design, manufacture, V&V
  - Reduced component and maintenance costs via cross-platform commonality, obsolescence mitigation
  - Flexible upgrade path through open interface standards

Capability Needs

- **Open Systems Development, Modeling & Design**
  - Future systems requirements definition
  - Open industry interface standards definition
  - System modeling tools development
  - Modular system integration and test techniques
- **Hardware Systems Development**
  - High temperature integrated circuits and systems development
  - Improved electronic component availability
- **Software Systems Development**
  - Software system partitioning
  - Software design and modular test capability
  - Software distributed system V&V

Who Is The Customer For Controls?



What Control Attributes Do Customers Value?

Engine Manufacturer

There is a need for improved control devices that are compatible with the control electronics made by different manufactures. In addition there is a need for specific purpose control devices of one manufacturer to be compatible with more general-purpose control electronics from a different manufacturer.

adapt the system to your *needs*

(Customer Requirements)

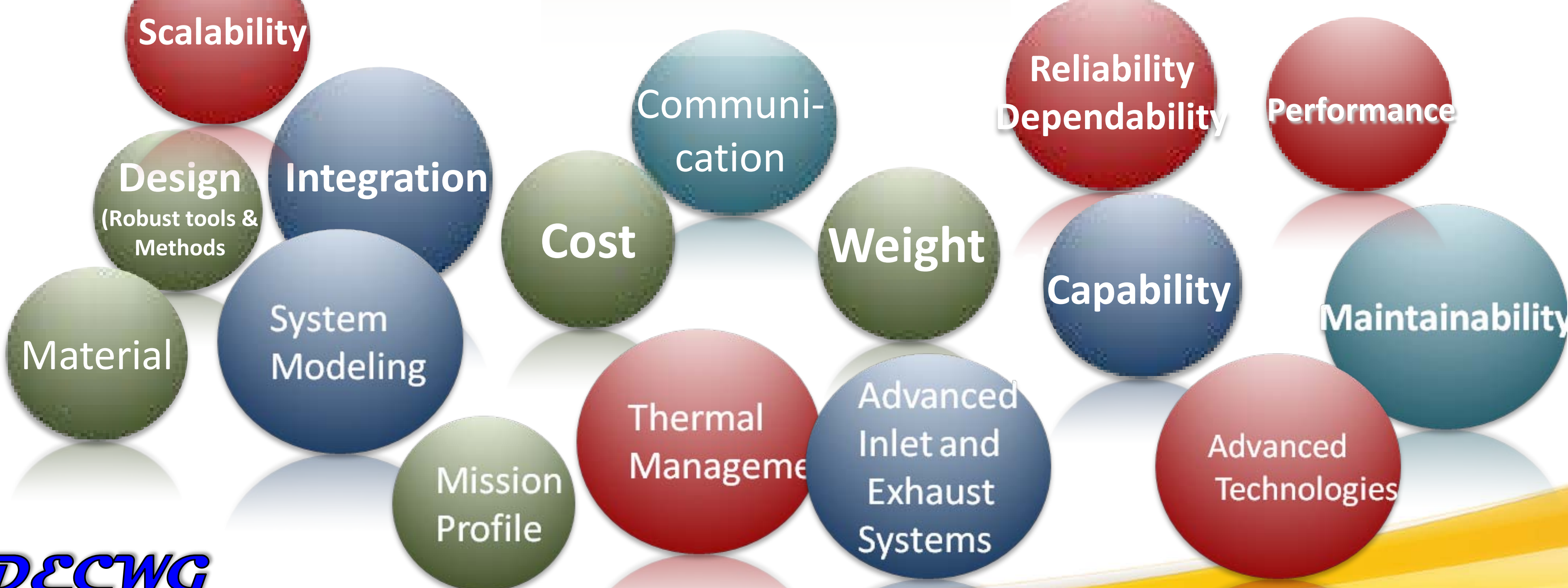
Airframe Manufacturer

Mission, Vehicle , and Customer/OEM Requirements

There is a need for control integration between engine , TMS, power, and the aircraft. An iterative process to meet all requirements including customer and engine requirements.

An integration Process with Interactive Approach

Adapt the system to your customer's and OEM's *needs*



Aircraft/Engine Owner

There is a need for improved autonomous control devices that are compatible with the control electronics made by different manufactures. The big issue is the cost and obsolescence the aircraft and engine owners need to achieve the minimum cost of maintaining their assets

Adapt the system to your *needs at lowest cost*

Performing maintenance and repair on the flight line or in the depot will have reduced cost for a distributed control architecture, since any maintenance issues are easily identifiable.

- Cost (Development, production, maintenance)
- Thrust/ Weight
- SFC
- Reliability Dependability
- Capability
- Performance
- Maintainability

A set of user interfaces needs to be developed to allow a single user to efficiently control the fleet of aircraft. Their impact and benefit derive from the convergence of new DEC architectures

Comparison: Commercial vs. Military

- GE & P&W each build 500-1000 Jet engines annually and build replacement parts for 17000 engines
- Distributed control design will increase COTS, reduce inventories, and reduce cycle time for design, manufacture, V&V, and cost
- Military engines push the SOA technologies
- To maintain adequate military capabilities in the years ahead, the US will have to design, develop, and produce defense systems with the needed performance at more affordable costs
- Embedded military S/W for controls must handle enormously complicated integration tasks. DEC solution offers common S/W & H/W for both military & commercial engines
- To extend or change control system capability to handle complicated tasks, designers must modify the H/W, S/W, and improve fault tolerance and fail-safe operation
- S/W can implement functions that would be extraordinarily time-consuming & costly in H/W alone

Comparison: Large Engines vs. Small Engine

- Large engines and small engine classes have unique S/W H/W requirements
- The current commercial airline and military "bear market" is leading the "Big Four" to engage on more partnership and collaboration with each other and with small engine manufacturers
- The current military aircraft UAV procurement means more new development for the small turbine engine
- For the next several years, strengths in the turbine engines sector are expected to continue to come from increased military fighter aircraft and UAVs
- A DEC is the methodology to improve engine performance & cost
- In addition to manufacturer collaboration and R&D programs, several important market factors present challenges that are stimulating significant improvements in engine technology

Transition: Commercial to Military

Commercial vs. Military

- Military demand is growing for FADEC & control systems with expert systems embedded in the S/W for fault tolerance.
- Civilian demand has spurred rapid technological progress for commercial aircraft.
- Escalating procurement and fuel costs will stimulate the DoD to leverage commercial FADECs & control systems S/W & H/W.
- Modular / Universal/Distributed design can reduce development time and cost. S/W could offer baseline for military-qualified FADECs.
- To promote dual use, the services must recognize the similarities between commercial applications & military needs; too often, they focus on the differences

Military to Commercial

- Avionics has been the chief success story in transferring military S/W and hardware to civil sector. Through VAATE and SBIR funding a lot of technologies has been transferred to commercial avionics.
- Modeling & real-time SIMULATION can reduce integration cost for both commercial and military engine controls
- Technology transfer also occurs from both commercial & military programs

What Does "The Customer" Value?

Engine: Pays Cost of FADEC Development/Production
FADEC Weight / Size Impacts Engine Design

Airframe: FADEC Impacts Aircraft Capability / Integration

Manufacturers

Operational Costs

Marketability

Aircraft/Engine Purchaser: Responsible for FADEC Repair Cost

Aircraft Operator: Impact of Failures i.e. Delays/Cancellations

Line Maintainer: Labor/Materials FADEC Troubleshooting & Repair

Typically Airlines

Transfer Risk

3rd Party Service Providers: Pay for FADEC Repair & Impact to Airline

Weighting of Values
Vary By Engine Application

Purchase Cost / Weight

Increasingly Valued As Engine Size Decreases

Control System As Percentage of Total Engine Weight/Cost

Engine Manufacturer Values

Often Transfer to Military Customers

DoD Owns Engine Design – Often Responsible for Development / Production Costs

Reliability

Even More Critical for Smaller Airline Fleets

Fewer Aircraft Means Fewer Options When One is Down for Maintenance

How Can FADEC Impact Customer Value?

Reduce Overall Control System Weight

Consider Electronics, Power Supplies, Housings, Connectors, Harnesses, etc.

Enable Reuse and Upgradability of FADEC Components

Provide Head Start on FADEC For New Applications

Improved Control System Component Reliability

Robustness Against Steady and Cyclical Temperature and Vibrational Effects

Easier Control System Troubleshooting and Repair

Reduced Training and Labor Hours via Automation

Implementation and Technology Challenges To Achieve the Vision

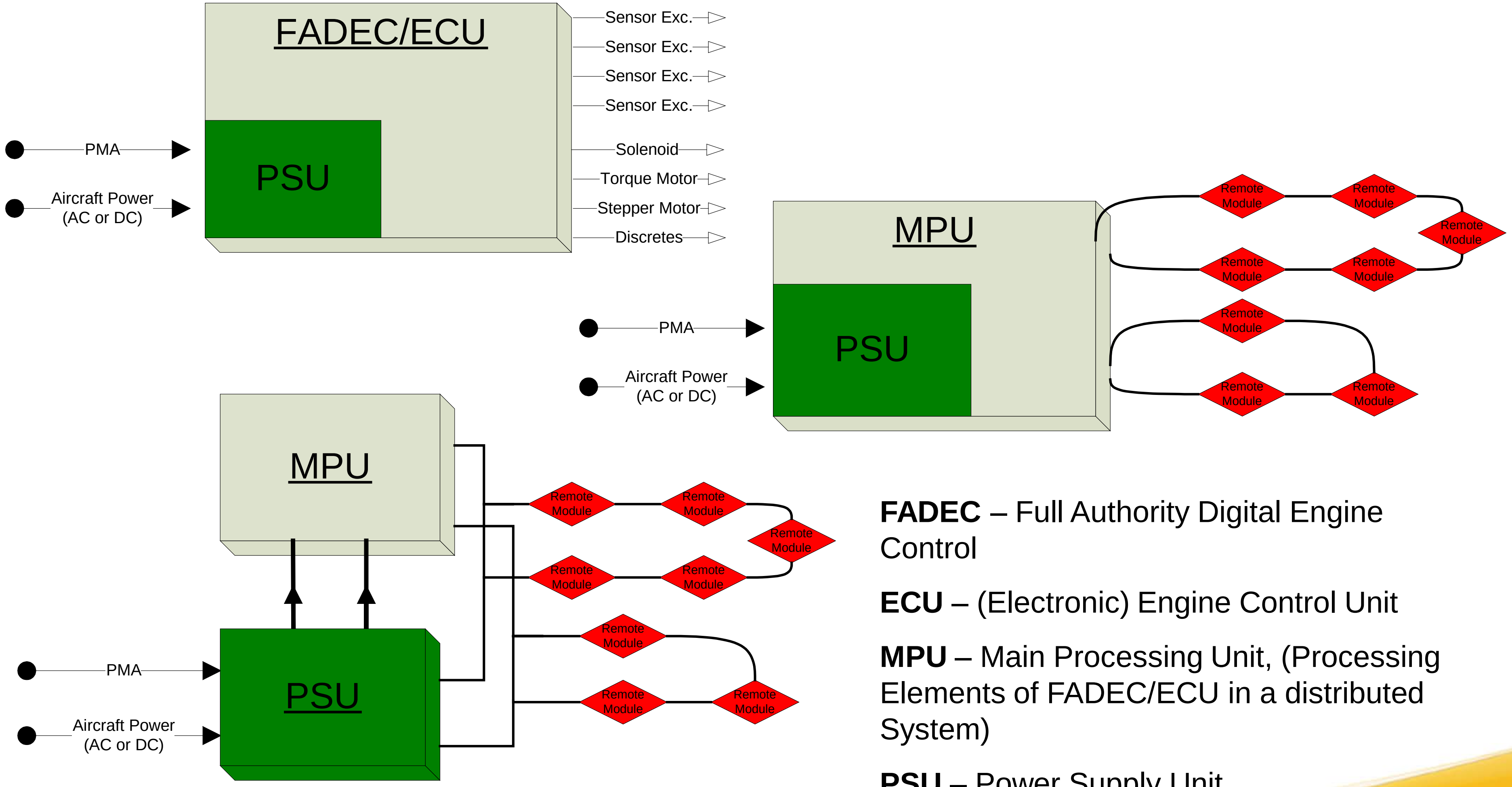
Bill Rhoden
Hamilton-Sundstrand

Andy Berner
BAE Systems

Considerations for Power Distribution in a Distributed System

- Currently in most centralized engine control systems the Power Supply Unit (PSU) is embedded into the FADEC or ECU
- PSU volumes can account for 25% to 40% of the total FADEC/ECU volume
- Power is classically supplied to the ECU by either an 115VAC or 28VDC aircraft input or from the Permanent Magnet Alternator (PMA)
- Energy harvesting for remote modules currently not seen as robust or reliable enough for a critical engine control system, therefore a dedicated PSU should be used to power the remote modules
- The power requirements for remote modules may vary depending on function/capabilities of the module (e.g. actuator driver vs. simple smart sensor)

Power Distribution Concepts



FADEC – Full Authority Digital Engine Control

ECU – (Electronic) Engine Control Unit

MPU – Main Processing Unit, (Processing Elements of FADEC/ECU in a distributed System)

PSU – Power Supply Unit

Considerations for an Engine Area Network

- Can a Commercial Off the Shelf (COTS) serial bus be used for an Engine Area Network (EAN) solution that supports an open distributed control architecture?
- Several busses exist from the industrial, automotive and aerospace control market areas. Which would be the best fit?
- Need to, as an industry, define the required performance requirements based on several distributed control topologies
- Key selection criteria should include:
  - Bandwidth
  - Compatibly with current high temperature electronics capability
  - Predictable communication response times between master and remote modules (deterministic)
  - Latency
  - Supports multi-drop physical layer
  - Low Cost
  - Minimal obsolescence risk
  - Stability of standards

Engine Area Network Selection Conclusions

- Does any one bus meet all of the selection criteria?
- Published studies and customer responses have shown a desire for a multi-drop bus topology (as opposed to star, ring, etc.) since it has been theorized to optimize cabling weight savings
- The current availability of High Temperature Electronics (serial bus physical and logical devices) is seen as the largest divider for a EAN bus selection
- Identification, detection and handling of faults also needs to be considered
- DECWG partners should work together to define a single bus protocol and physical layer options that support open distributed engine control architectures

Are there High Temperature Electronics to support the bus physical layers?

A Current View of High Temperature Electronics Market Space

- High Temperate Electronics is currently a niche market with a limited list of available components which are usually costly and with limited life and reliability… but evolving quickly
- Currently aligned to drilling or “down hole” application requirements that do not necessarily overlay with avionics requirements
  - Focused on remote sensing oriented and not actuation
- Some transfer of radiation hardened technology to high temperature
- Published avionics quality reliability data
  - Data is currently lacking even for some high temperature components
  - SEU and SEL Data availability
- Avionics component life and pricing needs are not met with current offerings
- Strongly suggest that DECWG work with electronics vendors and start to compile a list/library of available components to support future high temperature distributed controls development

What is the avionics that engine and aircraft operators are willing to live with for the price to improve efficiency and flexibility?

High Temperature Electronics Needs

- Predicted temperature range limits: -55°C to > +200°C
  - This reflects what is currently available with SOI technology
  - Estimate modules would be exposed to max temps 80-90% of life
  - Studies from engine OEMs could expand/contract temperature and duty cycle estimates
- Longer Life and Reliability
  - Current engine controls have long life requirements
- Competitive Cost
  - What are the sustainment cost or total cost of ownership benefits of a distributed system compared to a centralized system?
  - Current component cost is approximately 10 - 20 times that of equivalent military temperature parts
- Long Term Component Availability
  - Approximately 20 years
  - Can high temperature device vendors manage product obsolescence better than current commercial devices to decrease life cycle costs?
- Example Component Needs
  - Larger FPGAs, Processors, Micro-Controllers
  - Serial Bus Logic Layer and Physical Layer Controllers
  - ADC and DAC
  - PWB

FAR Part 33 Certification Rules

- Section 33-28 Electrical & Electronic Engine Control Systems
  - Loss of Aircraft Power or Data – No unacceptable change in thrust
    - Channel 1 to Channel 2
    - One control mode to another
    - Primary to Back-up control
  - Single-Point or Probable Combination Failures
  - Software Design & Implementation to prevent errors
- Section 33-75 Safety Analysis
  - Hazardous (10^{-7} to 10^{-9}) and Major Engine Effects (10^{-5} to 10^{-7})
  - Thrust changes
  - Erroneous Data Transmissions
  - Surge / Stall
- Section 33-83 Vibration Tests

FAR Part 33 Certification Rules

- Section 33-87 Endurance Tests
  - Engine control controlling the engine
- Section 33-91 Engine Component Tests
  - Temperature Limits
  - Fire Proofing
  - Sea Level to Altitude Testing
  - Salt Spray/Humidity/Fungus/Explosive Atmosphere
  - Electromagnetic Compatibility (EMC)
  - High Intensity Radiated Field Compatibility (HIRF)
  - Lightning Tolerance
  - Software Validation (DO-178B)
  - Control Integrity under degraded modes

Considerations for Certifying a Distributed Engine Control Architecture

- Different from the Norm
  - Failure Modes
    - Loss of Power
    - Single Point/Multi Point Failures
    - Software
  - Unintended Interactions
    - Latency
    - Data Integrity
  - Increased Connections
    - Reliability
  - Potential Harsher Environment
    - Smart nodes in hot section
  - Communications Protocol(s)
    - Coordination of multiple protocols?
  - EMI/HIRF/Lightning Susceptibility
  - Software Validation (DO-178B)
  - Dispatchable failures?

As Good As Current Architecture

Summary and Future Plans

Dennis Culley
NASA Glenn Research Center

Are control systems keeping pace with turbine engine system <u>needs</u>? (regardless of the vision)

Short answer: yes, but…

- FADEC implementation time is pacing engine development
  - Intense pressure to reduce weight and cost
- Control system upgrade costs can equal original design costs
  - Complexity and cost deters new technology insertion
  - Electronics obsolescence (determined by commercial markets) is unpredictable and uncontrollable
- Engine system advancements are increasing the physical burden on control system electronics
  - Reduced capacity for heat extraction
  - Reduced temperature margin (reliability) vs. weight of thermal control
  - Increasing need for higher density packaging to fit in shrinking envelope

What technologies are required for existing and future engine control systems?

- **Communication Network**
  - Distribution of control functions requires digital communications
  - Need for understanding the requirements for control ***and*** PHM
- **Power Distribution**
  - Distributed control functions require distributed power
  - Needs of control elements vary widely in current and voltage
- **High Temperature Electronics**
  - Reliable electronics require sufficient thermal margin
    - Add weight for thermal control, OR
    - Increase the operational temperature of the electronics
- **Flight Certification**
  - Cost benefit of distributed control is contingent on modular certification
  - Distributed systems are controlled by interface definitions; standard, well-defined interfaces are required

Why / How should engine control systems use emerging electronics and control technologies?

- High power control law processing remains in the realm of commercial electronics for the foreseeable future – ***we must be able to use it***.
- The modularity of distributed control systems have a huge ***potential*** in terms of design flexibility, life cycle cost reduction, and performance enhancement.
- High temperature electronics are necessary to enable on-engine control functionality ***without*** additional weight for thermal control
- High temperature electronics will not be available ***unless***…
  - Component/Functional needs are collaboratively defined
  - Development costs are collaboratively shared