Recent Technology Advances in Distributed Engine Control

Dennis Culley
NASA Glenn Research Center
Cleveland, Ohio

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Outline

- Overview
- NASA Research
  - Modeling and Simulation
  - Dynamic Thermal Modeling
  - Advanced Smart Node Development
  - Hardware-in-the-Loop – Integration
  - Very High Temperature Electronics
- The Community of Practice
- Conclusion

NASA Mega-Drivers, Outcomes, & Strategic Thrusts

https://www.nasa.gov/aeroresearch/strategy

NASA's Aeronautical Research Role

Address Research Needs within Three Overarching Trends Affecting Future Aviation

- Mega-Driver 1: Global Growth in Demand for High-Speed Mobility
- Mega-Driver 2: Global Climate Change, Sustainability, and Energy Transition
- Mega-Driver 3: Technology Convergence

Outcomes

Outcomes are Defined for Each of Three Time Periods

Near Term: 2015-2025	Mid Term: 2025-2035	Far Term: Beyond 2035

Strategic Thrusts

ARMD Research is Organized into Six Strategic Thrusts

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Commercial Vehicles
- Strategic Thrust 4: Transition to Low-Carbon Propulsion
- Strategic Thrust 5: Real-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

The Role of Propulsion Controls

Perception: The Focus of Propulsion Controls is Operability

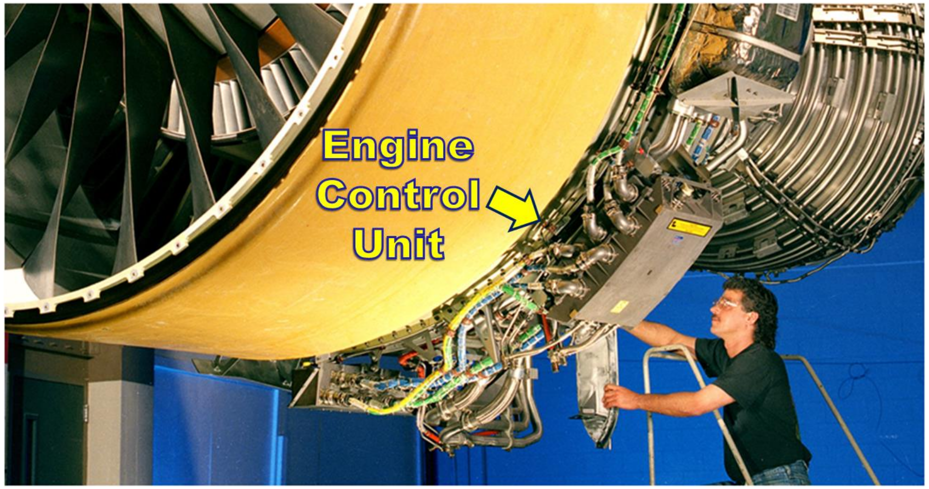
- Make the system perform as it was designed
- Not perceived as research, so much as it is engineering

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.

The Fundamental Problem

Fan Case Mounted - Air Cooled



Public Release Photo Courtesy of Pratt & Whitney

Core Mounted - Fuel Cooled

Public Release Photo Courtesy of Pratt & Whitney

The advances being made in engine system technologies are impacting the integration of control hardware on the engine, in general, to the point where control hardware is becoming a ***limiting factor in engine system performance***

The Problem is the Hardware Architecture

Heilmeier: What are we trying to do?

Technology Level:

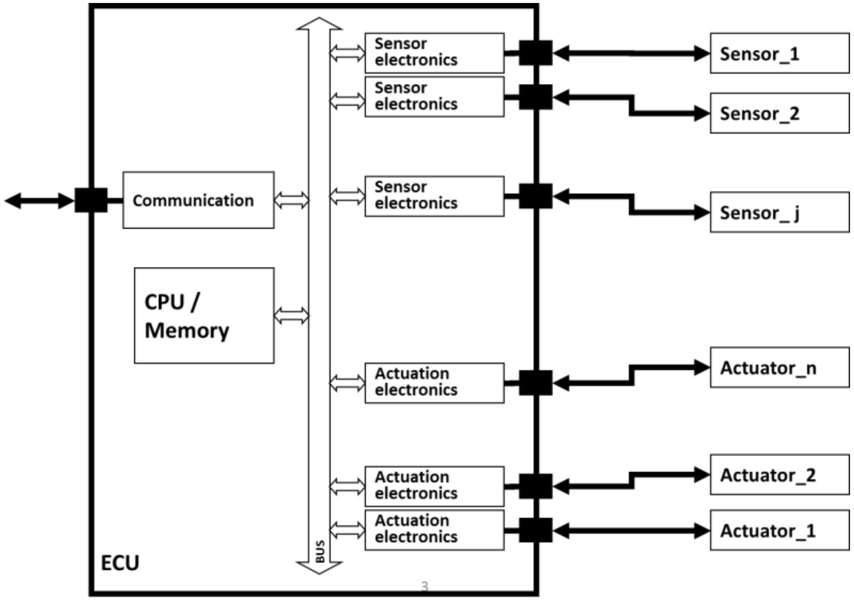
- We are changing interface definitions
- We are altering the way control systems are integrated

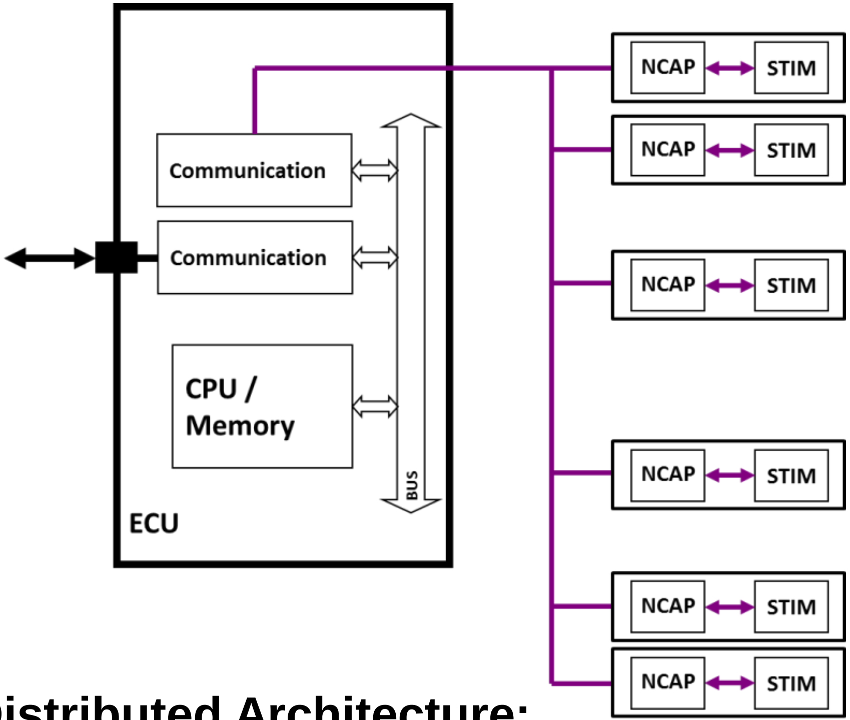
Customers Don't Buy Technology, They Buy Capability

System Level:

- We are trying to provide a new benefit in terms of performance and/or cost
  - ***Weight reduction*** by replacing analog signal harnesses with networks
  - ***Cost reduction*** by designing modular, reusable LRUs
  - ***Availability improvement*** by increased fault detection and higher reliability
  - ***Performance enhancement*** by providing a hardware platform for advanced control applications

Heilmeier: What changes in our approach?





<u>Centralized Architecture:</u>
A collection of transducers operated in a common system

<u>Distributed Architecture:</u>
A system of asynchronous systems synchronized by a network

What is Distributed Engine Control?

In the Baseline it is a change in architecture, not inherently a change in function

Heilmeier: Risks, Barriers, and Payoffs

Risks:

- Doing nothing is not an option – controls becomes a performance limiting factor

Barriers:

- High temperature embedded electronics
- High temperature materials

Payoffs:

- Weight reduction
- Life cycle cost reduction
- Improved Availability
- Increased Safety
- Advanced Control Applications
  - Wide-Bandwidth Sensing and Actuation
  - Local Loop Closure
  - Information Infused Control

NASA Research Effort

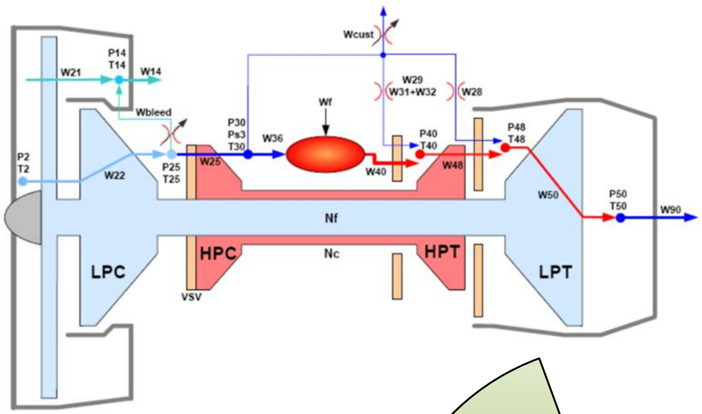
Distributed Engine Controls Research at NASA

- Modeling and Simulation
  - Smart node models
  - Communications
- Dynamic Thermal Modeling
- Advanced Smart Node Development
- Hardware-in-the-Loop – Integration
- Very High Temperature Electronics

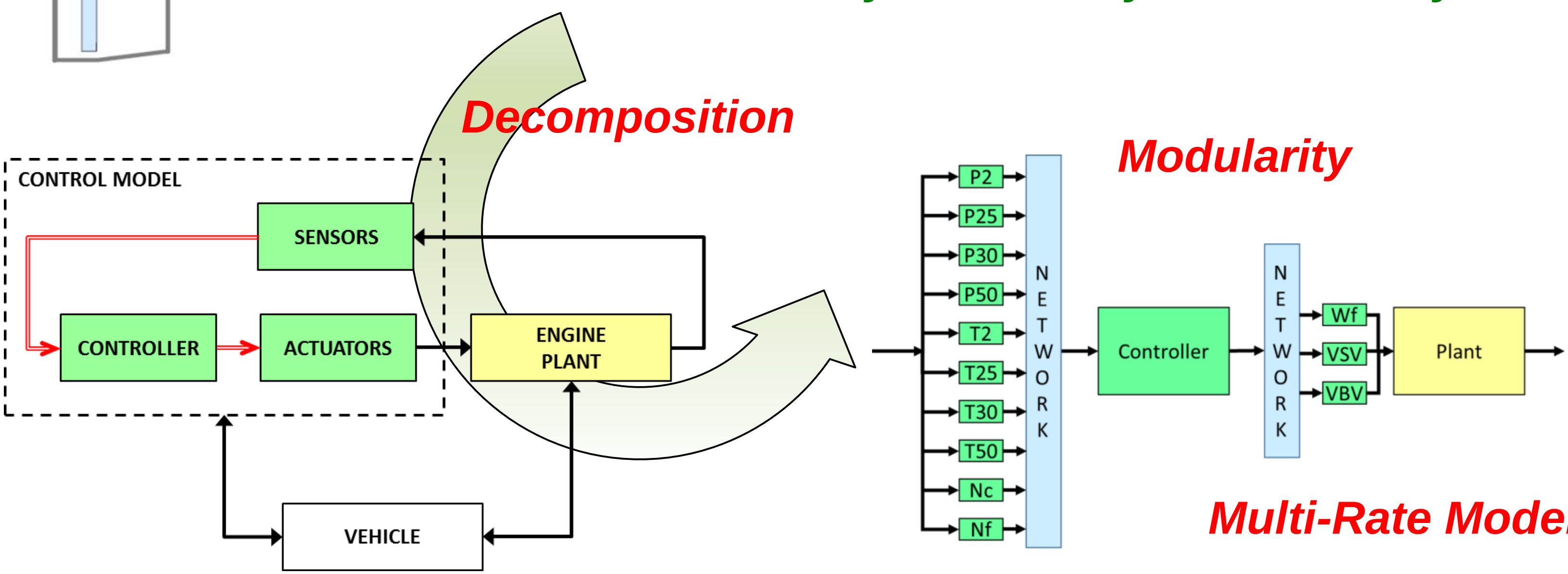
Modeling & Simulation

Commercial Modular Aero Propulsion System Simulation 40k

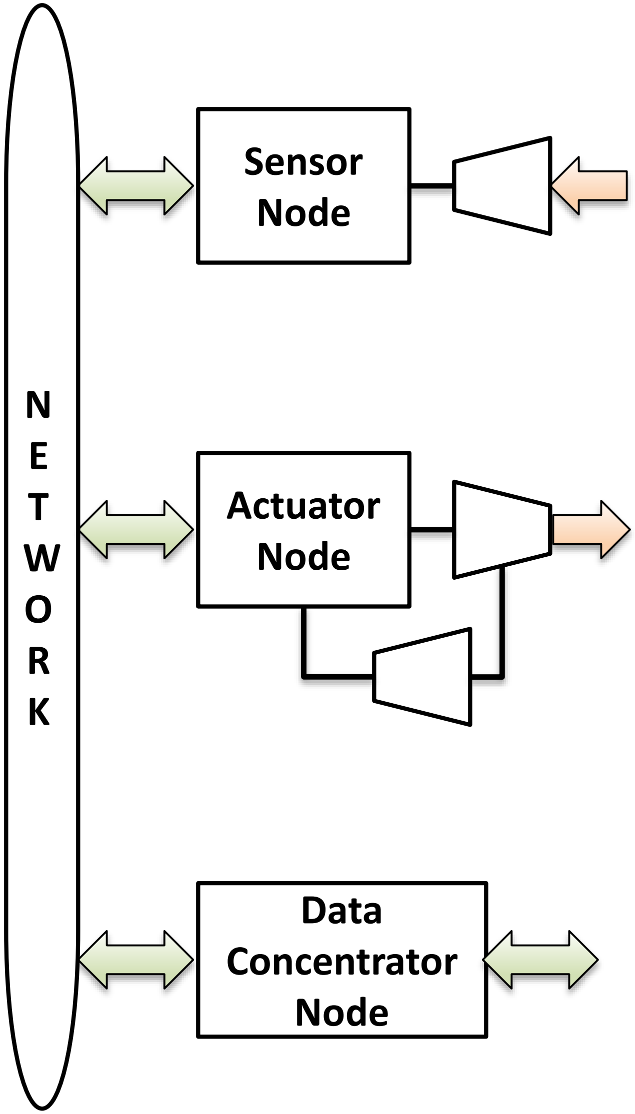
C-MAPSS40k



- 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***



Smart Node Types

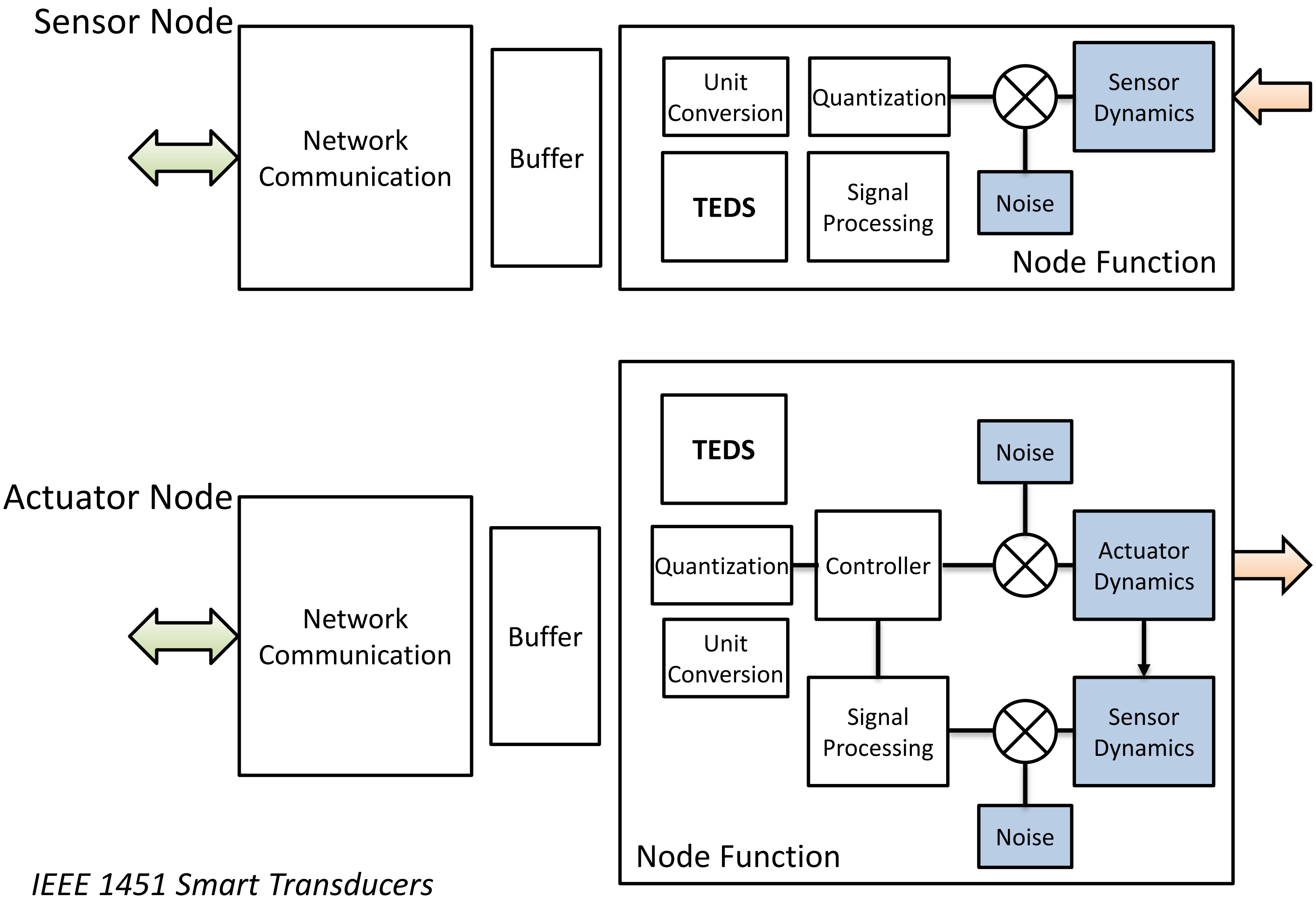


<u>Sensor Node</u>: Digitization at the source with signal processing

<u>Actuator Node</u>: Closed loop control of actuator subsystem

<u>Data Concentrator Node</u>: Communication bridge, local controller, or multifunction Node

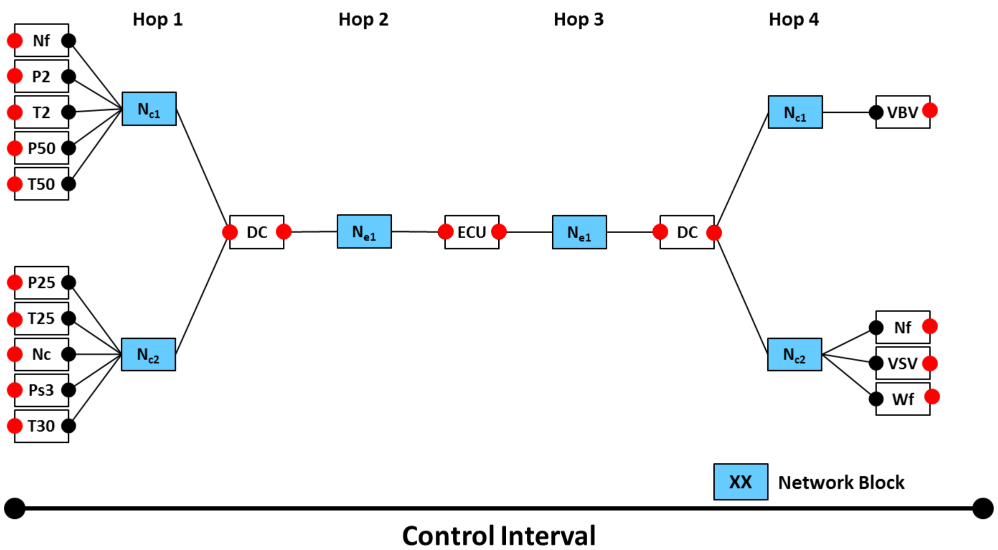
Smart Node Modularity



IEEE 1451 Smart Transducers

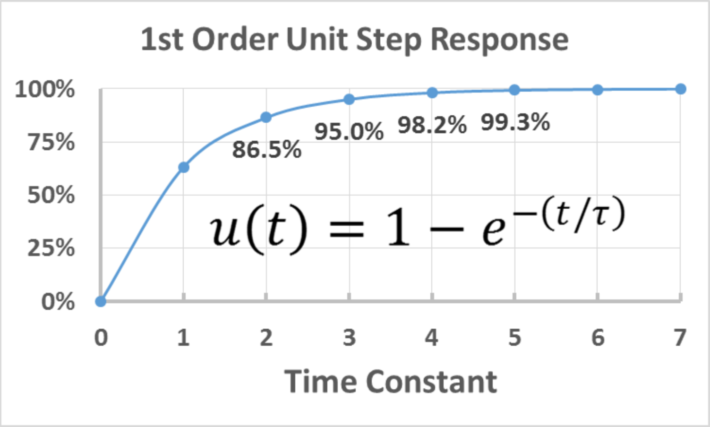
Communication Network Complexity

- Serial data transfer imposes significant effects in terms of delay
- May not be possible to transfer all the data within a single control interval

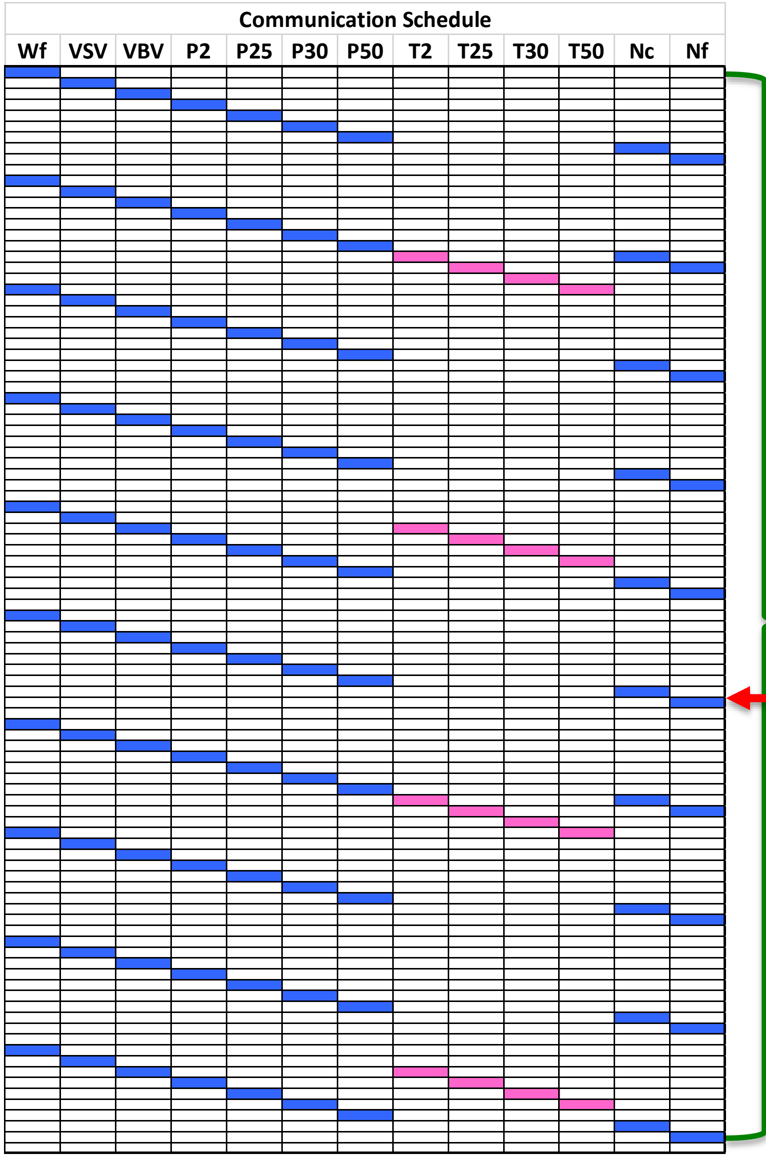


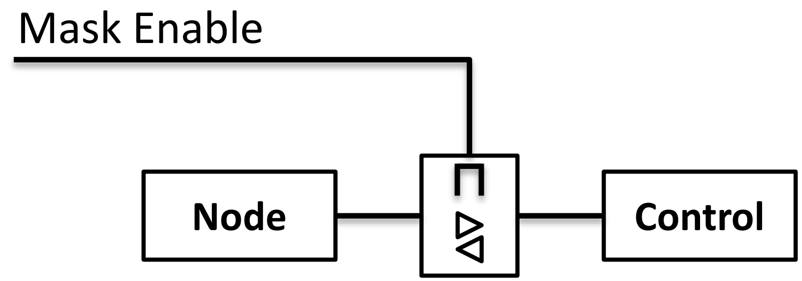
Parameter	time constant			Original over-sample
	rad/sec	Hz	sec	
Control interval	419	66.7	0.015	1
Pressure	25	4.0	0.2513	17
Temperature	9	1.4	0.6981	47
Speed	6	1.0	1.0000	67

Can the serial data transfer process be decoupled from control?



The Schedule Mask

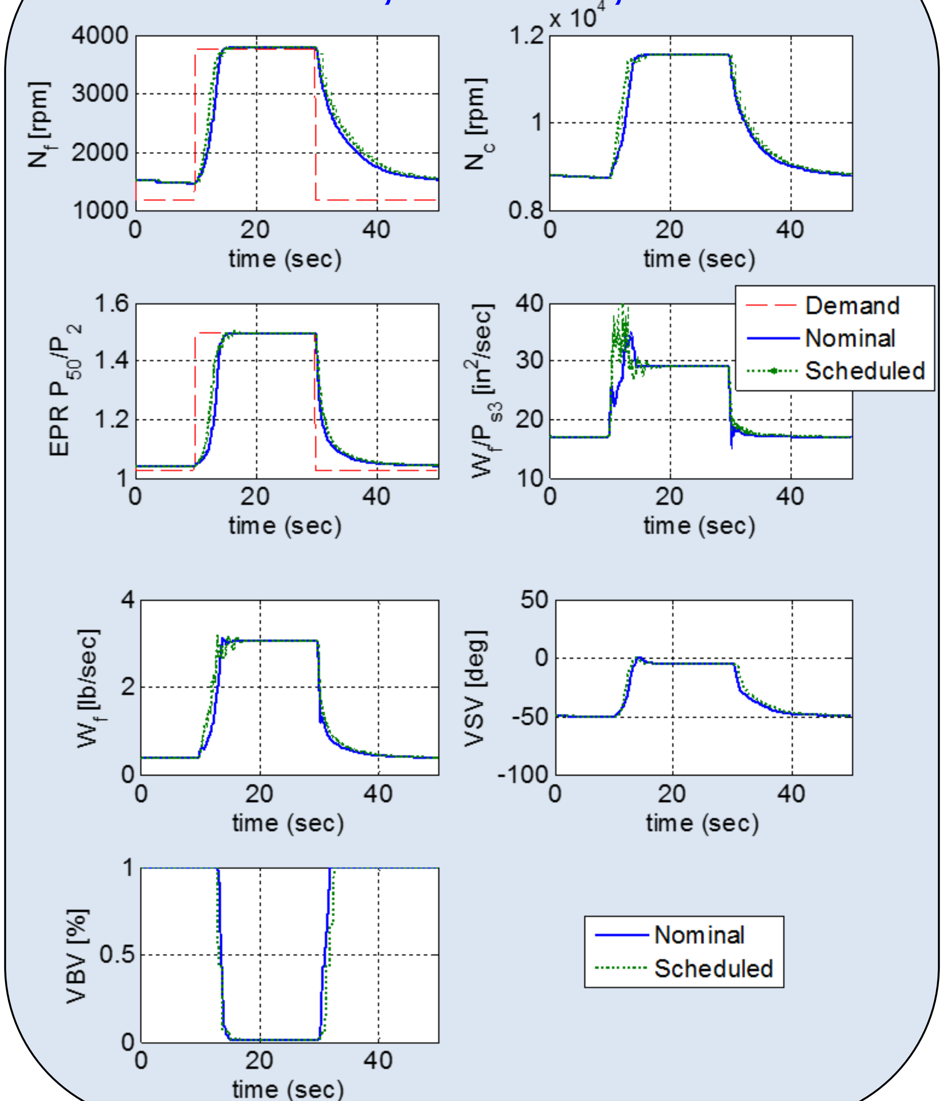




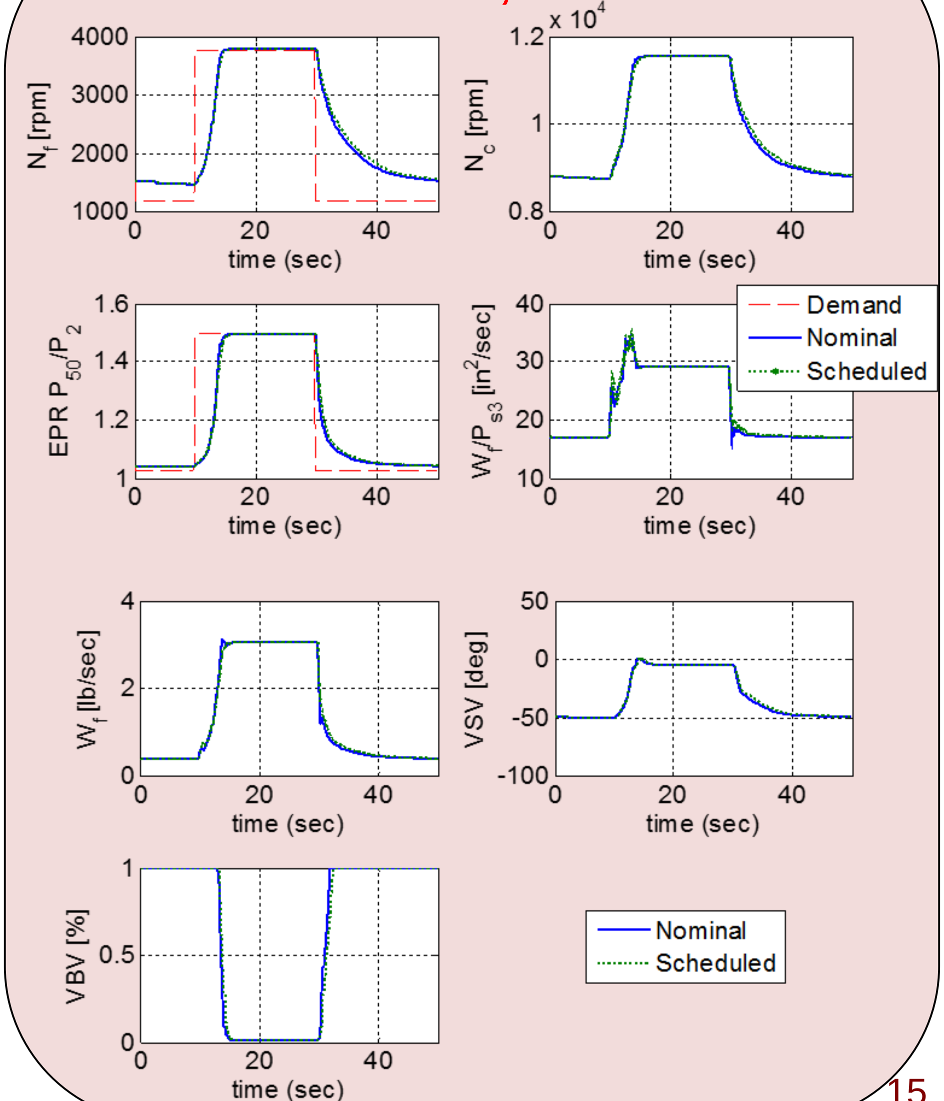
- *Schedule determines network throughput*
- *Enable block controls data flow*
- ***Major Frame** describes the periodicity*
- ***Minor Frame** describes the data transfer in and out of the controller within the control interval time*
- *Does not consider protocol, message size, transmission rate, or exact time of arrival*

Simulation with Scheduling

Sim 1: 150 ms, Tx 375 ms, Nx 750 ms

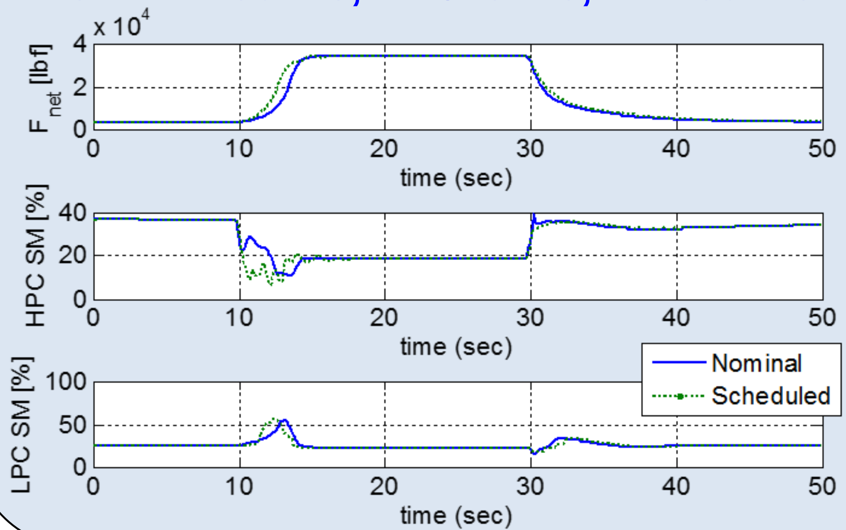


Sim 2: 150 ms, Tx 375 ms

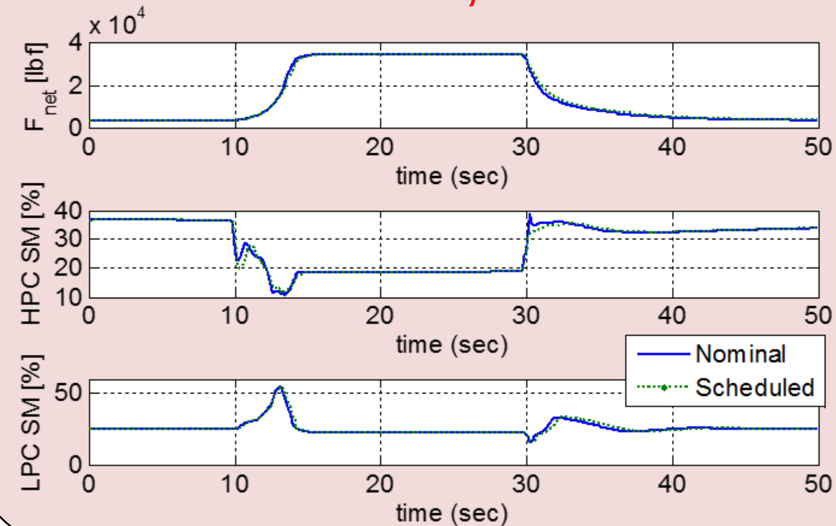


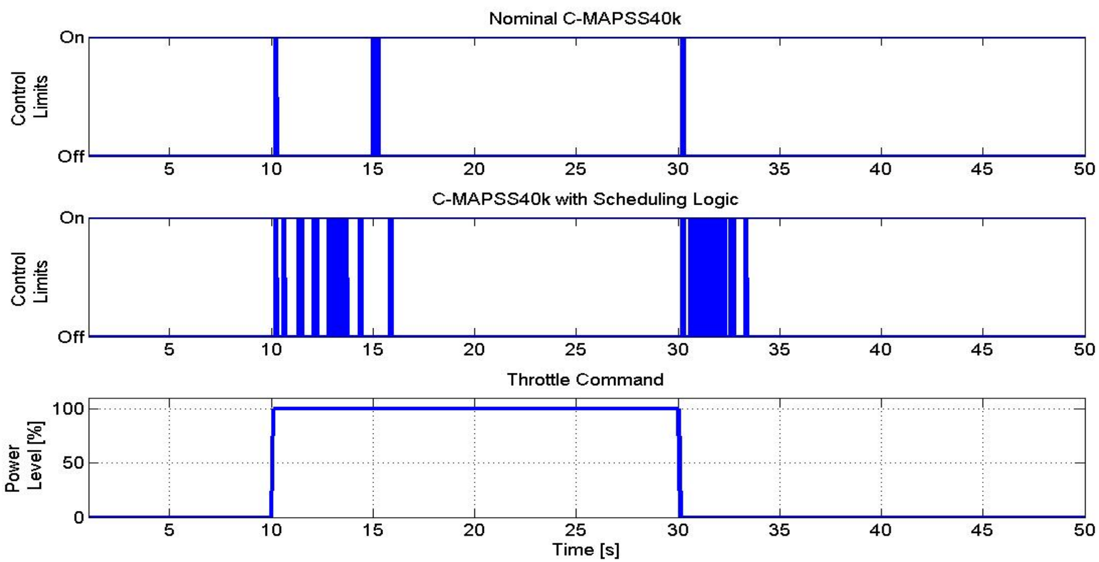
Simulation with Scheduling

Sim 1: 150 ms, Tx 375 ms, Nx 750 ms



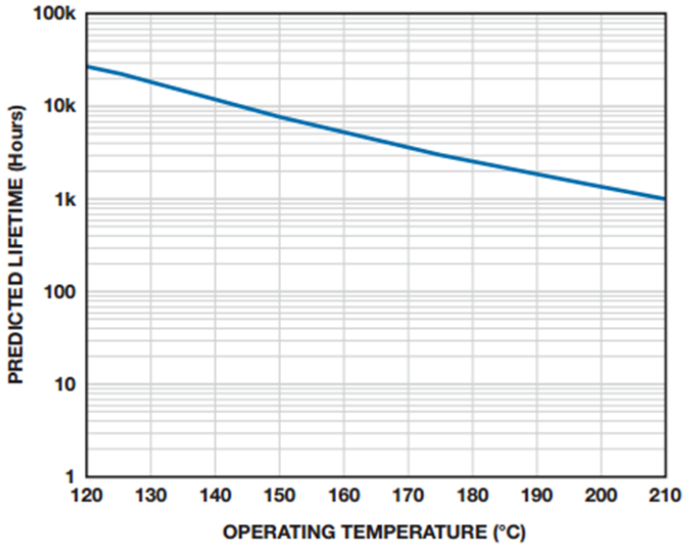
Sim 2: 150 ms, Tx 375 ms





Control mode relies on additional use of limit regulators

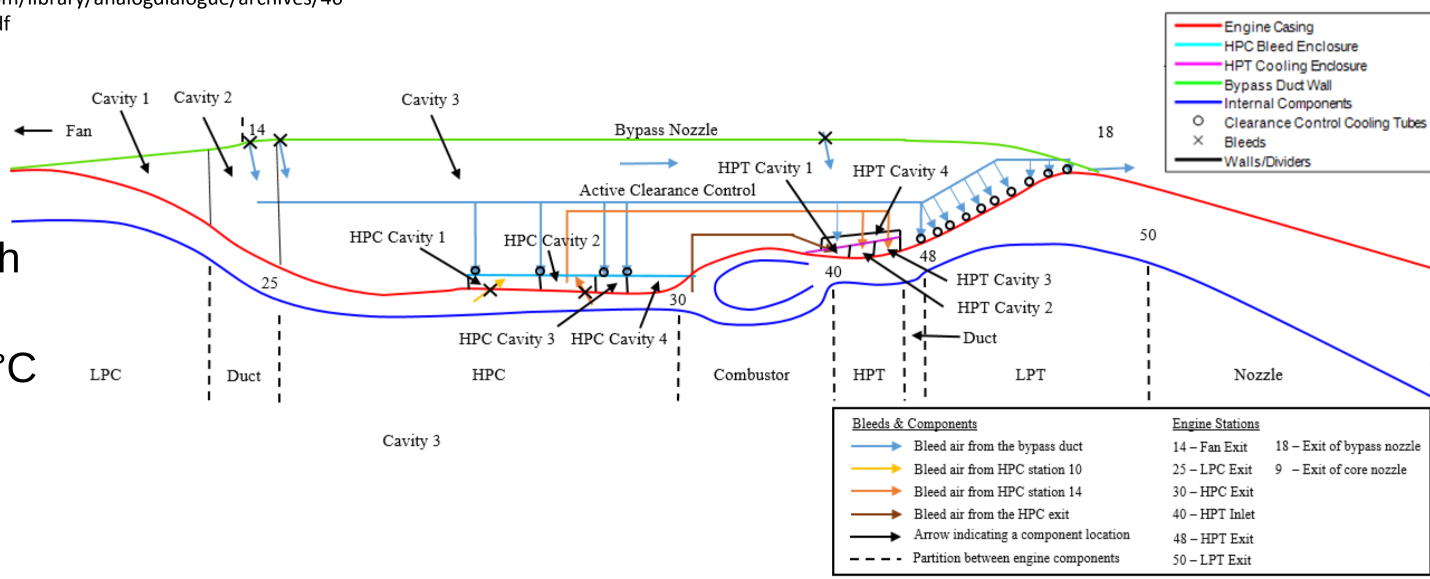
Dynamic Thermal Modeling



Example of the reliability vs. temperature relationship for an electronic device http://www.analog.com/library/analogdialogue/archives/46-04/high_temp_electronics.pdf

- 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.
- Standard **silicon electronics** have various temperature ratings based on packaging
  - Commercial: 0 ° to 70 °C
  - Industrial: -40 ° to 85 °C
  - Military: -55 ° to 125 °C
- **Silicon-On-Insulator** (SOI) electronics < 300 °C
- **Silicon Carbide** (SiC) electronics > 500 °C

Internal Gas Path Temperature in Excess of 1500 °C

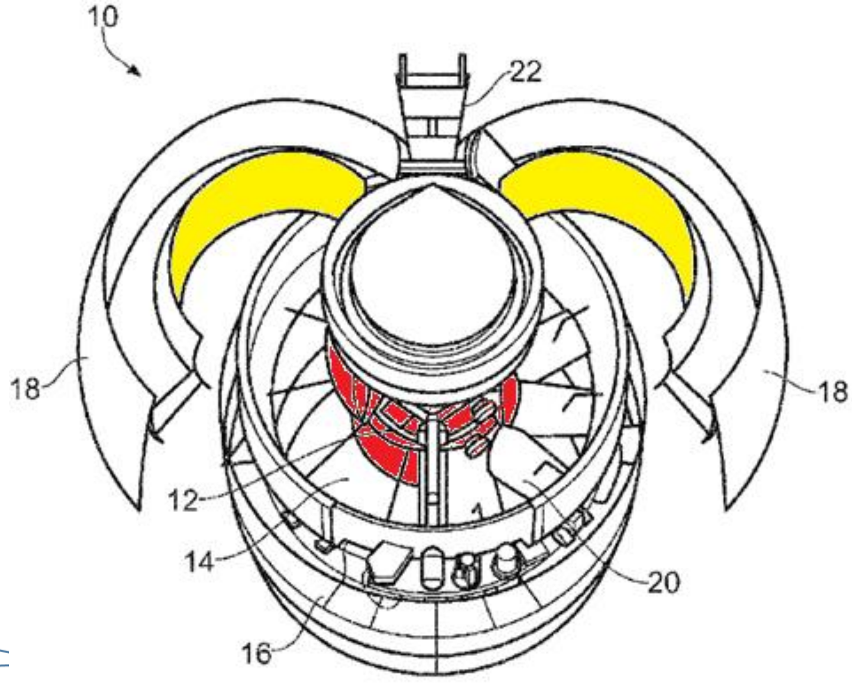


Thermal Model Development

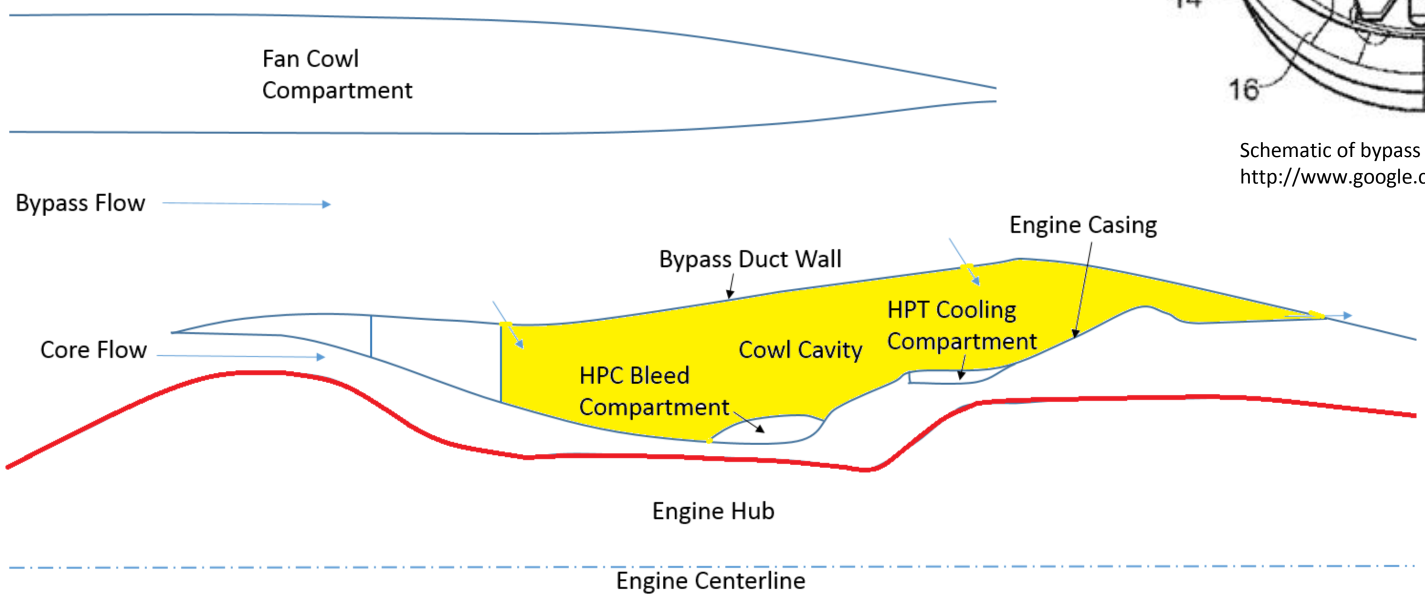
Dynamic thermal models developed for

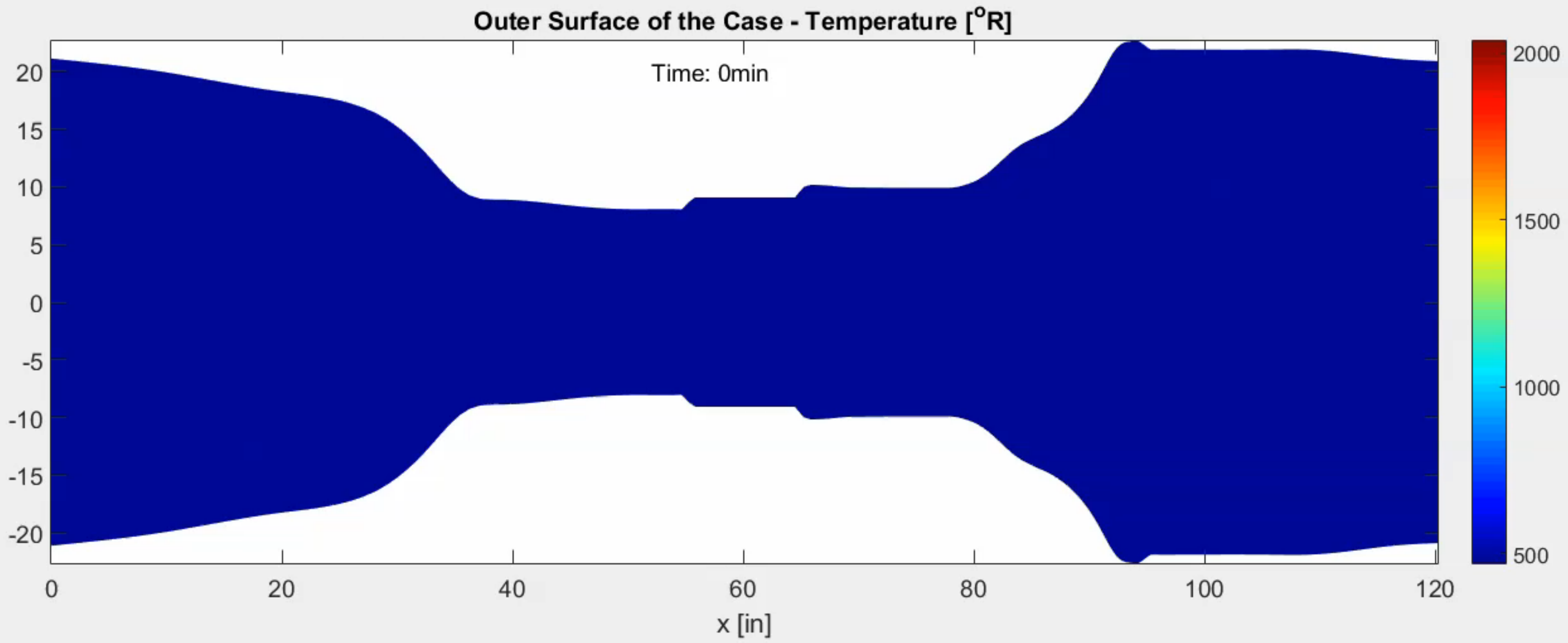
- Internal engine components
- Casing walls
- Cowl cavity
- Inner bypass duct wall
- Heat Soak-back

Linked to engine system simulation



Schematic of bypass walls opening
http://www.google.com/patents/EP2562405A1?cl=en




Outer Surface of the Case - Temperature [°R]
Time: 0min
20
15
10
5
0
-5
-10
-15
-20
0
20
40
60
80
100
120
x [in]
2000
1500
1000
500

Advanced Smart Node Development

A first order benefit of Distributed Control is the decoupling of the *Control Law Processing* function from the *Input / Output* function

- Game changer in terms of *access to computational resources*

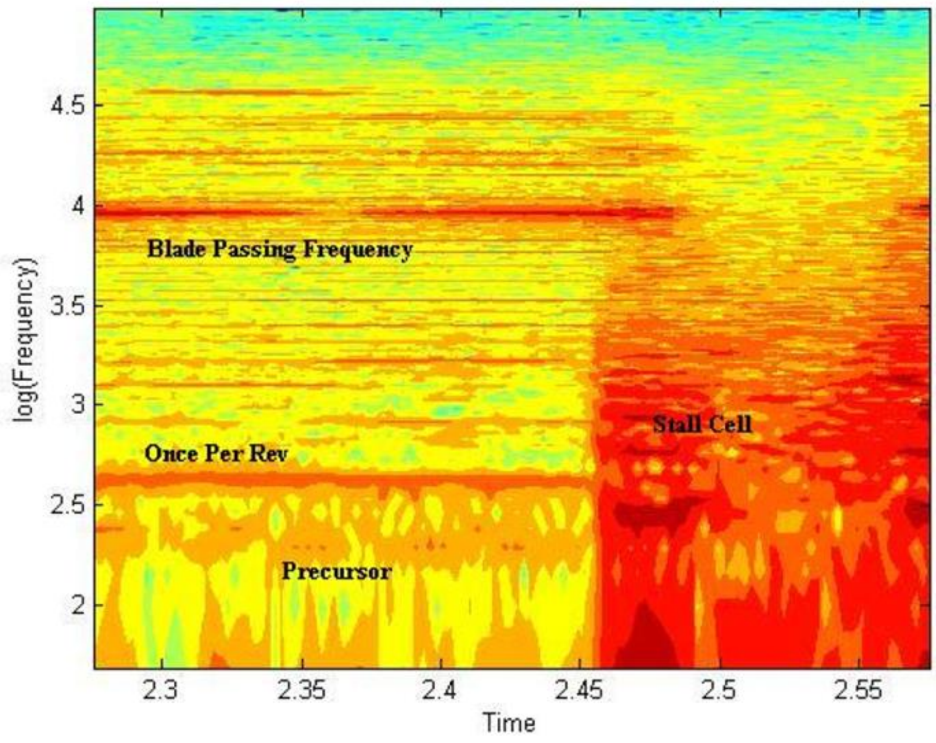
The processing power and capability of embedded electronics on/near the engine casing directly affects the available control functionality. Understanding this new potential, and the applications for local loop-closure, directly determines the complexity and potential for new performance-enhancing engine control.

Local closed loop control enables a paradigm shift in *capability, such as:*

- Active Combustion Control
- Turbine Tip Clearance Control
- Active Flow Control
- Data Mining
- Wide Bandwidth Sensing and Data Reduction

Exploring New Capability - Example

Pressure sensing at the source eliminates long pneumatic tubing that presents maintenance and safety issues as well as limited signal bandwidth.



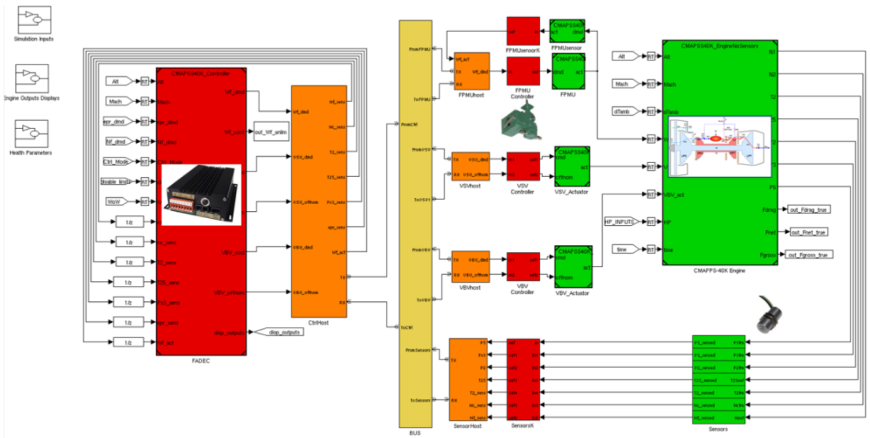
[1] Zarro, S.. (2006). Steady state and transient measurements within a compressor rotor during steam-induced stall at transonic operational speeds, Master's Thesis. Naval Postgraduate School

Smart Node Pressure Sensor

- What is the processing capability of a High Temperature Smart Node?
- What information can now be extracted from the plant and how can it be used?
- How does this impact control?
- What is the value to the engine system?

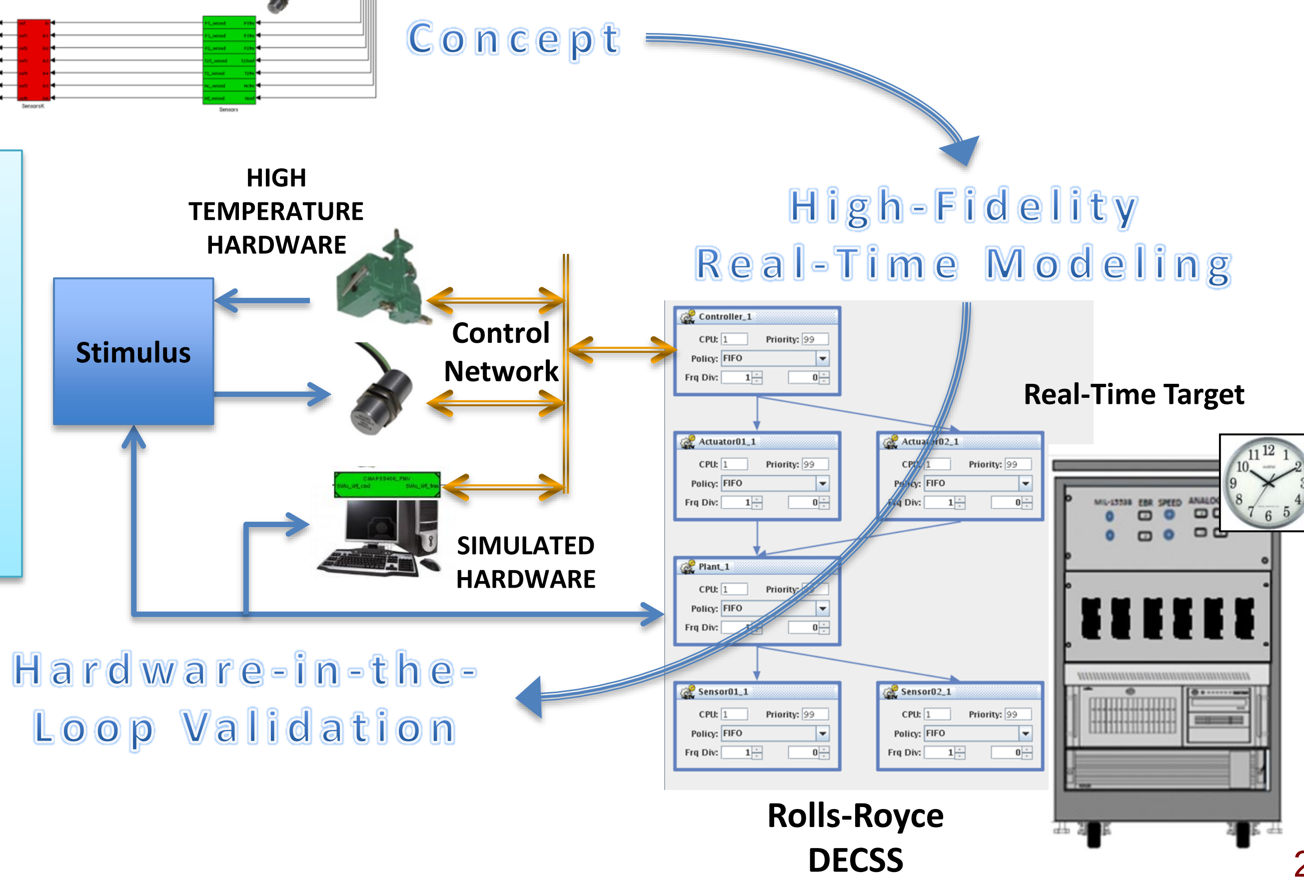
- *How do you model and test this type of system*

Hardware in the Loop simulation

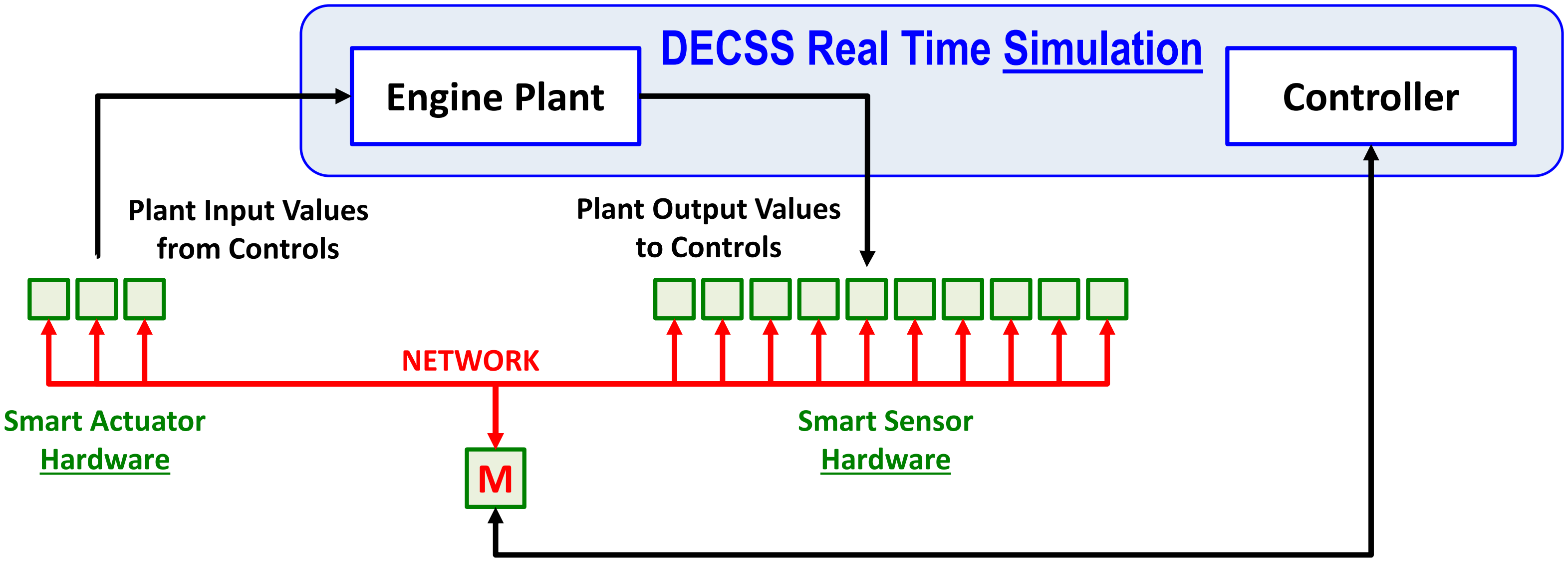


Collaborative Simulation Environment for SBIR and component suppliers to develop new technology concepts

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



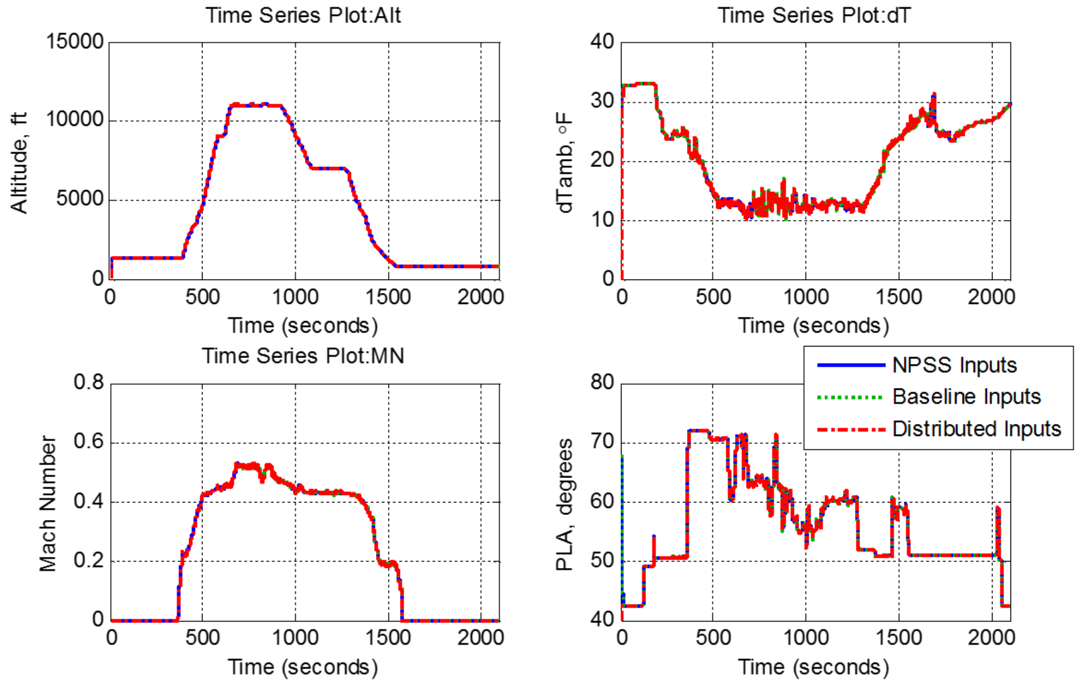
HIL Simulation Flexibility



- Currently a dry test bench
- Engine Plant model can be easily interchanged
- Any Control hardware element can be implemented in simulation or hardware
- Have demonstrated various hardware/simulation combinations of smart node functions
- Control data can be exchanged through a selection of interfaces both analog and digital
- Expect to incorporate control network interfaces as they become available

Multi Simulation Capability & Results

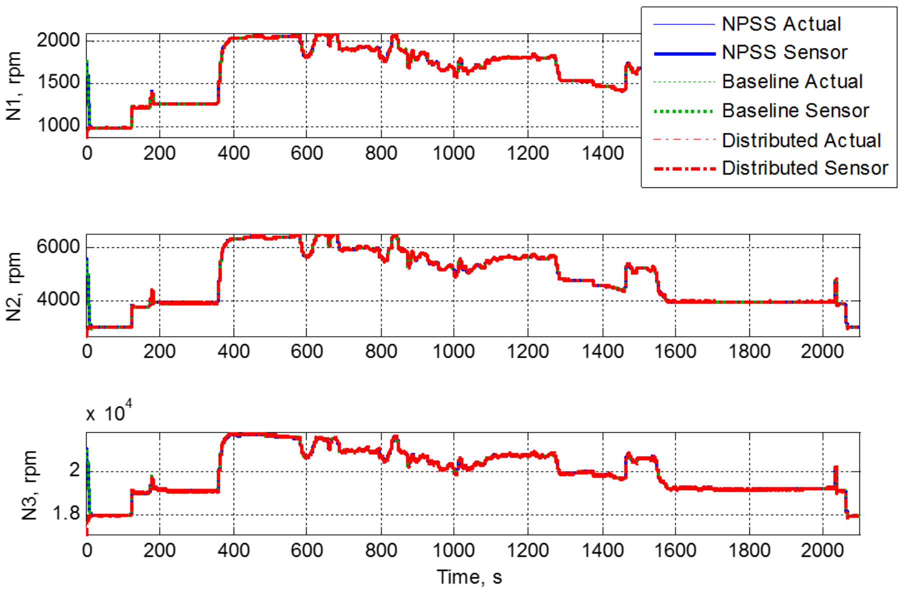
NASA Ames Flight Profile
FD_687200104131515

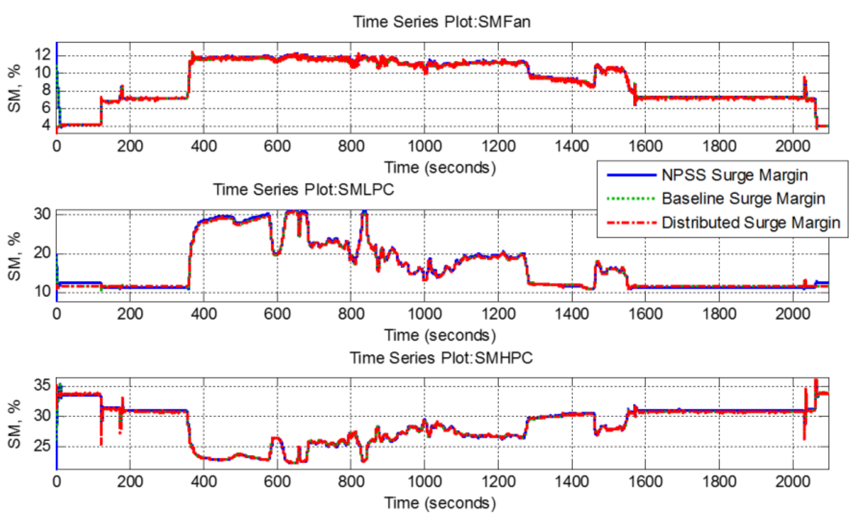


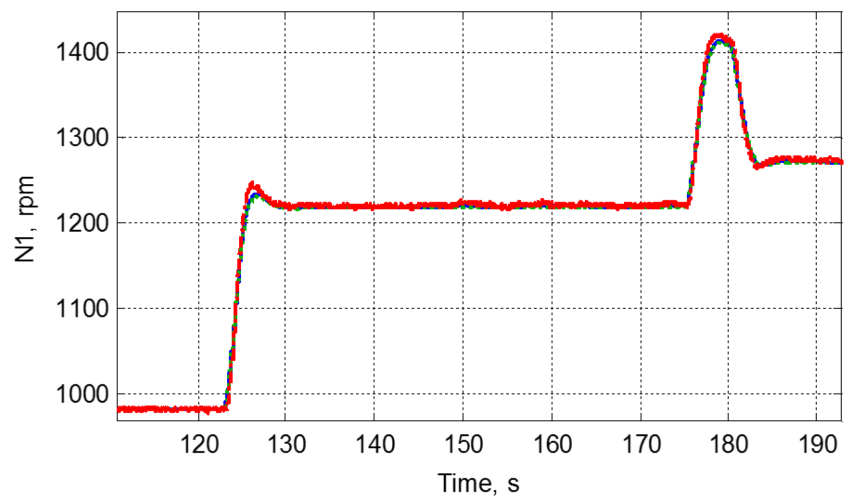
Results of simulations performed in different platforms

- **NPSS** (s-function) engine plant model with TMATS controller on Windows® platform
- **Baseline** TMATS AGTF30 engine plant model & controller on real time HIL
- **Distributed** TMATS AGTF30 engine plant model & controller with distributed nodes and communications on real time HIL

Multi Simulation Capability & Results

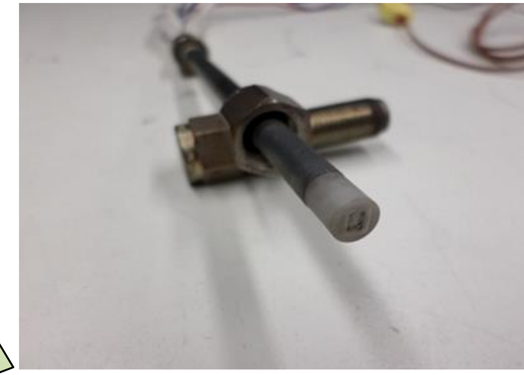






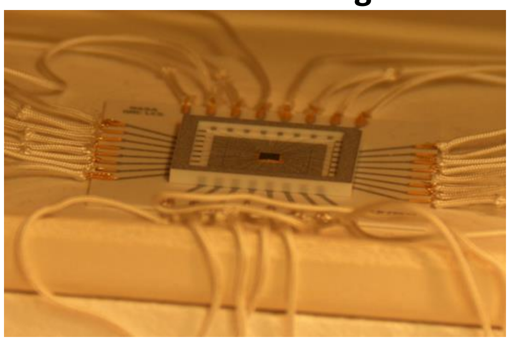
Very High Temperature Electronics

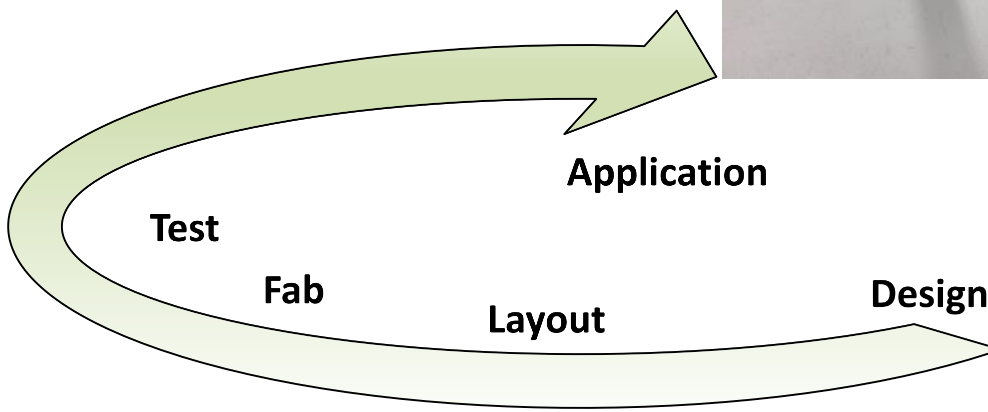
- Small signal silicon carbide electronics capable of +500 °C operation for thousands of hours
- Increasing complexity from 100’s to 1000’s of transistors

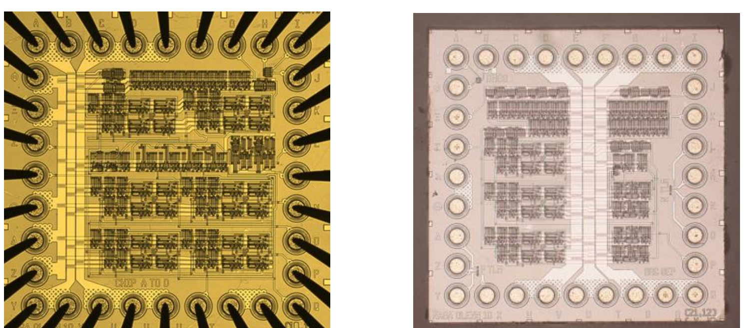


+500 °C Sensor

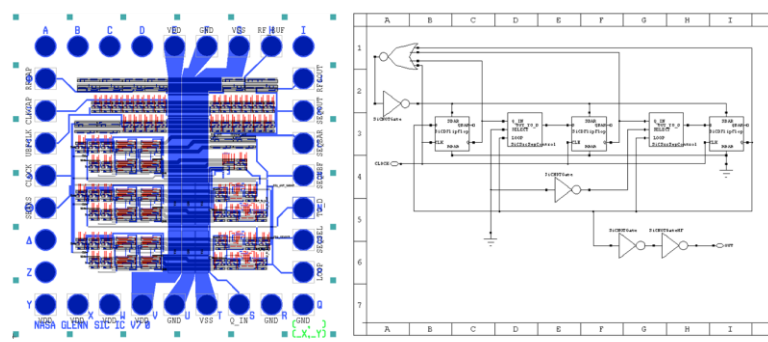
+500 °C Testing







A to D Chip in Probe Test

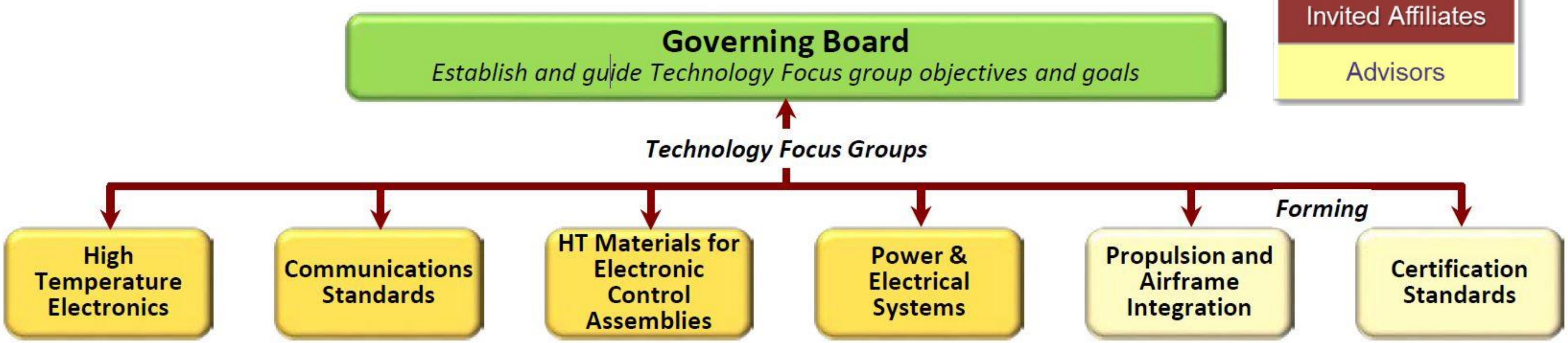


Frequency Divider

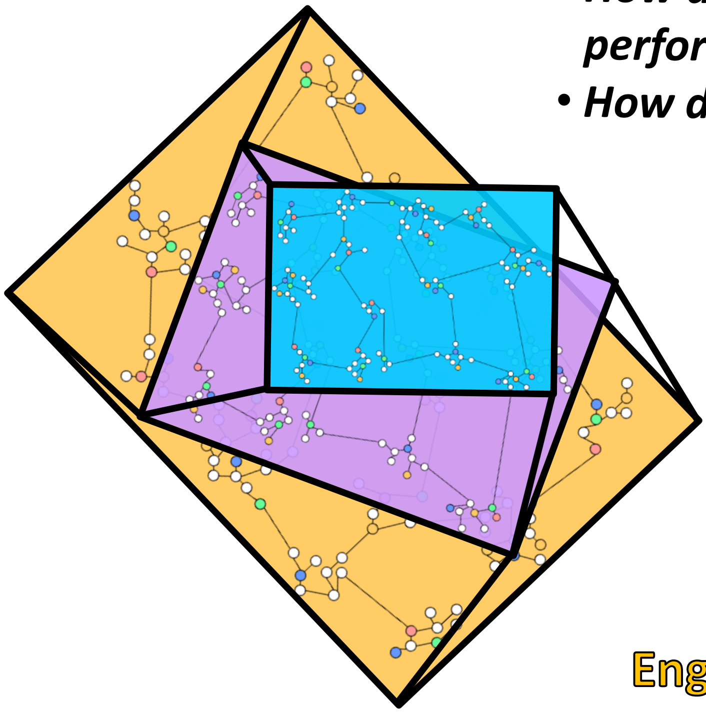
Community of Practice

DECWG®
Distributed Engine Control Working Group
Consortium

- DECWG
- General Electric
- Honeywell
- Pratt & Whitney
- Rolls-Royce LibertyWorks™
- BAE SYSTEMS
- UTC Aerospace Systems
- OAI
- U.S. Government
- Invited Affiliates
- Advisors



Engine Control Eco-System



NASA Controls Technology

- *Growth*
- *How do we use the technology to enhance performance, operability, & safety?*
- *How do you sustain the Eco-System?*

DECWG® Precompetitive Technology

- *Collaboration*
- *Common barriers*
- *The common "materials" for controls*

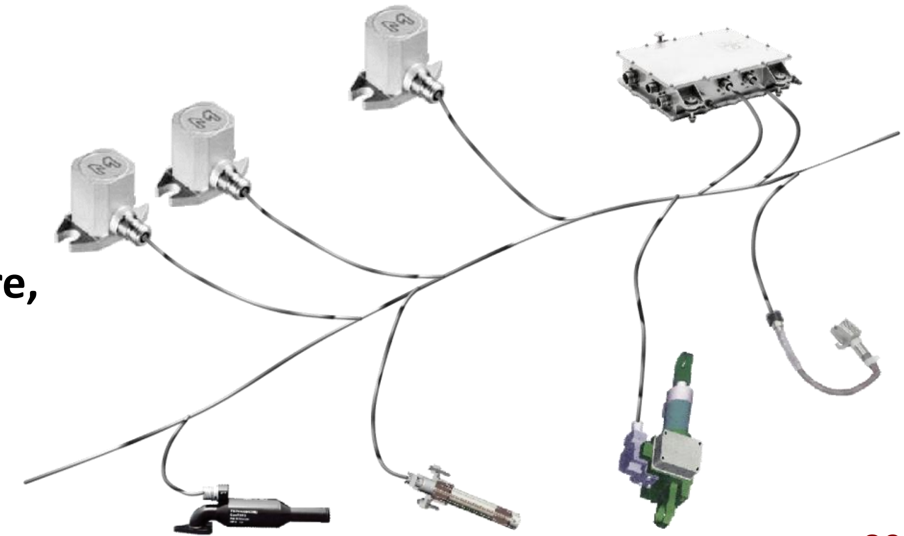
Engine Control System Technology

- *Differentiation*
- *Closely held intellectual property*

Summary

- Distributed Engine Control Architecture is a Response to the Implications of Next Generation Engine Technologies Identified in the NASA Strategic Implementation Plan
  - Ultra-high bypass
  - Compact Gas Turbine
  - Hybrid Gas-Electric Propulsion
- The Traditional Control Hardware Approach Would Impose System Penalties That Ultimately Limit the Capabilities of the Propulsion Engine and Vehicle.
- The New Control Hardware Architecture Enables New Capabilities for Engine Performance, Availability, and Safety.

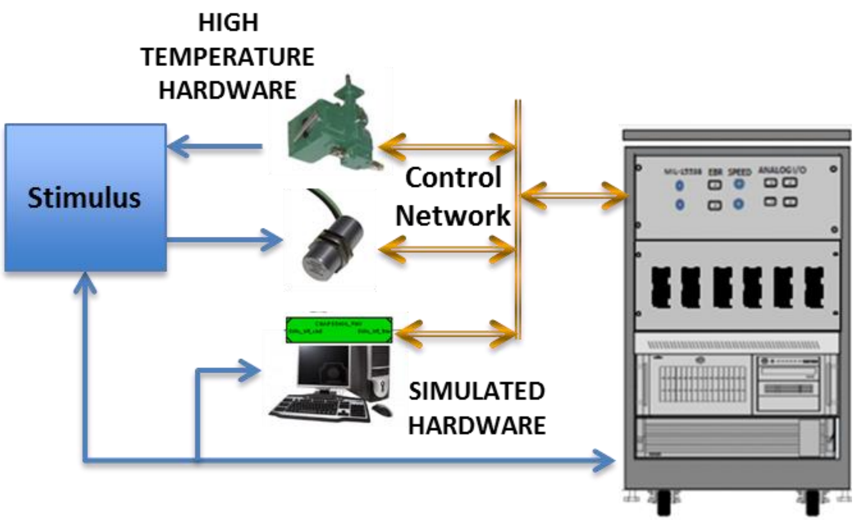
High Temperature, Distributed, Embedded

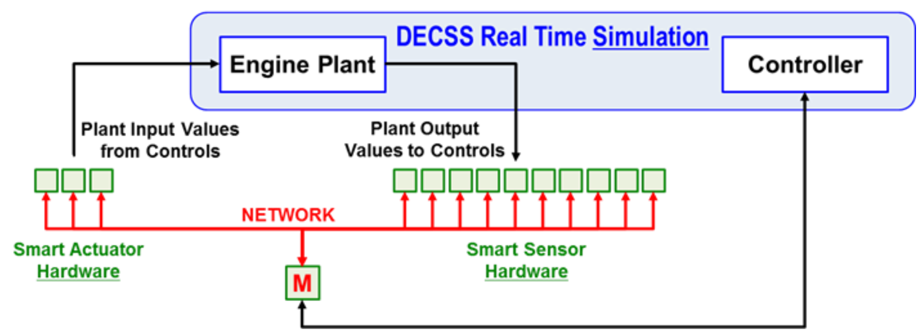


Progress

The Focus at NASA has been:

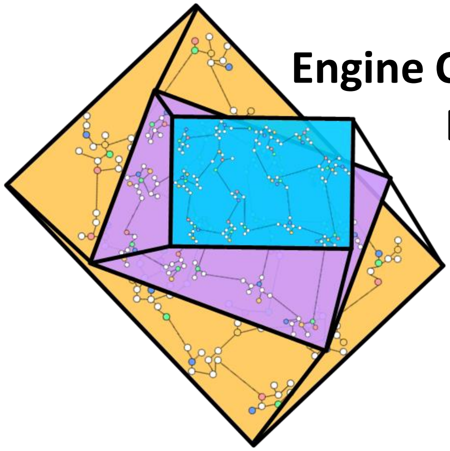
- Modeling and Simulation tools that represents the hardware characteristics of
  - Distributed Control Elements – Smart Nodes
  - Engine Control Network Communications and Data Flow
- Construction of a Real-Time Hardware-in-the-Loop Laboratory with ability to incorporate Next Generation Engines
- Modeling Tools for the Dynamic Thermal Environment on the Engine Core
- Development & Testing of Wide-Bandwidth, High Temperature Applications for Smart Nodes



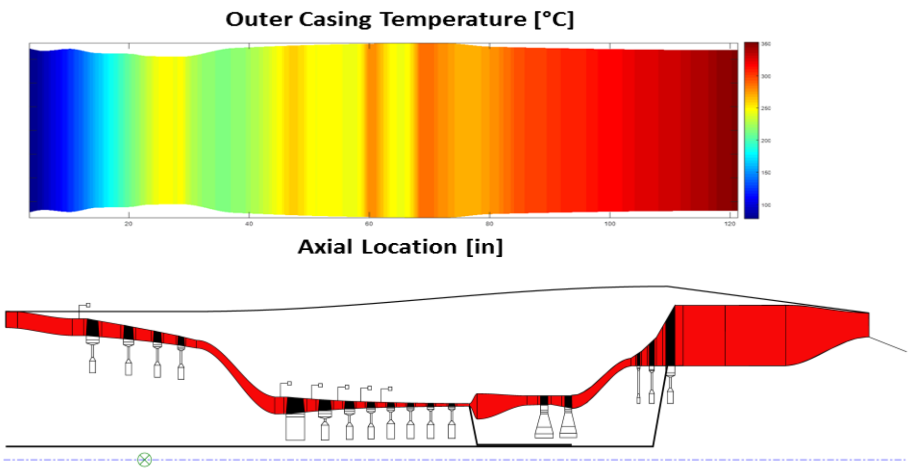


Impact

- Our Tools Help Define Control System Requirements and Inform Systems Analysis of the Net Benefits to the New Technologies Planned for Next Generation Engine Systems
- High Degree of Collaboration Between Government and Industry Helps to Leverage Research Dollars
- Initiates a New Emphasis on the Integration of Control, Power, and Thermal Management for Next Generation Propulsion Systems



Engine Control Community Eco-System



Compact Gas Turbine

Next Steps

- Integration of Modeling Tools for the Multi-Disciplinary Simulation of Next Generation Engine Systems
- FY18: Demonstration of Advanced, Wide-Bandwidth, High-Temperature Embedded Smart Node Technology
- Engine System Demonstrations

Team

Jonathan Kratz	NASA LCC
Eliot Aretskin-Hariton	NASA LCC
George Thomas	N&R Engineering
T. Shane Sowers	Vantage Partners
Glenn Beheim	NASA LCS
Phil Neudeck	NASA LCS
David Spry	NASA LCS
Norm Prokop	NASA LCP
Mike Krasowski	NASA LCP
Larry Greer	NASA LCP

The Evolution of Engine Control Architecture