AFRL-RZ-WP-TP-2008-2044

ADVANCED, ADAPTIVE, MODULAR, DISTRIBUTED, GENERIC UNIVERSAL FADEC FRAMEWORK FOR INTELLIGENT PROPULSION CONTROL SYSTEMS (PREPRINT)

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Structures and Controls Branch
Turbine Engine Division

SEPTEMBER 2007

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AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2007	Conference Paper Preprint	01 October 2006 – 30 September 2007

4. TITLE AND SUBTITLE

ADVANCED, ADAPTIVE, MODULAR, DISTRIBUTED, GENERIC UNIVERSAL FADEC FRAMEWORK FOR INTELLIGENT PROPULSION CONTROL SYSTEMS (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

6. AUTHOR(S)

Alireza R. Behbahani, Ph.D.

5d. PROJECT NUMBER
3066

5e. TASK NUMBER
03

5f. WORK UNIT NUMBER
306603TM

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Structures and Controls Branch (AFRL/RZTS)
Turbine Engine Division
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RZ-WP-TP-2008-2044

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RZTS

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RZ-WP-TP-2008-2044

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Conference paper presented at the Aerospace Control and Guidance Systems Committee Meeting.

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Technical paper contains color. PAO Case Number (for the presentation): WPAFB 07-0011, 04 Oct 2007.

14. ABSTRACT

Today, each FADEC is unique and expensive to develop, produce, maintain, and upgrade for its particular application. Each FADEC is a centralized system, with a redundant, central computer and centrally located analog signal interfacing circuitry for interfacing with sensors and actuators located throughout the propulsion system. It is to establish a universal or common standard for engine controls and accessories. This will significantly reduce the high development and support costs across platforms. What is needed is a Universal FADEC (UF) Platform with a flexible process with commercial-off-the-shelf (COTS) technology and product solutions that are fully independent and composable, and reliable. The term UF implies open system architectures with common or universal standardized inputs and outputs with reusable software, and a reduced number of components. A centralized or distributed multi-sensor system that is capable of fusing gathered data and using it as a basis for making decisions will provide greater robustness, timeliness and fault tolerance.

15. SUBJECT TERMS

turbine engine control, engine health management, FADEC, Universal FADEC, Distributed Controls, UF, UF Platform, common FADEC, Generic FADEC, Modular FADEC, Adaptive Control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	52	Alireza R. Behbahani **19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Advanced, Adaptive, Modular, Distributed, Generic Universal FADEC Framework for Intelligent propulsion Control Systems

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Abstract— Advanced intelligent, robust propulsion controls and health management technologies are critical for improving the safety and maintainability of future propulsion systems. Propulsion system reliability could be considered to be critical for aircraft survival, and the key component of the turbine engine is the Full Authority Digital Engine Control (FADEC). Development of an innovative advanced FADEC is essential to a modern integrated, adaptive engine. As the turbine engines become more integrated with the airframe, their respective control systems must also be combined into integrated system intelligence. This combined system might also need to transmit vital system information to ground stations.

Today, each FADEC is unique and therefore is expensive to develop, produce, maintain, and upgrade for its particular application. Each FADEC is essentially a centralized system, with a redundant, central computer and centrally located analog signal interfacing circuitry for interfacing with sensors and actuators located throughout the propulsion system. In the future, it is desired to establish a universal or common standard for engine controls and accessories. This will significantly reduce the high development and support costs across platforms.

What is needed is a Universal FADEC (UF) Platform. This is a system of flexible process and product solutions that is fully independent and composable, and the chief purpose of such a system is to greatly improve engine reliability. Developing and implementing modern intelligent engine systems will also require the introduction of many additional sensors, actuators, and distributed processors to provide the advanced functionality. The term “UF” implies open system architectures with common or “universal” standardized inputs and outputs. Other desirable features for the UF system include the use of common and advanced materials, reusable software, and a reduced number of components. UF reliability (reduced risk of failure) may also be improved through the use of high-reliability modules and improved manufacturing processes. A decentralized/distributed multi-sensor system that is capable of fusing gathered data and using it as a basis for making decisions will provide greater robustness, timeliness and fault tolerance. Composability implies that modules that are developed by different teams at different times, or in parallel, can be made to integrate seamlessly.

The Air Force Research Laboratory initially recognized the need for a UF in May 2003, and began working with the FADEC manufacturers to explore the possibility of building a UF platform. The purpose of that effort is to produce an integrated, hybrid, distributed, modular, and generic framework for the intelligent and robust control and health management of the complex propulsion systems of the future. The incorporation of proven Commercial off the Shelf (COTS) technology into FADECs and the application of artificial intelligence and knowledge-based system for both software and hardware should provide the foundation for building the intelligent control system of the future. The presentation will review the current state of the UF platform for turbine engine controls and examine the issues, challenges and technology gaps that must be addressed in order to realize the vision for the next generation UF.

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6.1

Advanced, Adaptive, Modular, Distributed, Generic *Universal FADEC* Framework for Intelligent propulsion Control Systems

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Oct 10 – 12, 2007

Aerospace Control and Guidance Systems Committee Meeting #100

Subcommittee E-Flight, Propulsion, and Autonomous Vehicle Control Systems

Cocoa Beach, Florida

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OUTLINE

- Full Authority Digital Engine Control (FADEC) Defined
- Problem / Challenge
- Alternative Solutions
- Vision / Recommended Actions
- Summary / Conclusion

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Historical Perspectives of Full Authority Digital Engine Control (FADEC)

What are the issues?

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Historical Perspectives of Engine Controller…

- Electronics offered improved performance and functionality
- This capability evolved into engine specific, centralized controls
- Functionality and complexity has continued to increase
- Highly specialized, complex controls are developed for each application

“POINT” Solutions

- **High development cost**
- **High support cost**

“One Box Fits All”

- **High recurring cost**
- **Size / weight / volume / power issues**
- **Each application is customized and updated**

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Typical FADEC Architecture

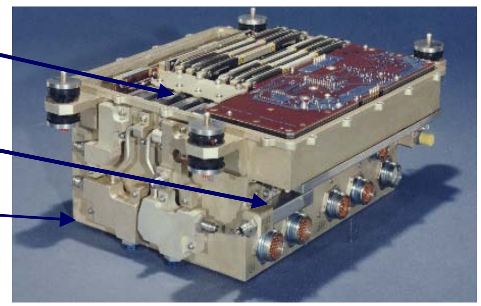
Currently, legacy FADEC systems are both unique and dedicated to the weapon system. Cost of design and support across DOD platforms is extremely high.

F110 DEC

Electronic Card Modules

Connectors

Transducers



F-110

- Each FADEC and its subcomponents are unique to individual systems and not interchangeable
- The Software/ Hardware Architecture is Specialized & Unique
- Today's architectures employ dedicated wiring for each measurement and actuation location.
- Cable harnesses weigh 60 pounds or more

Each FADEC is Unique

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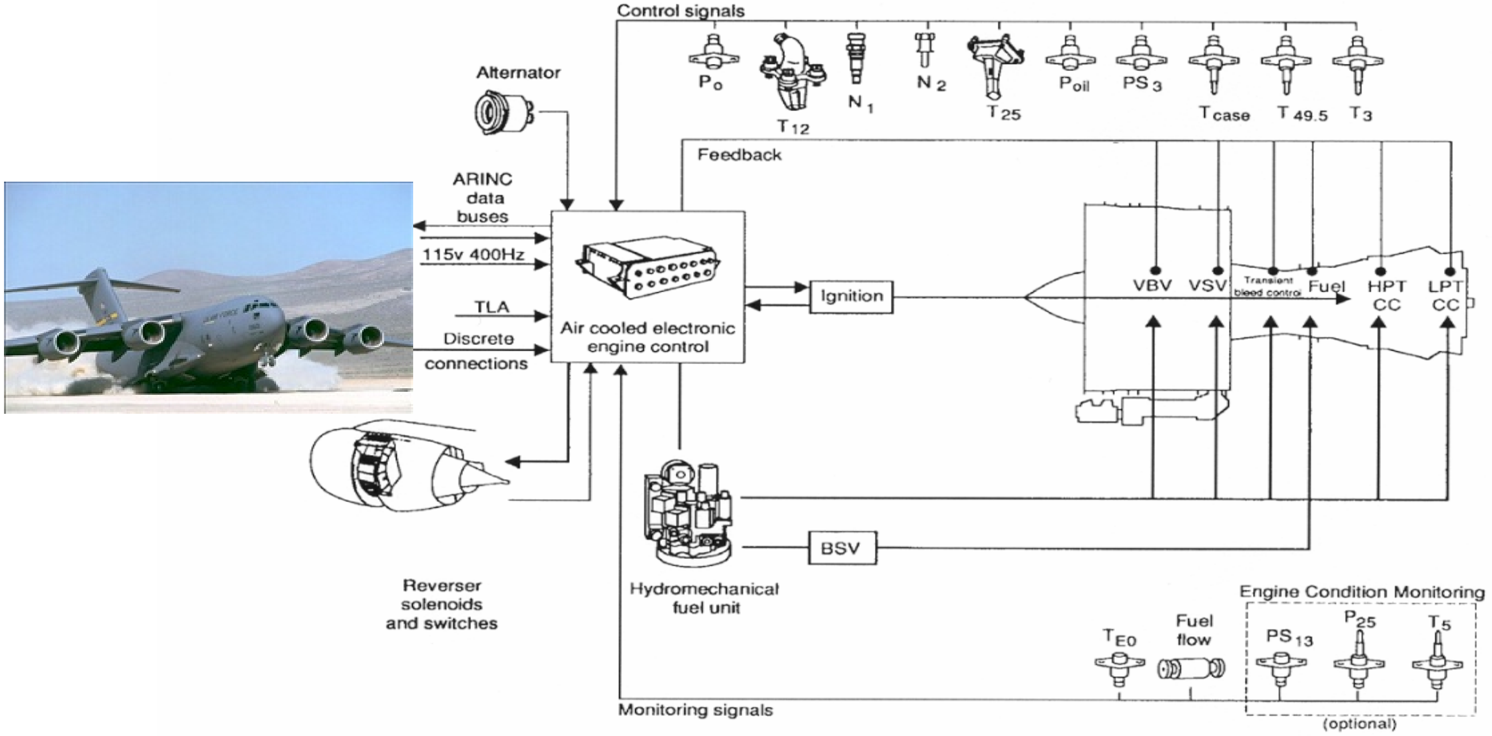
Typical FADEC System / Sensors

Over 20 Control loops are Required to Maintain Safe and stable engine operation Each is routed to a central Controller (FADEC)



- *Architectures employ dedicated wiring per measurement and actuation location*
- *Cable harnesses weigh 60 pounds +*

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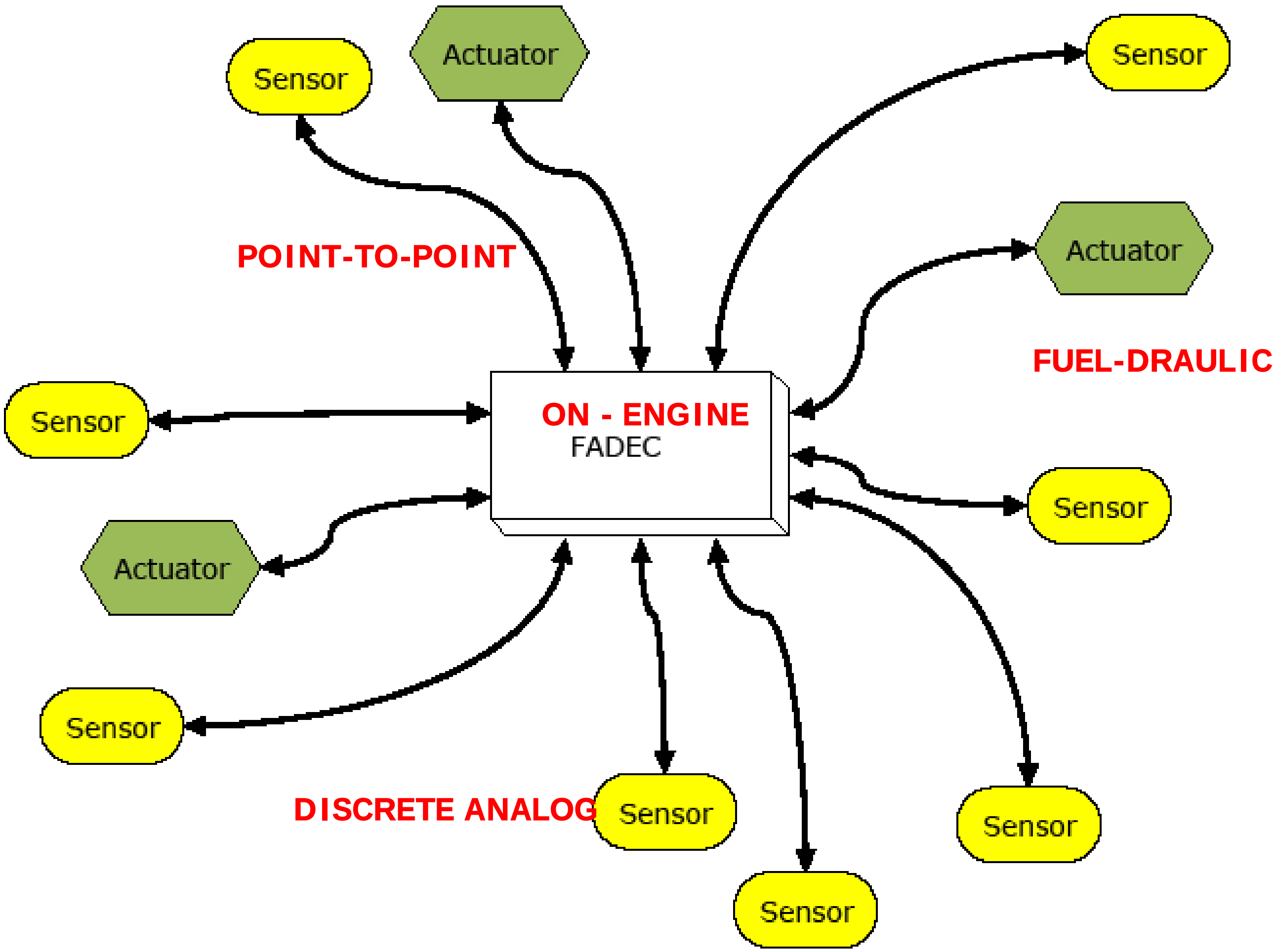
Central Control System

CCS…Invisible, Static Resources, Centralized Management



Harness
- Heavy
- Complex
- Reliability Issue

FADEC
- Hostile Environment
- Expensive
- Prone to Obsolescence

System
- Difficult to Isolate Faults
- Difficult to Modify and Upgrade
- How to Implement Advanced Controls?

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"Put all your eggs in one basket and – watch that basket!" -- Mark Twain

Engine Controls Products

Currently Commonality exits for Functional Class Groups

	Supervisory electronic control with hydromechanical control	Primary electronic control with hydromechanical backup	Dual-channel full-authority digital engine control with flow body
Military Engine Controls	 T700 DEC (APACHE)	 F110 DEC (F16)	 F414-400 FADEC (F-18 E/F)
Commercial Engine Controls	 RB211 (B757)	 FJ44 (Premier1)	 CFM56-5C FADEC (A340)

Aircraft with BAE SYSTEMS Engine Controls

Supervisory electronic control with hydromechanical control

Military

- F-18
- F-117
- AH-64
- H-60
- B-1B
- VC-25A (AF1)
- KC-135R
- E-6A
- E-3
- A-10
- S-3
- SH-2G
- AH-1W
- Bell 214
- JAS 39

Commercial

- B737
- B747
- B757
- B767
- A300
- A310
- RB211
- S340
- CN235
- CRJ
- DC-8R
- CL-601
- H-2G
- TU-204

Primary electronic control with hydromechanical backup

Military

- F-16
- B-2
- SK-60
- LCA
- F-14D
- F-2
- U-2

Commercial

- Premier I
- SJ-30

Dual-channel full-authority digital engine control with flow body

Military

- F/A-18 E/F
- YF-23
- YF/A-22
- T-50
- X-45

Commercial

- A300
- A319
- A320
- A321
- A330
- A340
- B717
- B737
- B747
- B767
- B777
- CRJ-700
- EMB-170
- EMB-190
- MD11

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Each One A Snowflake

What Is The Problem?
Issues?
Root Causes?
Challenge?
Goals?
Motivations?
Requirements?

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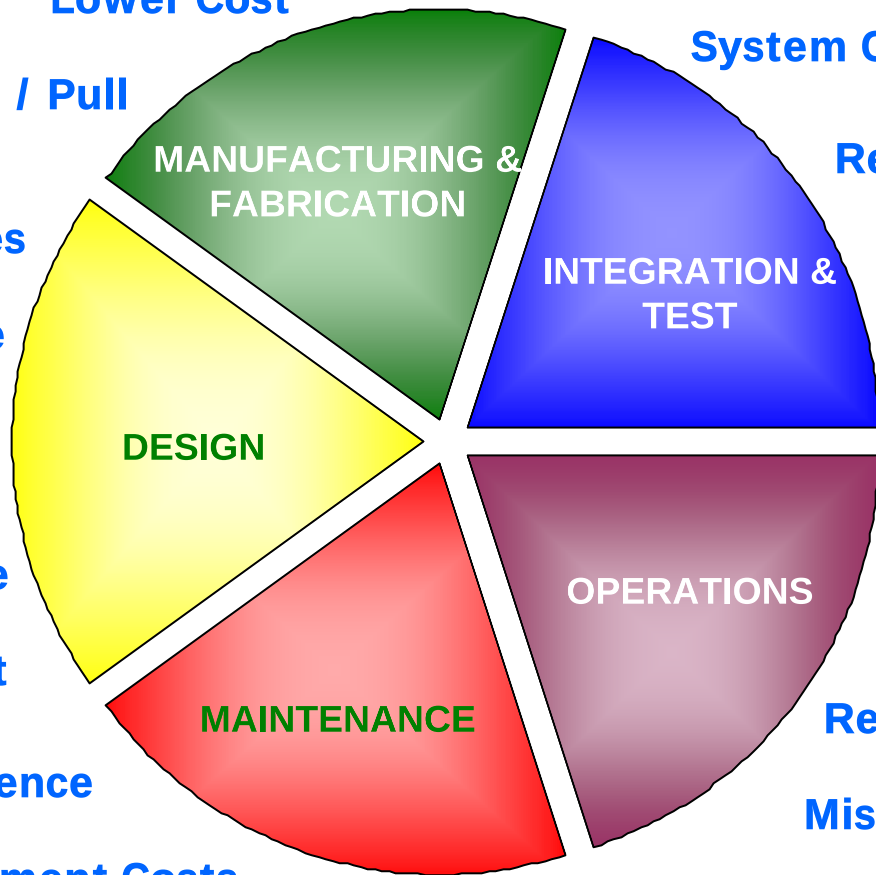
Motivation / Goals

Lower Cost
Technology Push / Pull
Simplify Upgrades
Add Customer Value
Add Features
Improve Performance
Reduce Weight
Mitigate obsolescence
Reduce Sustainment Costs
Proactive Health Management



System Compatibility
Reduce Certification Cost / Time
Capability Growth
Improve Reliability
Increase Availability
Real-time Life Tracking
Mission Success
Prognostic Capability

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Performance & Cost / Time

FADEC DRIVERS

Obsolescence
- Aging
  - Maintenance / Replacement Cost
    - S/W & H/W
  - Compatibility
    - Architectures
  - Availability
- Technology Updates

Technology Push / Pull
- Capability upgradeability

Capability Growth

Affordability

Reliability / Availability / Mission Success

Features

Prognostic Capability

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ROOT CAUSES FOR COST GROWTH
FADEC obsolescence

Causes due to aging of FADEC and its components

- Reduced sources / competition
- Rework vs. replacement of FADEC components
- Premium Prices and Cannibalization

Aging System (Physical Aging of components)

- Reaching Life limits
- Replacement Factors for repair Parts
- “Beyond Economic Repair/Replacement” Items

Capability Growth

Obsolescence is a key factor for Avionic Cost Growth

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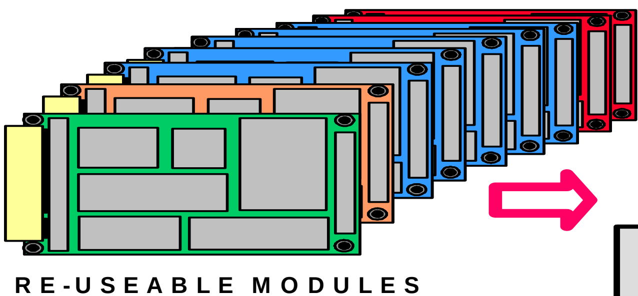
Problem, Issues and Challenges

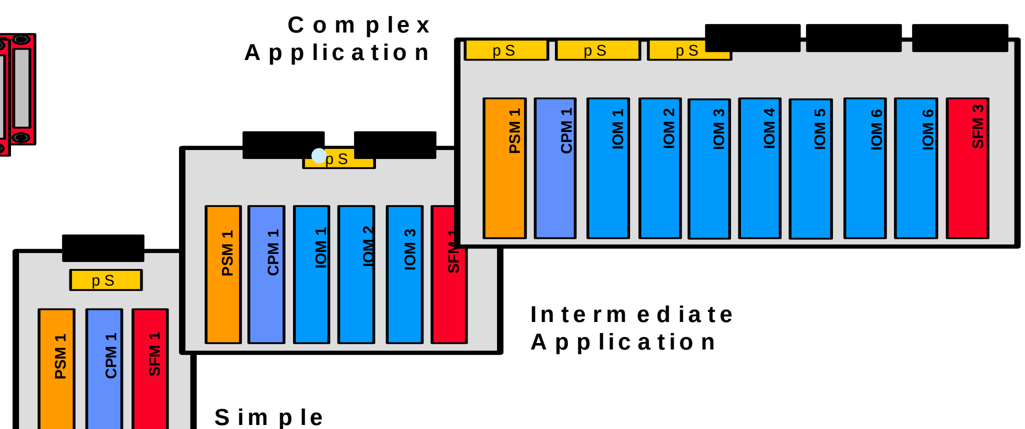
Present Modular CCS

- Monolithic Architecture
- Optimized for a Centralized Control Architecture
- Inherent Computational and Latency Limitations
- Proprietary, Inflexible to Technology Insertions
- Component Obsolescence can Break the Entire System
- High Sustainment Costs and Unworkable Logistics Support

Future Modular DCS

- Functional Partitioning
- Redundancy and Resource Management
- Market
- Safety / Certification / Regulatory Environment
- Increased Maintenance / Development Cost
- Distributed Systems Competencies
- Engine Environment and High Temperature Electronics
- Data Bus and Communications





Modular Designs Address the Application Space Issue But are not Easily Expandable or Sustainable

Monolithic Architectures do not Enable Technology Insertions or Effective Component Obsolescence Management

What is Required?

An intelligent engine Controller

- **System Easily Reconfigurable with a common Architecture (COTS Tools i.e. Time Triggered Architecture)**
- **Advanced Resource Sharing and Time Synchronization**
- **Smart Modules Distribute Computational Needs**
- **Modules can be Upgraded and Reintegrated Into the System**

- **Open Architectures and Standards**
- **Easily Expandable Systems**
- **Sustainable Systems**
- **Distributed Controls**

- **Modularity Principles:**
- **Maximal Cohesiveness of the functions**
- **Minimal Coupling among the elements**
- **Composability in the temporal domain**

Simple, Predictable, Systematic; Independent Modules and Global Time Guarantees Consistent Behavior

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Goals, Requirements, & Benefits

FADEC Goals:

- Improve Affordability
- Increase Reliability
- Proactive Health Management
- Integration
- Reduce Sustainment Costs
- Improve Performance
- Real-time Life Tracking

To meet those objectives, UF needs to be:

Integrated

Designed with the system

Distributed

No information bottlenecks

No single point of failures

Adaptive

React to new opportunities

React to sudden degradation / failures

UF Benefits:

- **In-flight mission preplanning, and increased reliability, reduce ownership costs, increase availability, and reduce the number of required spares.**
- **Systems Engineering Process crucial to assimilate disparate data types**
- **System data availability plays key enabler in defining prognostic horizon**
- **Open Systems approach required to maximize architectural benefits**
- **Easier said than done on Legacy Fleet**

Design paradigm shift required for successful UF and a sustainable operation

UF Framework Tasks

- Articulate the challenges and opportunities for Propulsion Control
- Present a vision that can be used to inform high level decision makers and OEM of the importance of Control design that will affect the entire propulsion system
- Identify possible Challenges and new opportunities
- Provide a compelling view of the field that continues to attract the brightest scientists, engineers, and mathematicians to the field
- Respond to the changing nature of control, dynamics, and systems research

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To Develop a process for UF platform one needs to do some preliminary tasks

Why We Need UF Platform?

- Engine Component Failure and Damaged Engine;
- Plant Characteristics Change;
- Changing Air Loads in Actuators;
- Changing Operating Conditions;
- Enhancing The Optimality Of The Control System;
- Performance Seeking Control Architecture;
- Support and Maintenance Cost;
- Aging Process of All Component; and
- Optimize the Controller.

The need for UF platform is based on several factors

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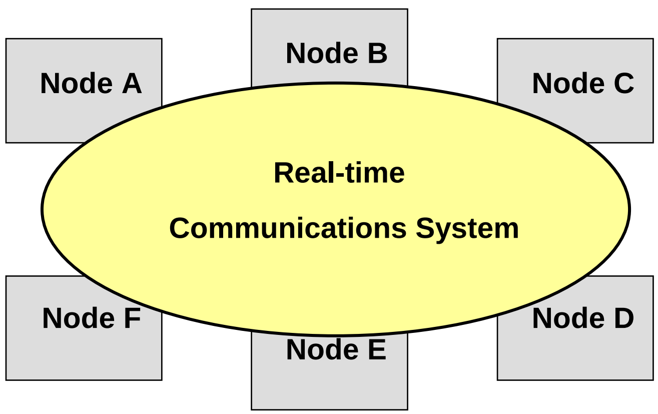
Alternative Fixes (Solutions) / Actions?

Logical analysis /
Design solutions

Where We Need to Go from here…?

- **Open Architectures and Standards**
- **Easily Expandable Systems**
- **Sustainable Systems**
- **Distributed Controls**

Composability in the temporal domain:
"Assuring that individual system elements can be designed and tested independently yet seamlessly integrated into the system"



Flexible architecture simplifies changes for obsolescence, added features or technology insertion

Migrate the Composable Module Concept to Distributed Controls

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Desired End-State
AFRL VISION

<u>Cost / Cycle Time Reduction</u>

- Use of COTS Modules
- Virtual Building Blocks
- Object Oriented Software
- Lean Design Initiatives
- Design for Six Sigma

<u>Vehicle Management Systems</u>

- Remote I/O Structure
- Distributed Control
- High Bandwidth Busses
- Open Architecture

"Universal" Backplane (motherboard) provides flexibility

Expandable and scalable, standard module interfaces

Adaptable to varied system architectures

Supports both serial and parallel inter-module communication using commercial data buses & chipsets (open standards and lower costs)

Utilizes simple serial communication bus (SPI) from a single MPC555 micro-controller (no extra HW & SW required)

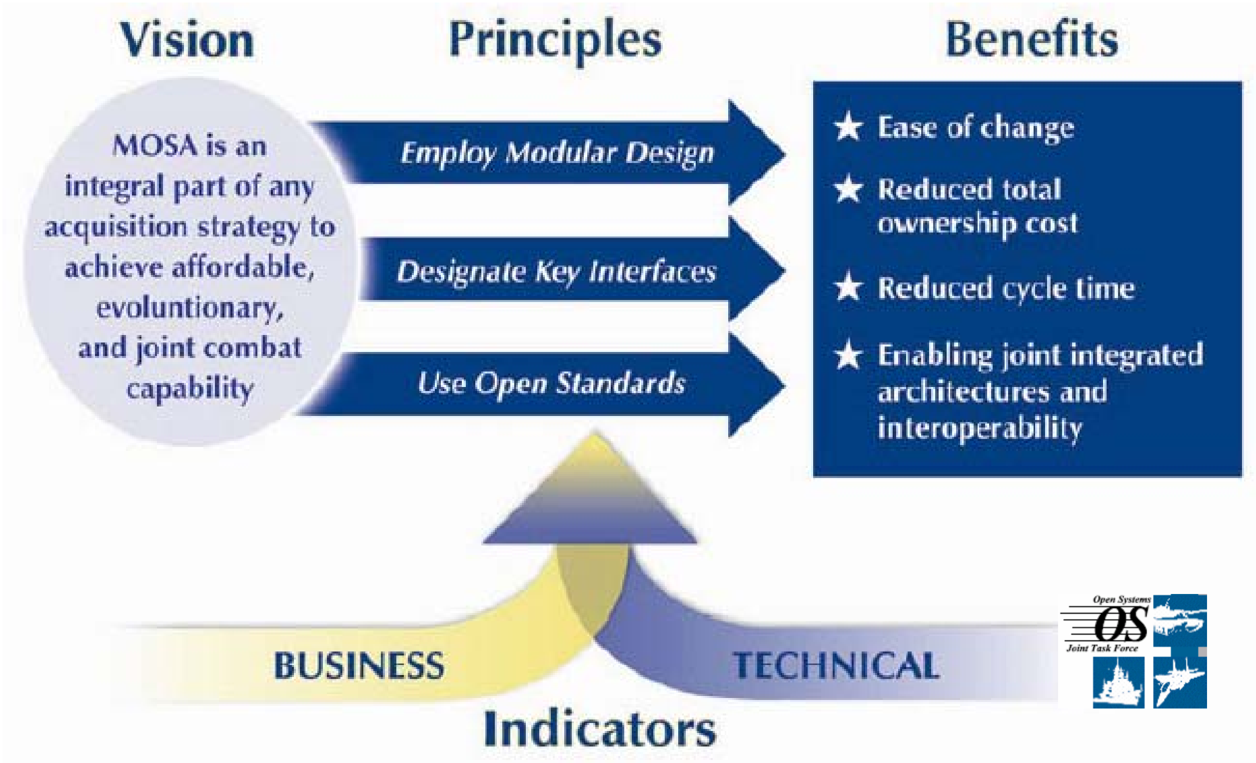
<u>Universal FADEC (UF)</u> is applicable to all military and commercial applications requiring lightweight, high speed, flexible, rugged, miniature, electronic controls. Has both common Software and Hardware.

<u>Standard Configuration</u> – "Plug & Play" – One Unit Reconfigurable for many Thrust Class Engines, standard specifications between OEMs. Open System H/W & S/W interfaces

"Plug & Play" with matched H/W & S/W modules, Mixed software criticality levels.

<u>Control Electronics Size and Weight</u> Will be Reduced – Performance and Maintainability will be Significantly Improved.

Modular Open Systems Approach (MOSA)



A Model for an Open Architecture to Enable a Sustainable and Expandable Engine Control Platform

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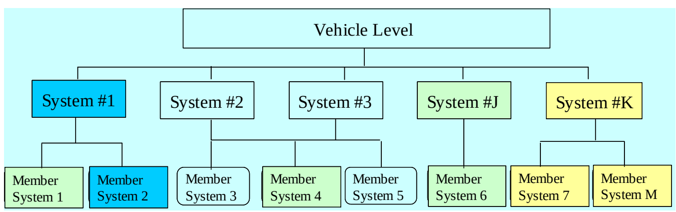
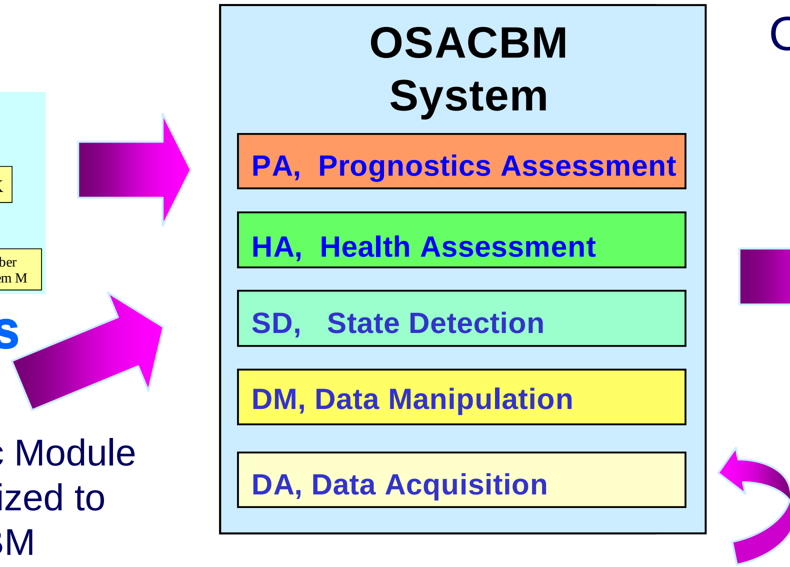
Propulsion Control Goals

- Aircraft Integration
- Helo Flight Control Integration
- Thrust Vectoring
- Vertical Lift
- Heat Management
- Generator Control
- Solid State Power Distribution
- Engine Control Functions
- Starter control
- Fuel Control
- Exhaust Nozzle Area
- Variable Guide Vane Geometry
- Propeller control
- Technology Insertions
- Distributed Controls
- High Throughput Processing
- Mass Data Storage
- Model-based control / EHM
- EM Motor / Actuation Control
- Energy Harvesting Sensors
- Wireless data transfer

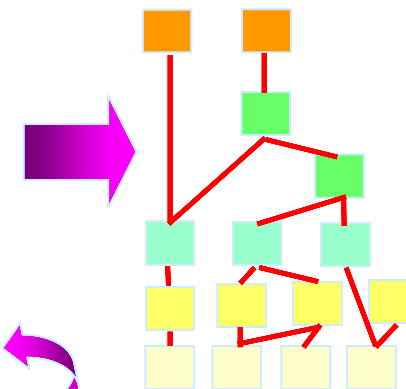
Open S/W Architecture Provides Modularity & Reduced Integration Costs

Functional Architecture



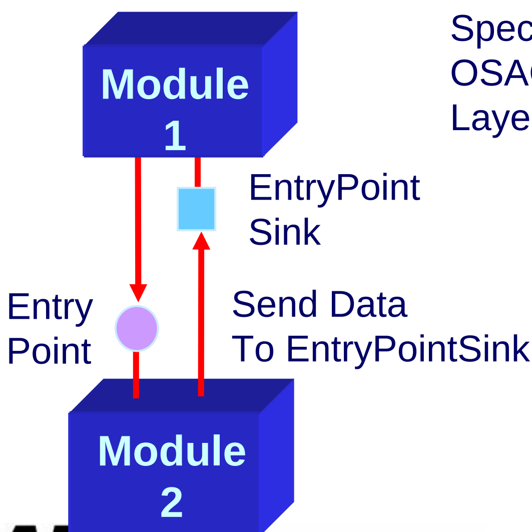


Onboard/Off-board Application



Generic Module defines I/F Protocols

Generic Module Specialized to OSACBM Layers



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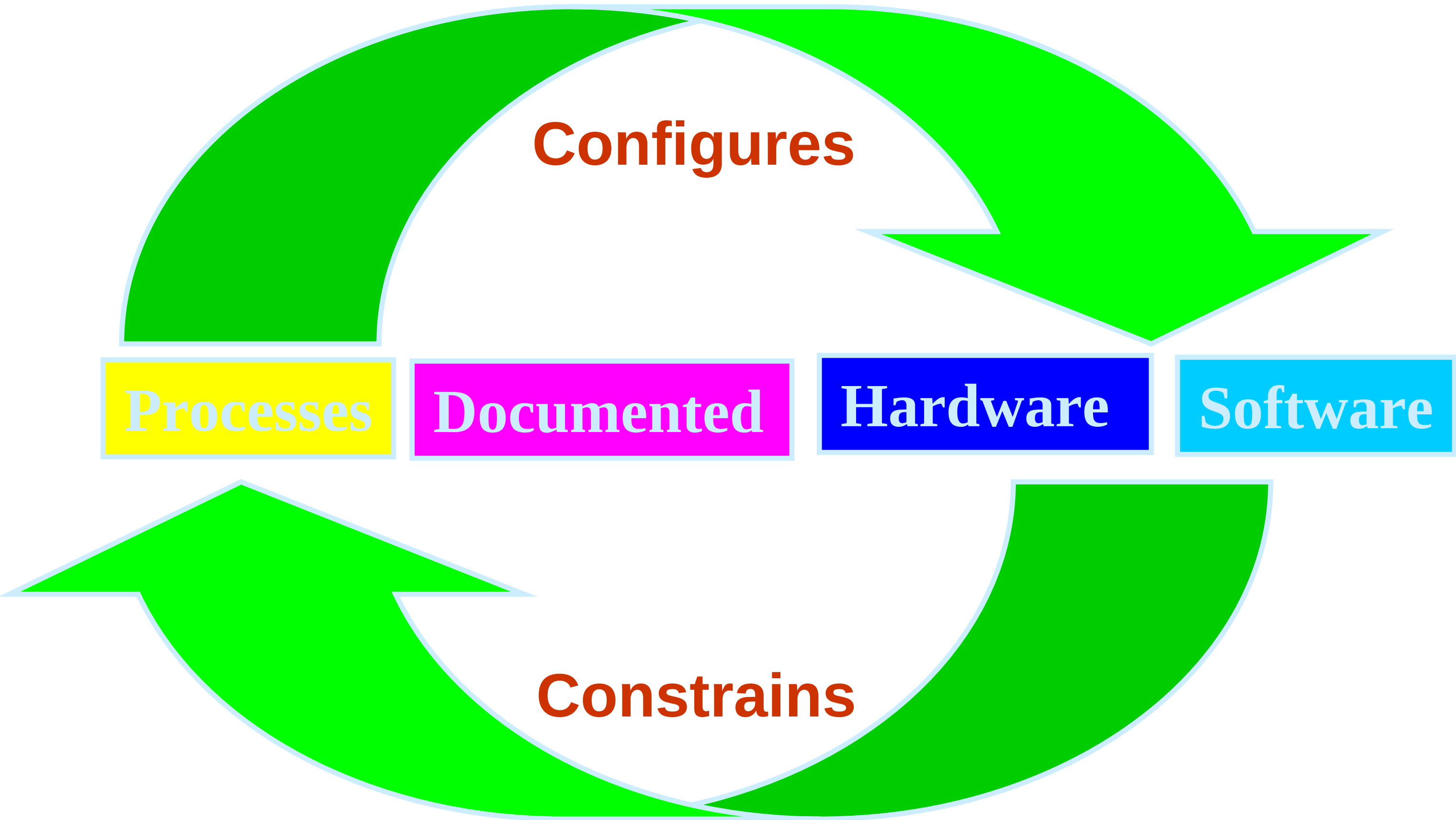
5 Colors of Modules 4 Types of Data

- **Configuration:** Account for Modules in System
- **Data Event/Data Event Sets:** Domain Data (Processed Signal, Diagnostic, Prognostic)
- **Explanation:** History/Data associated with an event
- **Control Vector:** Control reporting/data inputs from other modules
- **Application Specific:** Special purpose for domain.

UF DESIGN PROCESS:

Using COTS as much as possible …

Evolutionary Development Process…



COTS *IS* King… Define and Refine the Process and Configuration

THE SOLUTION-FUTURE SYSTEMS
Pro-Active Obsolescence Planning is needed

- TASK I (DESIGN INFORMATION)
  - Emphasize the Need to Understand System and Performance Requirements
  - Evaluate architectural options
  - Trade studies that drive electronic part selections
  - Obsolescence planning
- TASK II (DESIGN ANALYSIS)
  - Proper analyses to support architecture design
- TASK III (ENGINE LIFE MANAGEMENT)
  - Addressing obsolescence issues on fielded hardware

Pro-Active Approach to Obsolescence!

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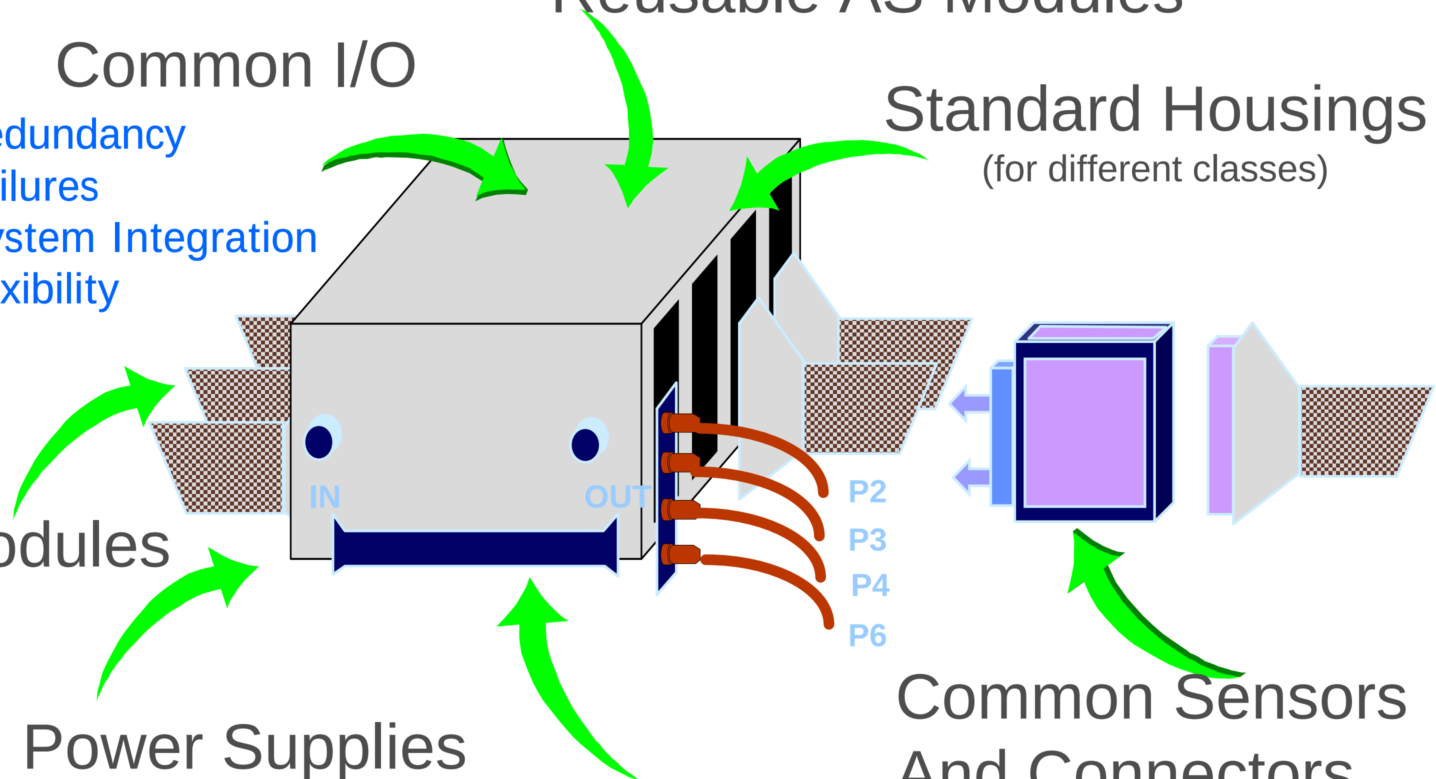
UF CONFIGURATION / STRATEGY
Different Classes of UF…

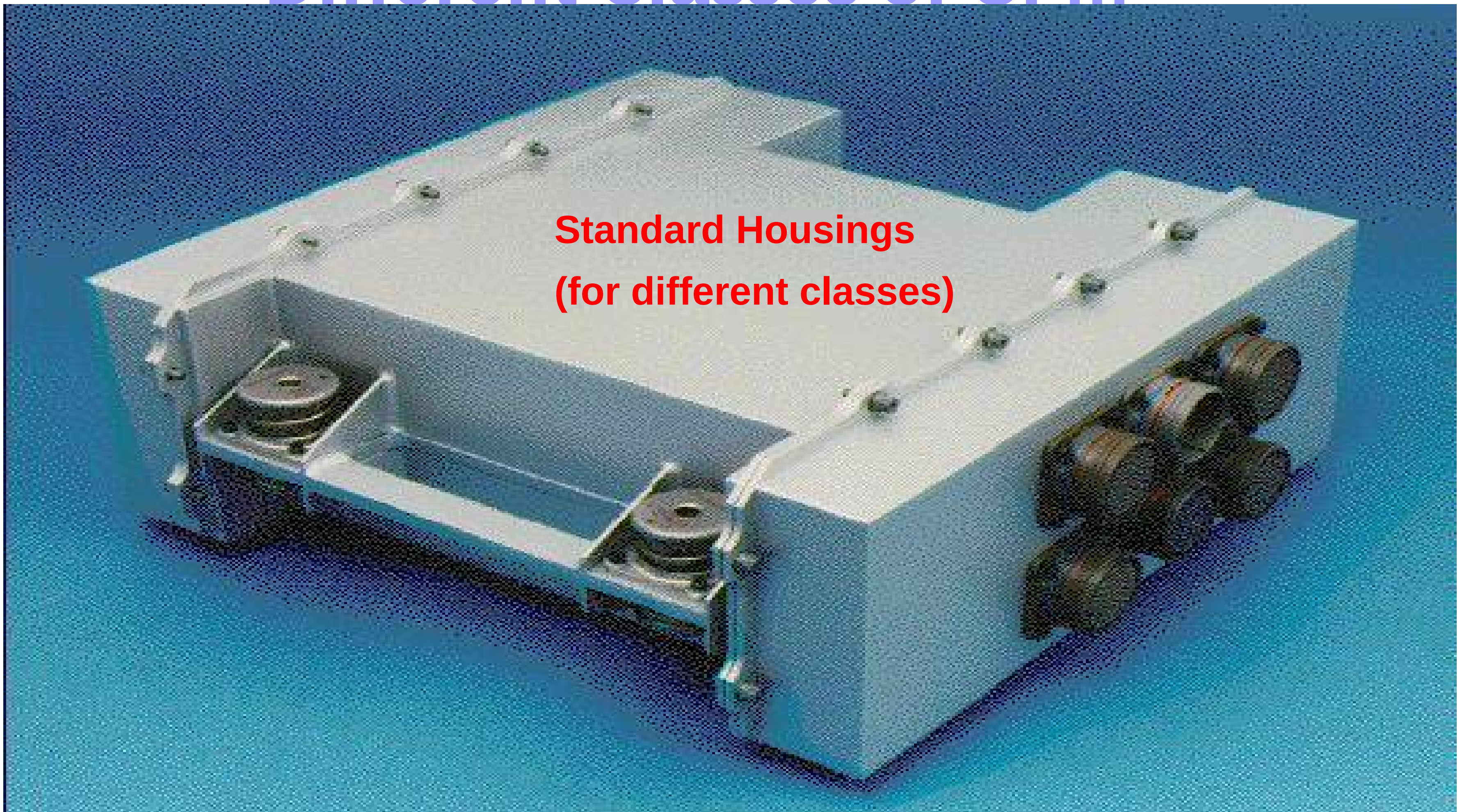
Standard Configuration – "Plug & Play" – One Unit Reconfigurable for many Thrust Class Engines

- High Levels of Redundancy
- Dispatch With Failures
- High Levels of System Integration
- Configuration Flexibility



"One size fits all" inadvertently smothers some!

UF Reconfigurable Platform
Different Classes of UF...



Open S/W Architecture Provides Modularity & Reduced Integration Costs

UF Benefit

in-flight mission preplanning, and increased reliability, reduce ownership costs, increase availability, and reduce the number of required spares.

Systems Engineering Process crucial to assimilate disparate data types

System data availability plays key enabler in defining prognostic horizon

Open Systems approach required to maximize architectural benefits

Easier said than done on Legacy Fleet

UF benefits are remained to be explored… However, there are several potential benefits

Recommended Actions

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UF GOVERNANCE PROCESSES / STRATEGY

UF Mission, Vision, Strategy

↕

UF Architecture

FADEC Architecture Alignment

Processes	Systems	Data	Applications	Technology

↕

FADEC Technology Portfolio Management

Select	Control	Evaluate

↕

System Development / Acquisition Management

Req'ts	Design	Build	Test	Train	Implement	Maintain	Evaluate

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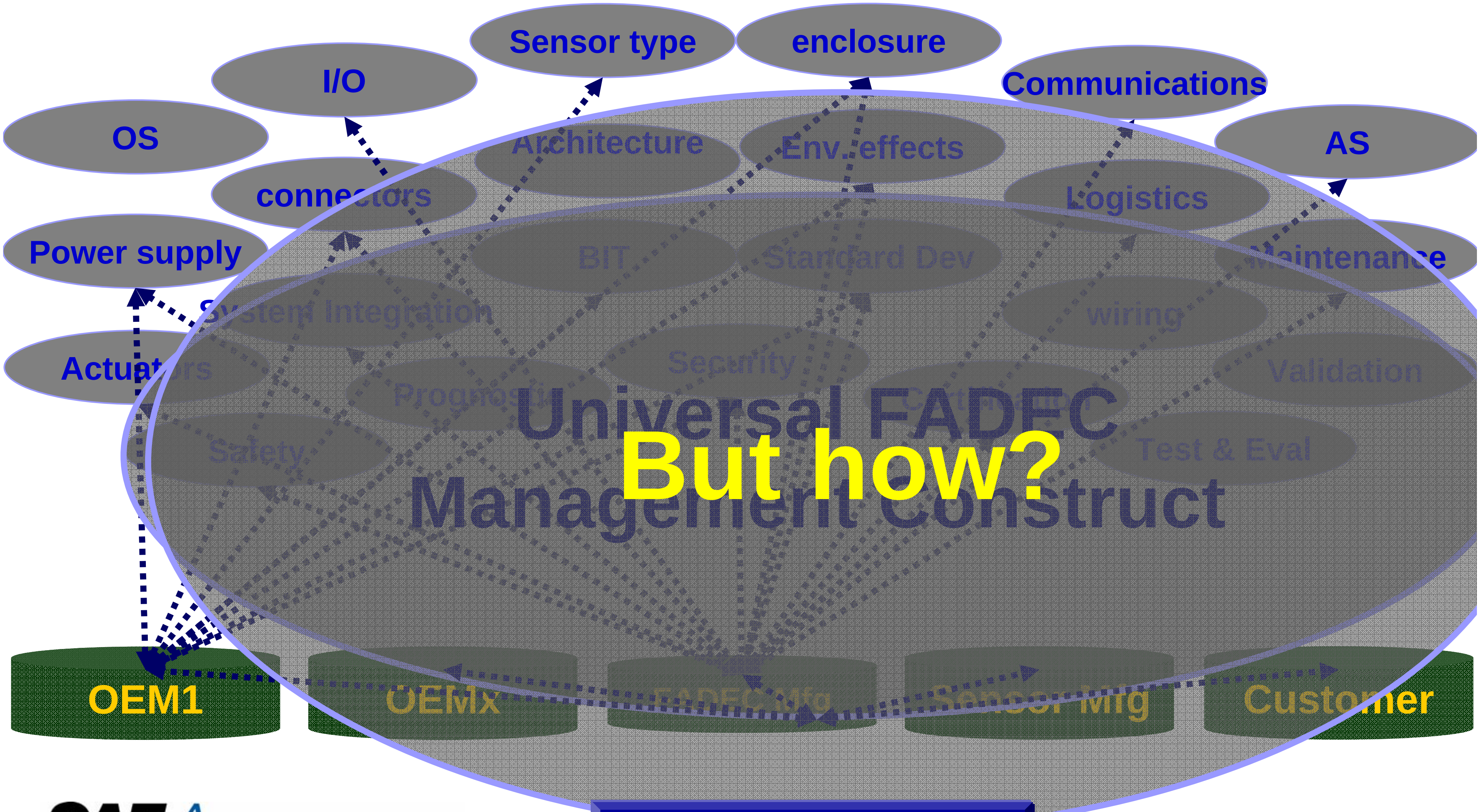
Stakeholder Collaboration / Integration



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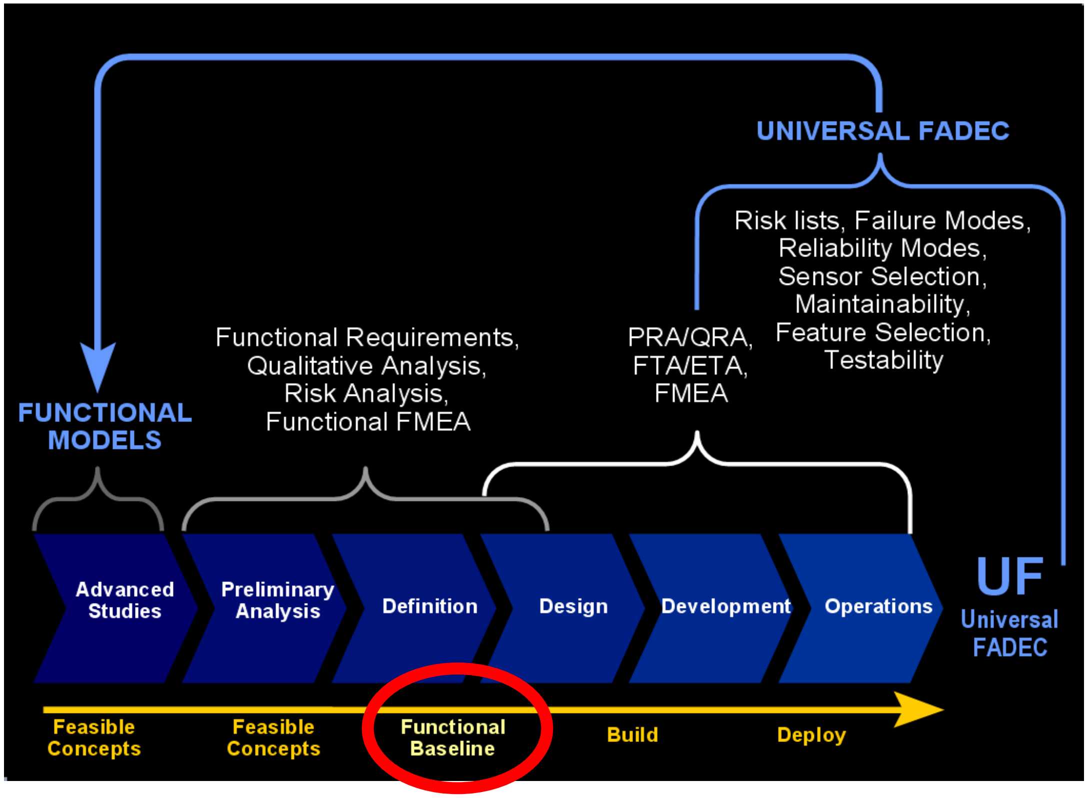
Integrated Solutions

THE FADEC DESIGN PARADIGM:

Changing the Way FADEC Design is Done



Proposed Design Paradigm Shift #1: Methodologies to integrate UF in the very early functional design stage by means of functional models and function-based failure and risk assessment

Proposed Design Paradigm Shift #2: Methodologies to assess impact of FADEC Federation Object Models (FOM) on the system level FOMs by means of multi objective multi level optimization, including all stakeholders in the mission lifecycle (design, maintenance, operations)

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Current Design Process Must be Changed!

THE UF DESIGN CHALLENGE

Key Challenge: Robust Integrated FADEC for Sustainability of a specific platform

Current Limitation: FADEC is typically retrofitted as an after-thought! As the demand for capability grows

Our only way out:

- “**DESIGN IN” THE FADEC FLEXIBILITY FROM THE BEGINNING across all platforms** with the Obsolescence in mind!

We currently lack methodologies and tools to achieve this!

Some successful attempts:

Specify Universal FADEC “shall” statements at the beginning of project

Integrate Universal FADEC design with system-level design

An S

UF Transformation requires commitment and decisive leadership

MITIGATING THE RISK OF FADEC OBSOLESCENCE

Minimizing the impact and cost of Obsolescence

Technology insertion can develop alternatives that leverage state-of-the art technology that not only resolves the critical part problem, but may also enhance performance and decrease cost. These alternatives will be developed through:

- Open system architectures / Common standardized I/O's
- Improve reliability (reduce Failures)
- Common and advanced materials / reusable software
- Decreased number of components among many programs
- High-reliability modules
- Improved manufacturing processes
- Making Obsolescence planning a part of the design engineering

If it is determined that a technology insertion resolution is potentially applicable, then should conduct a detailed design analysis and trade-off study to determine if the resolution is technically sound and economically feasible, and make sure the 3rd party would be able to make some components.

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Vision for Next Generation Controls: Intelligent, Adaptive, Modular & Distributed

Rationale

- Future Complex Missions Require
  - Intelligent, Adaptive Controls
  - Need to Adopt System Performance and Increase Availability Using All Available Control and Health Information
  - Validated Strategies for Real Time Control, Fault Accommodation and Remaining Life Assessment
  - Affordable, Reusable Implementations
  - Reduced Complexity
- Distributed Architectures Have Potential for
  - Scalable, Modular Open Architecture Building Blocks
  - Development Resource Optimization
  - Modular Partitioning of Complex Functions

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Future Generation Controls are:
Intelligent, Adaptive, Modular & Distributed

Vision for Universal FADEC Architecture

Decomposition of the Engine Control Problem into FUNCTIONAL ELEMENTS results in MODULAR components. These components create the building blocks of any engine control system.

MODULARITY

- **COMMONALITY**
- **EXPANDIBILITY**
- **SCALABILITY**
- **FLEXIBILITY**

- **OBSOLESCENCE MITIGATION**
- **LOWER PROCESSING REQUIREMENTS**
- **ENHANCED PERFORMANCE**
- **LOWER WEIGHT**
- **REDUCED COST**

The use of OPEN SYSTEM STANDARDS enhances benefits by leveraging the greatest possible market for components .

Summary

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UF Advantages
– Modularity, Flexibility, Adaptability, …

Modular system development, support, and evolution

- ✓ A different team designing each node
- ✓ Well-defined, tightly enforced interface (system message formats)
- ✓ Can upgrade individual models and limit effect of changes on rest of system

Limits competition for resources among different features

- ✓ Can add computing I/O power incrementally
- ✓ But, wastes resources on a node that might be inactive most of the time
  - – Difficult to "time share" computing resources

Reduces interactions

- ✓ Easier to make worst-case guarantees on a per-module basis
- ✓ Can re-certify only modules that have changed
- ✓ Can have "critical" and "non-critical" modules, reducing certification effo

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UF Advantages are yet to be proved for Propulsion System…

Summary

Incentivize and standardized Controls and accessories components across different platforms

- Vigorously implement policy, incentives and guidelines for using common / advanced components in controls and S/W, including sensors
- Control the life-cycle cost from the beginning
- Use only performance specifications
- Spiral upgrades and life cycle support
- Use Modular open Systems Approach

Long standing barriers and disincentives must be removed to take full advantage of the Universal FADEC technology to be transition into AF capabilities

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TAKEAWAY…

- Enable change
- Fund and execute rapid-response demonstration programs to build a broad C&A experience base
- Create mechanisms to increase awareness of future commercial technology and capabilities to transfer into propulsion
- Invest in R&D to increase the mutual compatibility of military operating environments and commercially produced components.
- Experiments and rapid response demos in C&A should be encouraged
- Using commercial controls parts and subsystems including S/W should be encouraged to reduce cost and maintain Technological superiority
- Use of commercial design standards and participation in standards setting bodies.
- In UF architecture much of the Hardware AND Software can be reused in the system AND across engine platforms

UF requires commitment and decisive leadership

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Summary Of Other UF Advantages

Flexibility

- ✓ Can modify or upgrade systems by changing components

Robust data transmission

- ✓ Digital network lets you use error coding, controlling noise on signals

Simpler to build and maintain

- ✓ Single bus means you can't hook the wrong wires up – there is only one "wire"!

Enables fault tolerance

- ✓ A single CPU is a single point of failure
- ✓ multiple CPUs support fault tolerance

Improves safety certifiability

- ✓ Separate CPU for critical functions means non-critical CPU can't cause safety faults

Take a fresh look at UF and see what it can offer to you…

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Thank You !

The End

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BACK UP

UF Platform Advantages – Modularity, Flexibility, Adaptability, …

Modular system development, support, and evolution

- ✓ A different team designing each node
- ✓ Well-defined, tightly enforced interface (system message formats)
- ✓ Can upgrade individual models and limit effect of changes on rest of system

Limits competition for resources among different features

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UF Advantages are yet to be proved for Propulsion System…

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DOD MANDATES

DoD/AFMC DMSMS Program

Diminishing Manufacturing Sources and Material Shortages (DMSMS) is the loss or impending loss of manufacturers of items or suppliers of items or raw materials. The military loses a manufacturer when that manufacturer discontinues or plans to discontinue production of needed components or raw materials. ***Source: DoD 4140.1-R Section 3.6, May 2003*** DoD Instruction 5000.2, Operation of the Defense Acquisition System, DoD Directive 4630.5, Interoperability and Supportability

Identification and implementation of common processes and effective tools across AFMC and DoD will result in cost avoidance and cost savings

GOVERNMENT OPEN SYSTEM MANDATES DoD MANDATES

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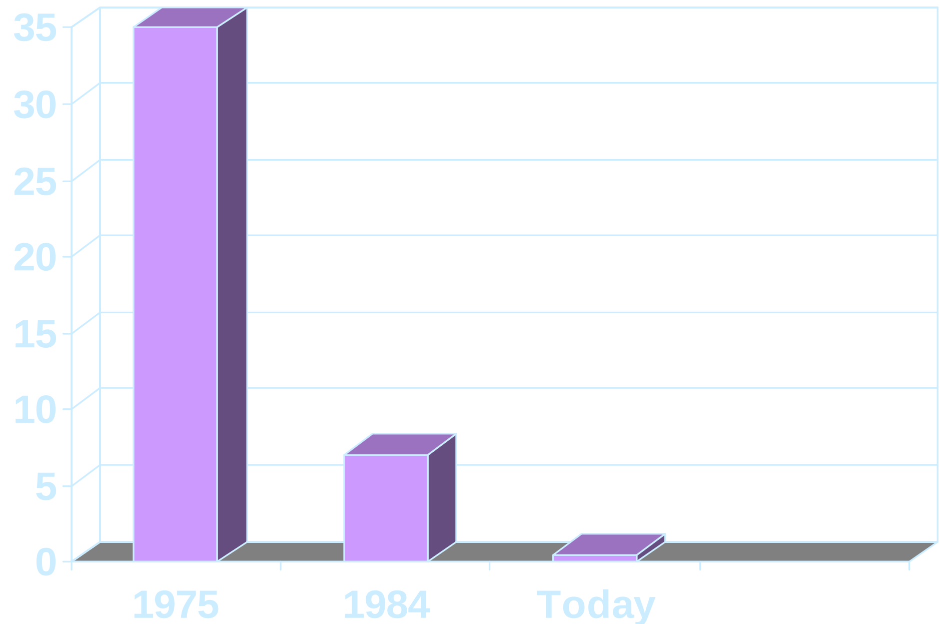
MILITARY PURCHASE NEEDS / ISSUES

Military Purchases of Total Semiconductor Industry Output

Serving the Military's Needs Involves Low Production Volumes with Stringent Manufacturing Requirements



Ref: Hamilton & Chin, "Aging Military Electronics: What Can the Pentagon Do?", National Defense Magazine, Mar 2001

Military Purchases no longer dictates the market!

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