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STATUS, VISION, AND CHALLENGES OF AN INTELLIGENT DISTRIBUTED ENGINE CONTROL ARCHITECTURE (POSTPRINT)

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Structures and Controls Branch
Turbine Engine Division

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Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture

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ABSTRACT

A Distributed Engine Control Working Group (DECWG) consisting of the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA)–Glenn Research Center (GRC) and industry has been formed to examine the current and future requirements of propulsion engine systems. The scope of this study will include an assessment of the paradigm shift from centralized engine control architecture to an architecture based on distributed control utilizing open system standards. Included will be a description of the work begun in the 1990's, which continues today, followed by the identification of the remaining technical challenges which present barriers to on-engine distributed control.

INTRODUCTION

The incentive for more advanced engine control systems is motivated by many influencing factors including increased performance, wider operability, and reduced life cycle cost. To address these needs increasingly sophisticated electronics have been incrementally added to the engine control system without a full, fundamental reconsideration of the overall architecture. This approach, while successful to some extent, has also exacerbated some inherent weaknesses.

This paper defines an approach for identifying the drivers impacting control system design and the means to make a value-based assessment of the impact of those drivers. It recognizes the technical obstacles that must be overcome, and a means for identifying useful new technologies. From within the Working Group structure, this paper recommends a process to lay out a roadmap for development and assessment of these technologies through a Government/Industry partnership.

From the late 1980's through 2003 the Integrated High Performance Turbine Engine Technology (IHPTET) initiative was jointly conducted by the United States Army, Air Force, Navy, NASA, and the Defense Advanced Research Projects Agency (DARPA). Two of the goals of this program, were to double turbine engine thrust-to-weight ratio while reducing production and maintenance costs on the order of 35%. In a study by Lewis [1], a compelling case was made that the engine control system is both a major factor in achieving future propulsion system goals but was also a major constraint in their realization. While recounting past progress in aero engine technology, Ballal and Zelina [2] described how future engine performance enhancements will be made. Key to these improvements will be the significant expansion of engine control responsibilities. Today, the most significant question remains of how will aero-control systems meet the challenges of the future propulsion systems?

Under any circumstances, the development, certification, manufacture, and maintenance of aero-engine control systems are a difficult and costly endeavor. Similar to process control applications, the performance of the overall system is dependant on the responsiveness and capability of the controls. The constraints which govern the implementation in an aero-engine system, however, are perhaps unlike any other application. Jaw and Garg [3] provided insight into how system designers have addressed this challenge in the past. Progress has not been easy and the application of new technology is typically delayed due to difficult system design constraints.

Today, in industry, there is what amounts to a revolution in control system design methodology and implementation. This revolution is a direct outgrowth of the dramatic progress in electronics and the use of open system standards in the development of new products and systems. The question of how the new challenges of aero-engine development will be met lies in the ability of control system engineers to adopt these new technologies.

Distributed control is a mechanism for the proper implementation of systems engineering processes in aeropropulsion engine systems. The distributed control approach is inherently more powerful, flexible, and scaleable than a centralized control approach. In the long term, businesses can achieve greater efficiencies and expect higher rates of return on investment by implementing this technology. At the same time, customers can expect greater value because new engine control technology will have fewer barriers hindering its implementation. This technology also offers effective strategies for the mitigation of obsolescence issues. Whereas centralized control effectively limits design choice, distributed control is about providing choices that add value to engine control systems. This includes the use of centralized control strategies where they are most appropriate, such as in small engines. This is explained in detail in the Vision section.

There are barriers to the implementation of fully Distributed engine Control Systems (DCS) primarily due to the limitations of electronics in high temperature environments. Continued advances in silicon on insulator technology have made available a range of analog and digital electronics, sufficient for most DCS functions, which can operate up to 225-250 °C. Further work is required on interconnects and failure modes to ensure acceptable life at needed temperatures, and for expected thermal transients. Silicon carbide technology holds the potential for very high temperature capability, but has not progressed sufficiently beyond simple junctions. Full DCS functionality can not be achieved using silicon carbide at this time. Silicon carbide power transistors and diodes can, however, be used for power output driver circuits.

These barriers do not preclude the partial implementation of distributed control and many opportunities currently exist to advance the technology and understanding of such systems on propulsion engine systems. These barriers, and a roadmap to negotiate the path toward fully distributed engine control systems, are included in the Challenge section of this paper.

BACKGROUND

In early aviation [3], engine controls were based on hydro-mechanical governors for fuel metering. As engine performance improved, the mechanical controls became larger and more complex, eventually reaching the point were they were no longer adequate. Some vacuum tube electronics were used prior to the 1970's, although not very successfully. During the 1970's, as solid state electronics were advancing rapidly, analog and digital circuits were used for high level supervisory control, trim, and other non-critical functions. Reliability was an issue which prevented their use in mission critical functions but the advantages of using electronics were, in almost every other aspect, readily apparent and their use steadily grew.

As the flexibility and accuracy of digital electronics overtook their analog counterparts, the impact of electronic controls progressed from performance improvement and weight reduction to decreasing the cycle time to add or modify control features during engine development. Modification of the control system through software was the key. Eventually the Full Authority Digital Electronic Control (FADEC) became the norm. Presently, this control system architecture accounts for 15 to 20% of total weight and acquisition cost of the engine [1].

A critical motivator for digital electronic propulsion control was the emergence of digital control and communications on aircraft. The designers of new aircraft in the 1980's moved to digital electronics and the glass cockpit for enhanced flight management. The status quo, where the engine sensors drove dedicated instruments in the cockpit and the pilot responded through mechanical linkages and electrical switches to set and limit engine speed, turbine gas temperature, and fan pressure ratio (or prop torque), became unacceptable. The airframe systems engineers demanded that the engine manufacturers take back the responsibility for setting and limiting thrust (power) as part of the engine scope, and required digital communication with the new digital flight management systems.

There continues to be new imperatives for engine-airframe system integration. The architecture of both commercial and military aircraft is rapidly moving away from the classic functional segregation of individual utility and mission systems. Data acquisition, control and execution of diverse functions are dispersed across general purpose input/output interfaces and computational assets, knit together by shared redundant data busses. The arbitrary partitioning of propulsion control from other aircraft systems results in sub-optimal propulsion and air vehicle performance. However, this integration will also result in greater functional interdependence, requiring an integrated approach to failure/fault accommodation and redundancy management, a challenge that we barely comprehend at present.

In a flight vehicle, weight is an ultimate constraint because of its direct impact on performance and fuel consumption. Overall cost of ownership is just as significant for both military and commercial engines. In military systems, the recurring costs of training, maintaining, and supplying a large and incompatible fleet is a huge burden. In commercial vehicles the initial cost due to development and certification are major factors in affordability in a highly competitive market, as are the recurring costs of maintenance and fuel burn. In all cases, electronic component obsolescence is a major concern because the production life of many electronic components is far less than the operational life of a flight vehicle.

The time is right for considering new paradigms for aero-engine control system development and the merging of propulsion controls with the state-of-the-art airframe control architecture. However, for any and all solutions there will be very little tolerance for compromise in terms of control system performance, weight, and overall cost.

The goals of the DECWG are to define the roadmap to a change in aero-engine control system development for the purpose of increasing performance, reducing weight, and lowering the overall cost of ownership.

FOUNDATIONAL DEVELOPEMENT

Much has been done in the past 20 years to address the issues with aero-propulsion control system design. The following is a brief synopsis of the major efforts, sponsored by the US government but with substantial involvement and investment by industry, aimed at migrating from centralized engine control architecture.

Lightweight Distributed Systems (LDS)

In the early 1990's, the Air Force Research Laboratory (AFRL) funded development of high temperature electronics for the Lightweight Distributed System program. This program specifically targeted weight reduction of the electronic assemblies comprising the various components and subsystems of engine Controls and Accessories (C&A). In particular, changes in the sensor and communications system were affected by the proposed developments and resulted in a well-recognized potential for weight savings in this portion of the C&A system. This research represented a major step forward for the concept of embedding intelligence in hot sections of high performance aircraft engines. Using government and industry-funded Independent Research and Development (IR&D) efforts as a base, this dual-phased program accomplished the early demonstration of technology and provided significant advances toward high-temperature integrated electronic circuits.

Phase I included documentation of design tradeoffs and the detailed design and fabrication of electronics for engine flame detection under high ambient temperature conditions [4]. Among the significant developments were a flame detector element, high temperature integrated circuit amplifier, and capacitors, among other components.

The Phase II effort included progress in the enhancement of silicon carbide (SiC) technology by developing the elements and the processing steps required to make SiC integrated circuits (IC's). The elements include the passive circuit components, specifically metallization, resistive elements, and monolithic capacitive elements which, in addition to the metal-oxide semiconductor (MOS) logic gates, make an IC possible.

High Temperature Electronic Components (HiTEC)

In the 1990's at the AFRL, a 14 member consortium was formed among industry and academia to explore dual-use (military and commercial) technology development of high temperature electronics. The program goals of HiTEC were to develop and commercialize an extensive set of high-temperature (200 ^{o}C) integrated circuit components based on silicon-on-insulator (SOI) technology. The impetus of the HiTEC consortium was the development of a sophisticated distributed control system architectures based on components that could be embedded close to the target application in a hostile environment.

The specific program elements of HiTEC were:

1. Design, construct and test "smart" actuator modules on an aircraft engine;
2. Design, construct and test a "smart" industrial motor with embedded control;
3. Develop automobile applications for commercialization, with the primary goal of driving component cost reduction by increasing component volume;
4. Develop an enhanced set of software tools that accurately predict the reliability of high temperature components and systems.

COntrolled Pressure-ratio Engine (COPE) Program

Between 1996 and 2000, the feasibility of a distributed engine control system was demonstrated in the USAF PRDA III COPE Distributed Control System Program. A team of four companies; GE Aviation, Honeywell South Bend Group, Honeywell Solid-State Electronics Center, and Rolls-Royce North American Technologies Inc. completed the program in synergistic cooperation. The objective of the program was to develop a smart actuator for the distributed control system in an avionics package hardened for the extreme environment of the turbine engine, and to validate the functionality and environmental capability of smart devices. Using conventional silicon-based electronics, a functionally complete distributed control system was successfully demonstrated in a "dry rig" setup where a computer simulates the operation of the jet engine.

The added weight incurred in environmentally hardening silicon electronics for turbine engine technology served to focus additional effort on high temperature electronics. Numerous government and industry sponsored research activities were directed at SiC and SOI technology. In the mid-1990's, GEAE recommended SOI to the Air Force as the technology of choice for the distributed control system due to the maturity and size of the industrial base. Subsequently, SOI technology has matured through a number of DARPA Dual Use Application Programs (DUAP) which demonstrated the feasibility of lightweight, rugged packaging technologies using SOI components. There remained, however, two key tasks which were not investigated.

1. The demonstration of high-temperature, “smart” sensors for a complete sensor suite necessary to implement the distributed control system.
2. The integration and engine testing necessary in order to mature the technology to the technology readiness level (TRL) for product transition.

Propulsion Instrumentation Working Group (PIWG)

AFRL funded the development of a high temperature dynamic pressure transducer work package under the Propulsion Instrumentation Working Group. This effort involved the collaboration of Rolls-Royce, Williams, Siemens, Pratt & Whitney, Honeywell, Kulite Semiconductor Products Inc., and Wright State University. Kulite Semiconductors was successful in developing a packaged silicon-based transducer capable of operating at temperatures up to 1100 ^{o}F and had nearly completed an initial SiC based transducer that was expected to operate at up to 1200 ^{o}F.

All engine companies completed the required rig and engine testing of the available silicon based transducers. In most cases the result was failure of the device. The mean time before failure (MTBF) was on the order of 10 hours and all failures were identified as cable and interconnect issues to the transducer.

Versatile Affordable Advanced Turbine Engine (VAATE) Initiative

Today, the controls work initiated under the IHPTET program continues through the Versatile Affordable Advanced Turbine Engine (VAATE) Initiative. This effort addresses future propulsion system instrumentation work being accomplished by a collaborative team that includes, General Electric, Pratt & Whitney, Rolls Royce, Honeywell Engines & Systems, Williams International, NASA Glenn Research Center, and Siemens Westinghouse Power Corporation. The Ohio Aerospace Institute (OAI) is the facilitator of this development team. The goals of the advanced development effort are to fabricate and test robust high temperature (1150 ^{o}F) sensors for turbine engine applications and facilitate technology transition of the results to aerospace and commercial engine applications.

NASA Glenn Research Center Initiatives

Kulite Semiconductor Products and the NASA Glenn Research Center worked together to develop silicon carbide (SiC) pressure sensors for use at high temperatures. At temperatures above 850 °F, silicon begins to lose its nearly ideal elastic properties, so the output of a silicon pressure sensor will drift. SiC, however, maintains its nearly ideal mechanical properties to extremely high temperatures. Given a suitable sensor material, a key to the development of a practical high-temperature pressure sensor is the packaging. The durability of the leadless SiC pressure sensor was demonstrated when two 930 °F sensors were tested in the combustor of a Pratt & Whitney PW4000 series engine. Since the gas temperatures in these locations reach 1200 to 1300 °F, the sensors were installed in water-cooled jackets. This was a severe test because the pressure-sensing chips were exposed to the hot combustion gases. Prior to the installation of the SiC pressure sensors, two high-temperature silicon sensors, installed in the same locations, did not survive a single engine run. The durability of the leadless SiC pressure sensor was demonstrated when both SiC sensors operated properly throughout the two runs that were conducted. [5]

Under the NASA Fundamental Aeronautics program a high-temperature silicon carbide (SiC) semiconductor transistor was fabricated, packaged, and electrically operated continuously at 500 °C for over 2000 hr in an air ambient. For the first 500 hr of electrical operation, less than 10-percent change in operational transistor parameters was observed. This demonstration of 500 °C transistor durability represented an important step toward significantly expanding the operational envelope of sensor signal processing electronics for harsh environments such as the high-temperature regions of combustion engines. Wide band gap transistors had not previously demonstrated sufficient long-term durability when electronically operated at these high temperatures to be considered viable for most envisioned applications.

More recently, fabrication of a wafer with silicon carbide (SiC) junction field effect transistors (JFET's) and small-scale integrated logic gate circuits using NAND and NOT gates have completed initial operational tests at 500 °C. The development of 500 °C integrated electronics will enable performance-enhancing sensing instrumentation and control circuitry to function directly in hot areas of jet engines.

Under the Aviation Safety – Integrated Vehicle Health Management (IVHM) program, wireless sensing devices integrating SiC transistors and high temperature passive components have been demonstrated at temperatures of 200 ^{o}C.

VISION

The vision of future engine control system architecture should be developed with knowledge of the past and an eye toward the future requirements of engine and aircraft systems. In looking at the past, we seek to address the known deficiencies of the centralized engine control architecture. In looking forward we expect to develop a control architecture which accommodates future needs while minimizing the impact on existing systems. Using standards-based system design processes each new generation of engine controls should build upon and compliment previous achievements in a manner which helps preserve the knowledge base in all life cycle phases of engine systems.

DECWG members approach the issue of control system architecture from a variety of perspectives. Issues such as fault isolation, weight, and component obsolescence are often cited as difficult technical problems which are frequently encountered during various life cycle phases of the engine system. In almost every instance, however, the impacts of these technical issues are stated in terms of cost and customer value. This reflects the reality that there is an engineering solution for almost any problem. However, the outcome is the result of a complex series of trade-offs which are designed to achieve an acceptable solution that maximizes customer value at an acceptable cost.

Each engine system is different, of course, because they have different objectives and reflect the current state of technology at any given time. For instance, very large engines may be designed to power large, long haul aircraft. The engine design reflects the fact that this type of vehicle spends a very large percentage of its mission profile at cruise conditions; therefore efficiency is of paramount concern. In contrast, short-hop aircraft may require a smaller engine and its mission profile may never allow it to reach cruise conditions. In this case operability may be of higher value to the customer. Every engine and its control system share similar issues to some extent, however, it is customer value which determines whether new technology is included in the system design.

In contrast, each engine control system is fundamentally the same regardless of application. Using the distributed control approach is inherently more powerful, flexible, and scaleable than a centralized control approach. Whereas centralized control is about limited design choice, distributed control is about providing choices to engine control system engineers including the use of centralized control structures where they are most appropriate.

Distributed Engine Control Systems Architecture - The concept of distributed engine control architecture should be more than just a hardware and software implementation. Distributed architecture is a design methodology which is intended to break the cycle of system interdependencies which exist under the centralized architecture approach. These interdependencies can be understood by examining this simplified sequence of design decisions as they unfold in a centralized engine control systems approach:

1. As Centralized control architecture is chosen it is implied that the FADEC will provide point-to-point connections to each system effector, i.e., sensors and actuators, and perform all processing functions in the system.
2. A portion of the FADEC processing capability is associated with direct interaction with the analog system effectors. This analog input/output (I/O) requires dedicated signal conditioning circuitry and analog-to-digital (A/D) or digital-to-analog (D/A) conversion within the FADEC for each system device.
3. Each system device requires multiple, independent electrical conductors to complete each circuit (power and signaling) and render the external device functional. Redundancy multiplies this requirement for circuit conductors. The ensuing wire bundle is shielded and terminated with a large connector at each end. The wire harness assembly impacts system weight and is difficult to route through the engine structure.
4. The need to minimize system weight forces the FADEC to be engine-mounted so that it is located in relative close proximity to the system effectors, thereby limiting wire harness length and weight
5. The engine-mounted FADEC enclosure must be designed to protect the fragile, high performance electronics from extremes in temperature; high vibration and shock loads; water, salt spray, hydrocarbon fuel and solvents; lightning and all forms of electromagnetic interference and susceptibility. The environmental concerns and the need for minimal weight drive the FADEC package to be highly optimized and customized for each engine system.

In this example each preceding design decision narrows the choices available to the system designer causing a cascade of interrelated events. Furthermore, any change or addition to the system hardware can cause changes in other parts of the system, such as the FADEC circuitry and wiring harness, which in turn, can require re-evaluation/re-certification of the entire control system.

In DCS the objective is to create control elements which perform discrete functions within the context of the overall system. Each functional element interfaces to the larger system via a well-defined interface specification which isolates the function and the larger system from changes in each other. The exact hardware implementation of the functional element or the system is irrelevant as long as the interface specification is maintained. Each element in the distributed system is defined by its input parameters, its output parameters, and the function which relates the output to the input.

In practice, the distributed architecture typically uses 'smart' devices to provide the functional elements. For instance, smart sensors provide digital data about some system parameter as opposed to the raw analog output of a traditional sensor which must be digitized, linearized, and interpreted by the FADEC processor. 'Smart' actuators can close the control loop around actuators and even execute control laws based on data it collects or receives from the larger system. The function of the FADEC is to perform higher level control around the system elements.

Distributed control does not imply a specific architecture; instead clustering of different system elements can be arranged in any configuration which best maximizes customer value. This is illustrated in Figure 1 which depicts the visibility of system functions in a distributed system. Figure 2 shows several system architectures that were investigated under the HiTEC program. Similarly, multiple levels of functional partitioning can be applied to system sensors and actuators. These were also described by HiTEC as fully distributed, partially distributed, and minimally distributed and are shown in Figure 3.

Open System Standards - The use of open system standards is not a prerequisite for distributed engine control technology. Its use, however, is strongly encouraged because of the many advantages which can be realized through collaboration and cooperation. In an industry with limited resources due to relatively small volume production any economies of scale will greatly benefit both the engine manufacturer and the component supplier. Open systems interface standardization can and should occur for all electrical interfaces, especially communication and power distribution. In many instances it may also be feasible to consider mechanical interface standardization, in the form of component packaging, as well.

The real intellectual property which differentiates competitors lies in the implementation of the control element functionality. The use of open system

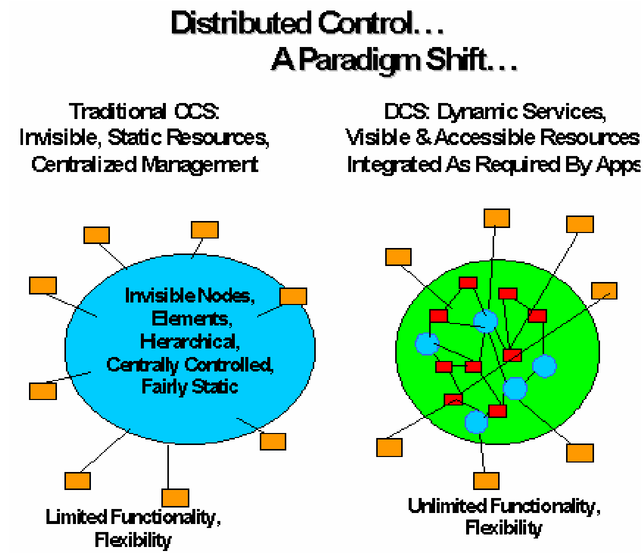

Figure 1: Distributed vs. Centralized control

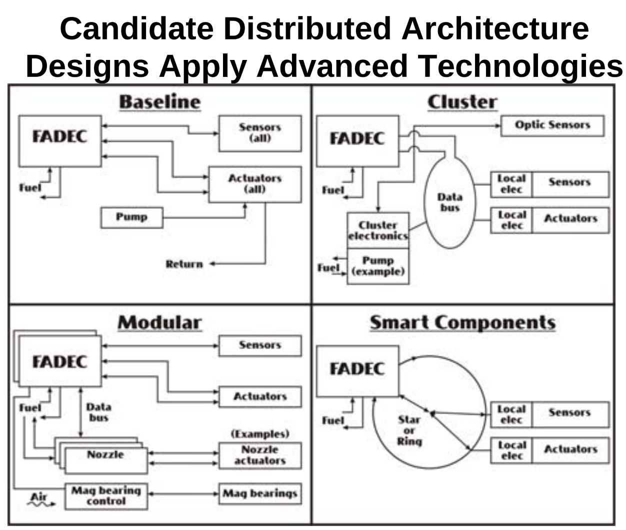

Figure 2: Distributed Control Architectures allows various system configurations.

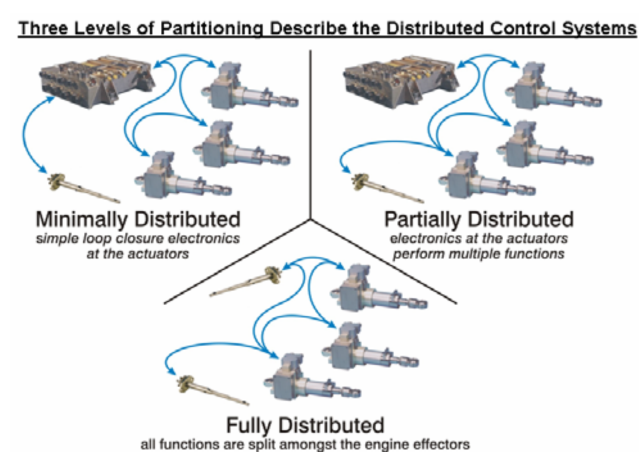

Figure 3: Functional partitioning is shown at three different levels in DCS (HiTEC)

standards affects the interface specification, not the function. Both engine system manufacturers and suppliers can differentiate their products by adding value to the product function without compromising the functional element's interface specification.

Distributed engine control is a technology which will be implemented in future propulsion systems regardless of the use of open system standards. At present, the industry is poised to begin this transition. There is now a limited opportunity which the DECWG seeks to exploit to coordinate the development of industry-wide standards for engine control system interfaces.

Modularity – Modularity is an attribute of distributed control system hardware and software. Modularity describes the functional compartmentalization of system components into the discrete building blocks which together comprise the larger system. A modular system can replace or upgrade any building block in the system without having to modify the remaining system. Modularity is enabled by the use of strong interface specifications which define the functional boundaries of system components.

In the distributed engine control environment this implies that any component in the system, perhaps a sensor, an actuator, or even the FADEC itself, could be modified or upgraded with a functionally equivalent component without having to redesign the remaining components in the system. An example of a modular design for a sensor and actuator is shown in Figure 4.

Modularity allows systems to be configured for current needs, and expanded as needs change in the future. DCS with its modular concept allows optimum integration into the customer's industrial environment. Modular Growth: In a centralized system, the system is upgraded to a newer faster-larger system as the application demand grows. The older-slower-smaller system is retired. In a distributed system, the system can

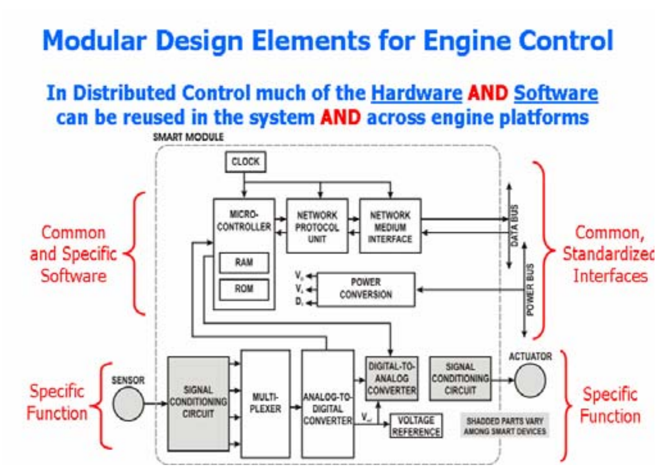

Figure 4: A modular design for a generic sensor and actuator (HiTEC –GE)

grow in increments as the demand grows. The existing hardware is not retired -- rather it is augmented with additional hardware. Most applications find it impossible to predict future demand for the system, so modular growth of hardware is a very attractive feature of distributed systems. The extreme argument for modular growth applies when no single system is big enough to handle the whole problem. In such cases, one is forced to use a several cooperating systems. A DCS using the modular technique allows new applications to be added to the system without disrupting existing applications. In addition, it gives clean high-level interfaces between the components of an application so that a service can be reorganized without affecting its other components or controllers.

In the present CCS, if a specific application requires an additional processor, the FADEC needs to be redesigned, and it will affect the entire system. You cannot simply make additional changes to the hardware or software. For any upgrading, one is stuck with that FADEC, unless it has upgrade capability.

Modularity here applies to both hardware as well as software. In the modular design of DCS, most components (hardware and software) are reusable. In addition, because modularity is a main means to reduce the system construction effort in the DCS, the applied software style should be able to support the implementation of certain functionality at module level. Besides functionality encapsulation, the component style should also be able to separate functionality from its implementation, such that the pure internal modification of one module will not affect other modules in the system.

A modular system allows the client to build a tailor-made system that fulfills his requirements without having to implement systems that are not needed. At the same time it makes it possible to add more modules or even renew individual modules at a later stage, without compromising the reliability or the economy of the b nodes/subsystems and limit the effect of changes on the rest of the system.

Obsolescence Mitigation - Typically, high-end electronic components (e.g. processors, communication interfaces, etc.) have production lives that span 10 to 15 years and may, in fact, decrease as future progress in electronics continues at its unprecedented pace. This has major impacts on engine control systems since the FADEC development-to-fleet insertion cycle can easily use half of the production life of the electronic components it contains. Early retirement of electronic components with little or no prior notice are not uncommon and can drive unanticipated FADEC upgrade projects which cost the industry tens of millions of dollars of unplanned funding, and have major financial ramifications in the short-term period in which the obsolescence must be addressed. The primary cost driver for FADEC obsolescence is the cost of re-qualification of the replacement system.

The modular approach espoused by distributed engine control can minimize the amount of hardware that has to be redesigned, re-qualified, and recertified for flight worthiness by isolating the obsolescent component within the functional module, thereby reducing the impact on the larger system. A distributed control system that partitions out obsolescence-prone electronics will increase the availability of the engine system for many years and have a significant impact towards reducing a major source of unplanned cost.

Commonality – Commonality implies the capability of reusing hardware and software elements across engine platforms. A common misconception of commonality is that system components will be used in applications for which they are less than optimally suited, reducing system performance and/or increasing system cost. However, modular systems, which are advocated by distributed control, can define distributed system components as themselves being modular. This functional decomposition into increasingly smaller functional elements provides many opportunities to share common hardware and software elements at scales which are appropriate for a given engine control system. This adds value by cost sharing development effort.

Expandability – When adding functionality to a centralized engine control system an increasing burden is placed upon the system processor which is commensurate with the complexity of the added functionality. In distributed control, processing is integrated within the functional element thereby limiting the impact of new components and subsystems on existing systems. Expanding the scope of the engine control system is more readily accomplished under distributed control because of the minimal burden imposed on the existing system.

Adding additional sensors or actuators to the distributed engine control system, whether it is for engine control or for health management, would be more easily accomplished. Following the modular format, additional system components can be integrated into the communication structure without impacting existing system elements, as long as the system bandwidth and latency specifications are not exceeded. New control algorithms and methodologies can be developed without changes to hardware systems as long as the availability of data, a parameter of inter-element communications, is not exceeded.

In a distributed architecture, all system elements are linked together virtually, regardless of their spatial location. More components, new sub-systems, updated micro-processors and controllers can all be integrated under a common architecture. Due to the virtual linkages, what were once physical boundaries between engine control and airframe control are now artificial limitations on processing elements. The location of processing components can be combined in a central location or distributed throughout the engine/airframe for purposes that best serve customer value.

Lower Processing Requirements - Presently in centralized control systems, the processing of system functions is executed in a sequential fashion by one or several powerful, high-speed microprocessors and associated digital logic components. As additional burden is placed on the control system, through more complex control law processing or additional sensors and actuators, the need for faster, more powerful processor and memory components grows. In distributed control this burden is spread out among system elements so that the processing requirement of the basic function is fulfilled by the distributed component itself. High level controllers, such as the FADEC, are relieved of much of the specific, low level processing associated with data acquisition, scaling and linearization which contribute to task switching and inefficiencies in computational execution. While more powerful processors are generally beneficial in control systems (except for electrical power consumption) the overall performance of distributed control systems are not as dependent on the processing capability of a single system element.

This fact has major implications in engine control applications. The choice of processing elements in the FADEC becomes much less restrictive in terms of cutting edge technology. The processing function itself becomes more general purpose, opening the possibility of satisfying system requirements with commercially available processing components which are available from a wide source of suppliers.

Scalability - Scalability is an attribute of DCS which allows for successive improvements and enlargements according to the needs of different engine platforms. Thus, a scalable control system can be implemented according to the needs of the engine system using some common components but augmented with others that satisfy unique requirements.

For example, DCS can be implemented on a large engine which may emphasize efficiency for long haul flight. It may require different sensors with different accuracy requirements and different actuators than a

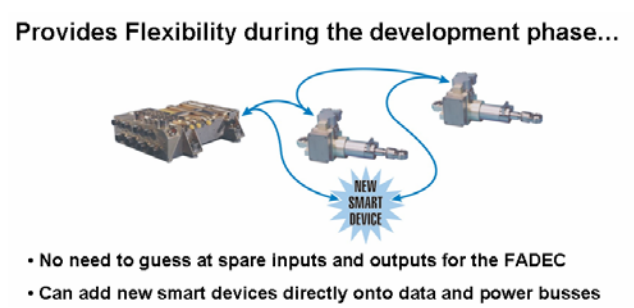

Figure 5: The flexibility of DCS enables changes in the system to occur more readily than in CCS.

small engine system which emphasizes operability. Yet both systems will take advantage of certain common control elements because all engines, regardless of their purpose, share some basic common principles.

Flexibility – DCS is the ideal solution for integrating processes when there are multiple control systems or sub-systems, or for segmenting control across units, providing the ultimate flexibility for both operations and control. DCS also provides the maximum flexibility for geographically distributed components. For example, it allows multiple actuators and sensors with some form of intelligence to be controlled through a central FADEC, as well as locally by “smart” sensors and actuators. In addition, during the development phase of design, any component can be modified or upgraded without significantly affecting other components as shown in Figure 5.

In today's highly competitive complex control design, however, FADEC manufacturers increasingly need the flexibility to cross traditional control boundaries to offer greater customization and tighter integration with Engine health management, power and thermal management, and to run more complex processes. The need for open system with greater flexibility is desirable.

Impact on Engine System Performance - Engine performance is a benchmark which measures thrust efficiency, fuel burn, emissions, noise, operability, safety, time-on-wing, etc. Engine control plays an increasingly important part in positively affecting all of these parameters of engine performance.

Changing the engine control architecture is seen as an enabling technology for aeropropulsion systems. For example, the implementation of a high-response, adaptive control technology, like compressor stability control, will most likely require closed-loop actuation based on high-response sensors. Integrating such a control into an existing FADEC would drive a major change to the system requirements and design of the control system.

Taking a broader view, the engine could be used as an airframe actuator for flight control. This would require a level of coordination not currently possible in present engine control systems. Using a distributed control strategy would enable a solution for the arguable boundary problem that segregates the engine from the airframe.

Impact on Engine System Weight - Engine weight is a benchmark which is typically evaluated as a ratio of thrust-to-total-engine weight. Many technologies, especially in materials development and aero-thermo-dynamics are effecting a reduction in total engine weight. Control systems, because they are continually being relied on for performance improvements are actually increasing in complexity, pervasiveness, and weight. As thrust to engine weight increases the impact of control system weight is effectively trending in the opposite direction.

Using alternate control system architectures, based on open system standards, will provide an opportunity to reduce the overall weight of the control system. The control system can be viewed as consisting of three major component groups; the FADEC, the wiring harness, and system effectors.

The FADEC weight can be reduced because the signal conditioning circuitry is removed from the unit (relocated to the remote nodes) and replaced with a standard, shared, communication interface. The function of the FADEC is limited to control law processing, and because its location is no longer dictated by harnessing restrictions, it can be located anywhere. Off-engine locations for the FADEC could enable its weight to be reduced due to a reduction in severity of the vibration and temperature environment experienced by the FADEC, as well as eliminating the requirement to design the FADEC mounting structure to endure the acceleration loads expected following a fan blade-out failure.

In the traditional CCS, as additional control systems components and accessories are added, the wiring harness becomes more and more complex. The increased complexity and wiring weight often results in difficulty during the original assembly of the FADEC control system and in any subsequent diagnosis and repair of the system. In DCS, complexity and weight of the wiring harness can be substantially reduced by eliminating the point-to-point analog connections between the centralized control law processor and the system effectors. Implementing a standard digital serial communication protocol to communicate between the various components of the DCS requires far fewer conductors in the cable harness. In general, DCS greatly reduces the amount of wiring through multiplexed communications and power distribution to save weight, wire cost and cable thickness. This simplification of the wiring harness also positively affects engine manufacturing and integration because it is physically smaller. There is also a substantial reduction in

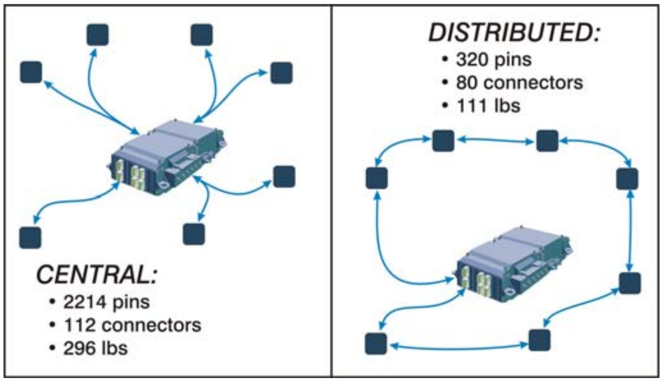

Figure 6: Expected wiring harness savings between CCS and DCS for the turbine engine.

reliability issues associated with many large connectors and their electrical contacts. Figure 6 shows an example of the expected wiring simplification which resulted from a trade study analysis.

A comparison of the different approaches to the wiring architecture for CCS and DCS in the turbine engine is shown in Figure 7. The CCS uses point-to-point connections while the digital communications employed in DCS allow sharing of fewer wires. Figure 8 shows a specific example of the wiring simplification achieved through the development of a smart engine control actuator in the HiTEC program.

System effectors, because they incorporate the signal conditioning circuitry and additional intelligence for communicating with the FADEC over the standardized interface, will increase in weight. The physical size and complexity of these circuits need to be minimized. Even with this redistribution of electronics to system effectors, the overall effect may be a reduction in control system weight, because of the significant amount of wiring associated with redundant feedback devices.

Total engine weight directly impacts engine performance. As the control system expands through new requirements and additional capabilities, the tendency will be to increase control system weight independent of the control system architecture. In the past, this has required the development of unique, highly engineered and optimized components and avionics specifically to meet the weight constraint. A major objective of the DECWG is to analyze and determine the weight benefit of centralized versus distributed propulsion systems.

<u>*Impact on Overall Cost of Engine Systems*</u> - Overall cost of the engine is defined by the phases of the engine life cycle, including development, production, and operation. Development costs are affected by the length of the design cycle including testing and certification. Production costs are affected by fabrication, integration, and the cost of materials and components. Operating costs are affected by engine performance, maintenance, and the logistical cost of stockpiling replacement parts.

Cost is a much more difficult parameter to assess partly because it affects multiple organizations in different ways. In the short term component costs are expected to rise because of the increased complexity of system effectors and the harsh environmental conditions. This can be offset somewhat because of the reduced cost of designing with components using standardized interfaces. System characterization should become more straight forward, predictable, and quantifiable. The ability to reuse components and software will reduce the non-recurring engineering costs. Costs to redesign and re-qualify FADEC hardware in the centralized control paradigm can be very significant, and costs to redesign electrical harnesses are not insignificant. Both of these costs are mitigated substantially due to the flexibility

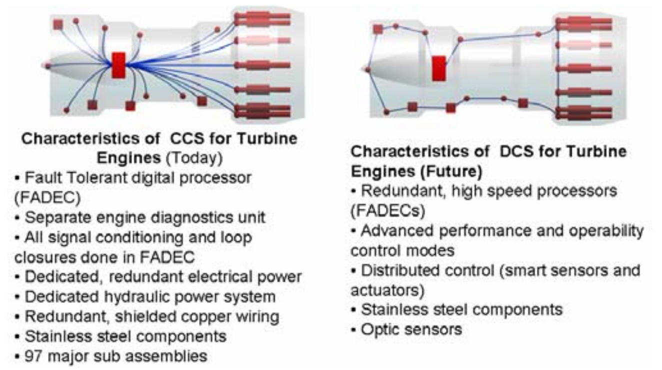

Figure 7: A Comparison of CCS vs. DDS for the turbine engine

possible with a modular, distributed building block approach.

In production, cost efficiencies through cross-platform

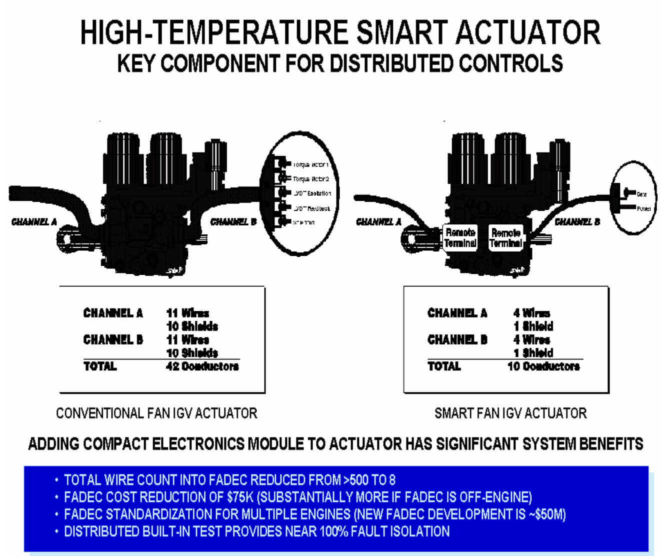

Figure 8: Comparison between conventional and

use of components and higher volume production are expected to lower manufacturing costs. The FADEC could feasibly be designed around military-off-the-shelf (MOTS) processing modules, based on open system specifications, which is a common design philosophy currently used in other critical systems. In general, higher volume production can lead to increasing reliability through both manufacturing knowledge and field performance data.

In the field, the ability to isolate system faults, due to functional compartmentalization and line replaceable units (LRU), will substantially reduce system maintenance costs. This is shown in Figure 9. Technicians will not require specific training for each engine system because diagnostics can be designed to conform to a uniform standard and the control system itself will perform most of the diagnostics. The capability for increased and better diagnostics could reduce the need for scheduled mechanical teardown of the engine.

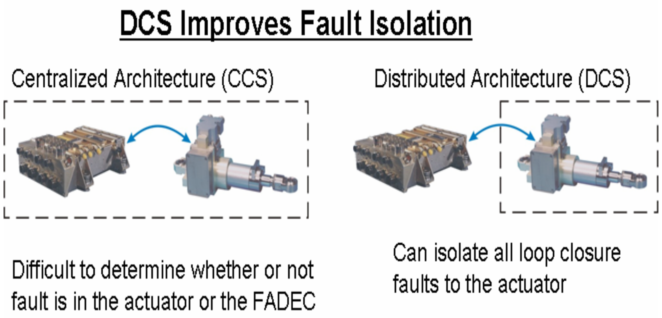

Figure 9: Fault isolation can be improved in DCS through clearly defined functional boundaries and a strong interface specification.

Perhaps most importantly, the logistics of stockpiling components and all their variants for the life of each engine system will no longer be a requirement. The design of components based on functional elements with standard interfaces will substantially reduce, or at least localize, obsolescence issues so that they may they may be addressed within the distributed control modules with lower overall system impact.

Once overcoming the transition cost to an engine control system architecture based on open system standards it is projected that overall cost will continue to decrease. Using open system standards is a key element, which will allow increased competition from suppliers, lowering cost and increasing performance and reliability.

The need to drive down weight and recurring costs is always present, but the system trades (expense) which must be made have to be tempered against customer values. It must be understood that other benefits have greater value to the customer, and these values may vary according to engine scale. Smaller engines are typically more sensitive to the weight and acquisition cost metrics, whereas larger engines are more driven by life cycle costs.

CHALLENGES

There are many opportunities which presently exist to begin implementing and exploiting the benefits of alternatives to centralized control. These were described in detail above. However, there remain several challenges to be overcome for the full implementation of DCS throughout the aeropropulsion engine. These challenges are explained in detail.

<u>Engine Environments & High Temperature Electronics</u> - Environmental conditions are perhaps the single biggest factor in utilizing centralized control architecture because it allows all of the sensitive electronic components to be housed in a single hardened avionics package. Centralized architecture simplifies the requirement to protect sensitive electronics. Of these environmental factors, high temperature is the most significant constraint because of its affect on reliability and its impact on system weight when designed to be actively or passively cooled.

Functional and operational needs of control system elements generally dictate the placement of particular sensors and actuators, most often with environments that are hostile to conventional electronics technology. Because distributed control involves significant local processing, the sensitive electronic circuits in DCS modules will often see harsher temperature and vibration conditions than a centralized electronic control unit. Overcoming the temperature limitation of silicon electronic components will enable the embedded application of electronic circuits in hotter sections of the engine. This, in turns enables complete functionality to be embedded in the functional elements of the DCS.

The environmental conditions in the engine assembly are severe and are listed below for reference:

- Temperature extremes can range from -60 °C at high altitudes to 500 °C or more near the combustor, or over 1400 °C in the hot gas path itself.
- Vibration from rotating parts in the engine and aerodynamic effects on the aircraft can cause fatigue in circuit assemblies and harnesses.
- Shock loads from landing can destroy components unless reinforced.
- Water, salt spray, hydrocarbon fuels, and cleaning solvents must be prevented from contacting sensitive circuits and materials.
- Circuits and components must be shielded from lightning and for electromagnetic susceptibility and emissions.

The issue with temperature is interrelated with the digital communication needs of distributed control as well. Digital communications require some level of processing to facilitate the protocols which enable communications [6-9]. The availability of the electronics to perform this processing at the distributed component is a key element for the success of distributed control. Expected data rates, latency, and robustness are some of the factors which must be considered when determining the high temperature processing requirements for distributed control elements.

With conventional silicon electronics the junction temperatures must be kept below 125 °C. This often results in temperature limitations at the packaging level to be 85 °C or less. Silicon-On-Insulator (SOI) technology increases the junction capability to 225 °C to 250 °C. In addition, many engines use fuel as the hydraulic medium for actuators and the fuel temperatures at these locations do not typically exceed 150 °C. The temperature capabilities of SOI technology alone, or in conjunction with fuel cooling, can be exploited for a substantial number of distributed control functions in engine applications.

The thermal challenges in and around engine bays are increasing due to many factors related to engine performance and this trend is expected to continue. This has implications for FADECs as well as any embedded electronics in distributed modules on the engine. There are only two alternatives for engine-mounted components; provide better thermal management in the form of active cooling, or increase the temperature capability of electronics. For the long term, the development of electronics with even higher temperature capability than SOI is preferred because of the lower impact on system weight.

A second thermal management alternative is the off-engine mounting of electronics which are not required to be engine-mounted for purposes of weight reduction.

Functional Partitioning - Implementation of DCS must consider partitioning of the high-end algorithm processing functions from those that are less processing intensive. High-end processing is generally associated with high level engine control law implementation and health monitoring functions. The processing requirements for sensor and actuator applications, such as communications, signal conditioning, digital-to-analog (D/A) and analog-to-digital (A/D) conversion, built-in test, and limited control processing are generally less intensive and can impose weight penalties if located away from the sensor or actuator.

Partitioning high-end algorithm functions from those associated directly with the sensor or actuator enable the isolation of high-end electronics. This has desirable implications:

1. High-end electronics are generally more sensitive to thermal and environmental constraints and isolating these functions enables their placement in off-engine locations which can minimize the constraints on their design.
2. High-end electronics are generally more prone to obsolescence issues because the commercially driven technology changes so rapidly. The functional replacement of high-end electronic processing modules can often be accomplished via a well-planned, technology driven, backward compatible, upgrade path.
3. The very high temperature capability requirement for electronics is limited to specific functions rather than being a general need for all engine functions

Logical functional partitioning must consider bus bandwidth, object oriented concepts to localize changes to control development costs over the life cycle of the product, and optimize fault isolation with a minimum of ambiguity.

Redundancy and Resource Management - The DCS offers considerable flexibility on use of resources to provide high functionality after faults. Accommodation logic to optimize the use of available resources to minimize performance impact or disruption is an essential design area that should not be underestimated. Simply adopting the traditional paradigms associated with the typical dual centralized channels of a central FADEC control would limit the achievement of the full potential of the distributed system for significant improvement on fail-operational capability.

Data Bus and Communications - The hostile operating environment of a typical engine poses a number of problems in developing a reliable high-speed communication system. For such applications, a communication system must have sufficient reliability and bandwidth (or bit rate) to accommodate real-time closed-loop control of systems which are essential to engine and vehicle safety. The system must also be sufficiently immune to electromagnetic emissions and susceptibility (EMI/EMC and noise) generated by the operation of various switches, motors and other electronic circuits. Generally, this requires some physical separation between power distribution lines and control signal delivery lines.

Data bus design must include sufficient bandwidth for future growth plus provide a high degree of fault tolerance against single node failures which can disrupt or disable bus operation. Figure 10 considers three different designs for power distribution and data bus architecture.

There are many modern, robust high speed data networks, such as SAE-5652, ARCnetPlus and IEEE-1394B (Firewire) which provide very high data transfer rates when compared with the common Mil-std-1553 used in many critical control applications. It is not clear, however, what communication media and protocols exist which would be suitable for high temperature engine control systems in the present and future.

Market Size - The market size for aerospace qualified hardware is relatively small, and the barriers to entry are high. While making distributed components which can be universally used may increase potential market share, the over-design required to support all possible applications in all possible aircraft environments will make the component prohibitively expensive for most applications. To overcome this barrier, the DCS should best begin with rugged components that are universally used, and universally challenged to meet needs.

One example is the need for increasingly accurate pressure sensors. Controlling an engine with improved Specific Fuel Consumption increasingly relies on accurate pressure measurements. Most off-the-shelf pressure sensors with an analog interface provide accuracies in the 1 to 2% range. Customers are increasingly demanding accuracies in the 0.5% or better range. To improve the accuracy of the basic sensor, each sensor must be characterized, and the characteristics captured with the sensor. In most cases, this characterization is either built into analog circuitry in the sensor itself, or provided as digital constants to compensate the reading. Sensors which digitally compensate the data internally are not readily available for the temperature and vibration environment of the engine.

A second example is the need for increasingly accurate temperature measurement. By more accurately measuring temperature, the engine control system can push engine components closer to their materials limits, with lower risk of exceeding those limits. While current technology supports temperature measurement system accuracy at the 5 °C to 10 °C level, customers are increasingly demanding accuracy at 1°C to 2 °C. Raising the internal engine temperature improves the engine's theoretical thermodynamic efficiency, and increases engine output for a fixed size machine.

Inexpensive, accurate, aerospace qualified, remote sensors for pressure, temperature, speed etc., with real-time, deterministic, digital communication capability, are necessary for distributed control systems. As various components of engine control adopt a distributed architecture the motivation for industry to develop additional distributed components will grow.

Safety / Regulatory Environment - One overall assumption that must be made during the consideration of any DCS is that safety and reliably metrics versus a single box FADEC must not be negatively impacted. Architectures utilizing plug-in boards and electronics located in thermally challenging locations must retain comparable safety/reliability metrics in order to be viable; otherwise they will negatively driver other Customer Value metrics. It must be verified that with any DCS, we are not negatively impacting safety and reliably metrics versus a single board single box FADEC. Architectures utilizing plug-in boards and electronics located in thermally challenging locations must retain comparable safety/reliability metrics in order to be viable; otherwise they will negatively driver other Customer Value metrics.

The government rigorously monitors and regulates the qualification and certification of aircraft systems including engine controls. This process not only challenges the safety and integrity of each component, but it also challenges the quality and safety of the design and integration of the system. While a specific component may be qualified for application to a specific use in a specific aircraft type, this does not imply that the same device can be arbitrarily placed in a different application on the same aircraft, nor in the same application on a different aircraft type, without re-qualification of the component in that application.

From this perspective, the benefits of the open distributed architecture may initially be gained in the new system design area. These designs will benefit from the optimal application of a ready pool of qualified components, but will still require extensive system verification testing. However, as the industry gains experience with the use of a pool of portable components, and demonstrates proficiency at the optimal integration task, there will be pressure on the regulatory agencies to adjust or relax the regulations. However, the policy shift will not likely happen until the regulatory agencies have seen many new systems successfully deployed, and many older systems successfully updated.

Increased Maintenance Cost - Integrated hardware DCS components could have increased maintenance costs. For example, consider a fuel pump and controller. In a CCS there is a controller and a pump, whereas in the DSC those two components are integrated. If the physical pump fails then the whole unit might have to be replaced or refurbished. This issue has been noted in other industries. However, if replacing a faulty integrated module is more time-efficient than troubleshooting and replacing separate components, then it may represent more value to the customer since it creates an engine system with higher availability.

Distributed Systems Competencies – There are several systems skill sets that must be considered in the transition from centralized to distributed engine control. At the present time these can be considered as challenges since it represents both a change in technology but, in some instances, a change in culture as well.

Distributed Control is a very systems oriented process which is multidisciplinary in nature. Often controls technology is considered a back-end process during the design phase in which the engine system is optimized for aero-thermo-dynamics, mechanics and structure before considering the needs of control. The processes and tools to evaluate and implement a distributed engine control system should themselves be developed and optimized to realize the maximum benefit.

While this paper has largely considered the hardware aspects of distributed engine control technology, the challenges in software implementation are just as great. New methods for the development, distribution, and configuration management of software must be considered, especially when these software modules are developed by multiple organizations over time and geographic location.

Finally, the maintenance and logistics systems must be developed to track and maintain engine systems. This involves the development of common and consistent troubleshooting procedures for service personnel across a variety of engine platforms to quickly resolve system problems and inevitable component failures. It also means the development of systems to properly configure a common hardware element for a specific system configuration.

ROADMAP TO THE FUTURE

The traditional paradigm of centralized control has adequately met most functional needs of aircraft engine controls. However, system cable weight, limitations in fault isolation that results in ambiguity groups and limited flexibility to expand or modify the system without redesigning the FADEC are clear disadvantages to the centralized system. Increasing demands on the control system to enable greater engine performance through additional controls functionality are exacerbating the limitations of a centralized system.

Distributed control can mitigate all of those factors. Cable weight can be substantially reduced and standardized. The FADEC can become a pure digital component, without the myriad of custom analog input/output (I/O) normally present that drives both the need for close proximity of the FADEC to the engine, as well as the need for expensive FADEC redesign when the I/O needs change. The overall system becomes much more expandable and flexible, while enabling a common building block approach that simplifies inventory logistics. Proper functional partitioning can help minimize data bus bandwidth, as well as optimize fault isolation and control loop dynamic performance.

New functions such as active stall control that require high bandwidths, very disparate from conventional control sensor and loop bandwidths can be efficiently implemented with local processing without sub-optimizing the rest of the system. With the increased availability of a range of analog and digital parts in SOI technology, closing position loops at fuel driven actuators is at hand. A logical paradigm for local processing of specific sensors or groups of sensors must still be developed. Continued challenges are to increase the range and capability of SOI devices, develop interconnect and packaging methods that are robust over the expected temperature cycles, and to optimize system partitioning and logic design for best performance and fail-operational capability. Significant advances in semiconductor or cooling technology are needed to enable distributed control at temperatures above 250 °C. Even with the remaining challenges, the key enablers for distributed control have progressed to the point where distributed control can be implemented in many engine control situations. The inherent advantages over a centralized system make it compelling.

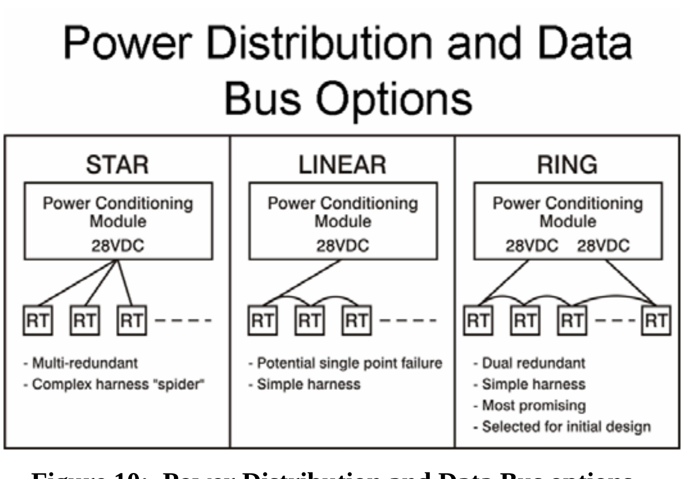

Figure 10: Power Distribution and Data Bus options

In this paper we have identified the advantages and disadvantages of distributed and centralized control for the turbine engine. We need to understand and use the appropriate control strategy for each specific application. The engine control industry, at large, currently remains committed to centralized control solutions based on point-to-point wiring and hierarchical logic systems. The result is functional, but it is difficult and expensive to service, maintain, and expand. It is also highly susceptible to obsolescence.

From the software point of view, the DCS allows developers to create their own local repositories for their changes at their engineering sites. The local developer repository is similar to the original source repository (it's been distributed). The key difference is that instead of changes that are made in the centralized approach, the distributed approach allows developers to work with their repositories while disconnected using known standard I/Os. They can make changes, commit them to their local repositories, and merge changes from others without affecting the main controller. Developers can then make changes. All components can be designed using "open system" components, which will result in reduced cost to both manufacturers and customers.

In this approach, as the system becomes more complex, it is much easier to design a controller using the distributed approach. In addition, each component does not need to be recertified. This will result in lower cost. For less complex controls, the best choice may still be centralized control. But since the engine becomes more complex the trend is toward distributed control, and each case needs to be examined carefully to justify its use. The novelty of this new approach is on the benefits of a distributed (decentralized) versus CCS method in which interactions between sensor nodes are modeled topographically and manipulated locally to produce desired global behavior. These technologies will be integrated and demonstrated using a network of mobile sensors applied to a class of applications. Communication among the nodes may be peer-to-peer (distributed control) or master-slave (centralized control). In either case, intelligence in the nodes (computational capability) permits the distribution of processing loads (sensors can be intelligent, for example, performing local data analysis, conversion, normalization, and reporting only significant changes in their environment). If the control functions are also distributed, both system performance and reliability can be dramatically enhanced.

Control systems are fundamentally the same regardless of application; a DCS (networked control system) is significantly more powerful, flexible, and scaleable than a non-networked control system (centralized control), and businesses can save and make more money building distributed control over the long term than they can with centralized control systems. Fundamentally, distributed control is more diversified, and may be the choice in the long term. We must not shy away from this approach, if we are serious about lowering cost. Perhaps it is time for all to increase collaboration, to start sharing component design, and using a networked approach to designing more complex, integrated control systems. The CCS strategy should not be abandoned either, and its use may still make sense in certain applications. The best approach is to begin to develop a comprehensive suite of distributed control-enabling technologies and incrementally introduce these technologies into increasingly more distributed systems. The Distributed Engine Control Technology roadmap is shown in Figure 11.

CONCLUSION

It is widely recognized that the performance, complexity, and pervasiveness of aero-engine control systems will be a deciding factor in the success of future aero-propulsion systems. To meet the impending challenges it can be argued that transforming the control system architecture, from a centralized structure to one of a distributed configuration based on open system standards, is necessary. As observed in the past, however, the aero industry is slow to adopt new technology because of the severe environment and the implications of failure.

High temperature electronics is the enabling technology for aero-engine distributed control. As outlined, much progress has been achieved through government and industry collaboration in research activities leading to the development of electronic components for embedded applications in the hot section of an engine. However, additional research is necessary to mature the technologies to the point of product transition. A roadmap describing the final steps to this end is included.

In any case, it is likely that the transition period will be one in which acquisition costs initially increase, perhaps substantially. This is due to the fact that no compromises can be made in system performance. In the long term, if given the opportunity, these acquisition costs will be reduced as open competition, enabled by open system standards, allows more vendors into the market. At some still to be determined point after transition occurs, overall cost of ownership will be lowered and customer value enhanced, while future

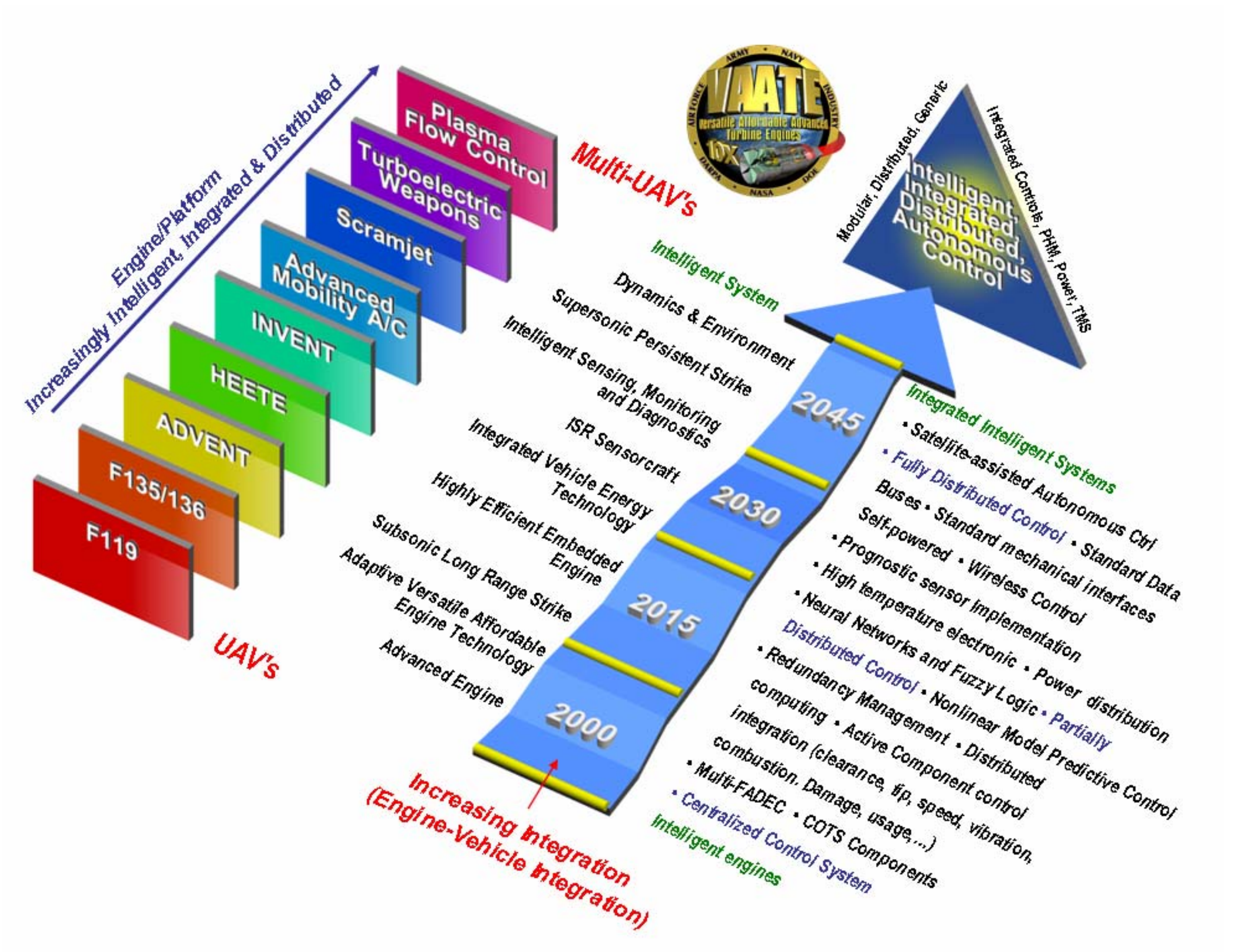

Figure11: The Distributed Engine Control technology roadmap

metrics for weight and aero-engine performance are achieved.

The main perceived benefits of the distributed engine control system are largely agreed upon by members of the DECWG. These are: 1) reductions in size/weigh/cost of wiring harnesses 2) simplified potential for system upgrades, 3) distribution of computational burden, 4) potential increased robustness of the control system against faults/damage, and 5) mitigation strategy for obsolescence issues.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CCS: Centralized Control System

C&A: Controls and Accessories

DARPA: Defense Advanced Research Projects Agency

DCS: Distributed Control System

DECWG: Distributed Engine Control Working Group

EMC: Electromagnetic Control

EMI: Electromagnetic Interference

FADEC: Full Authority Digital Engine Control

HiTEC: High Temperature Electronics Consortium

IHPTET: Integrated High Performance Turbine Engine Technology

I/O: Input/Output

IR&D: Independent Research and Development

IVHM: Integrated Vehicle Health Monitoring

LRU: Line Replaceable Unit

MOTS: Military Off The Shelf

SIC: Silicon Carbide

SOI: Silicon On Insulator

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Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture

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Outline

- Distributed Engine Control Working Group
- Motivation / Goals
- Vision
- Challenges
- Roadmap
- Conclusion

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Distributed Engine Control Working Group

Charter

The Distributed Engine Control Working Group (DECWG) is **a forum for the discussion of aero-propulsion systems with a specific emphasis on the future development of engine controls**, including both hardware and software, for military and commercial engines. By examining the current and future requirements of propulsion engine systems, the group will lay the foundation for a future distributed engine control architecture based upon **open system standards**.

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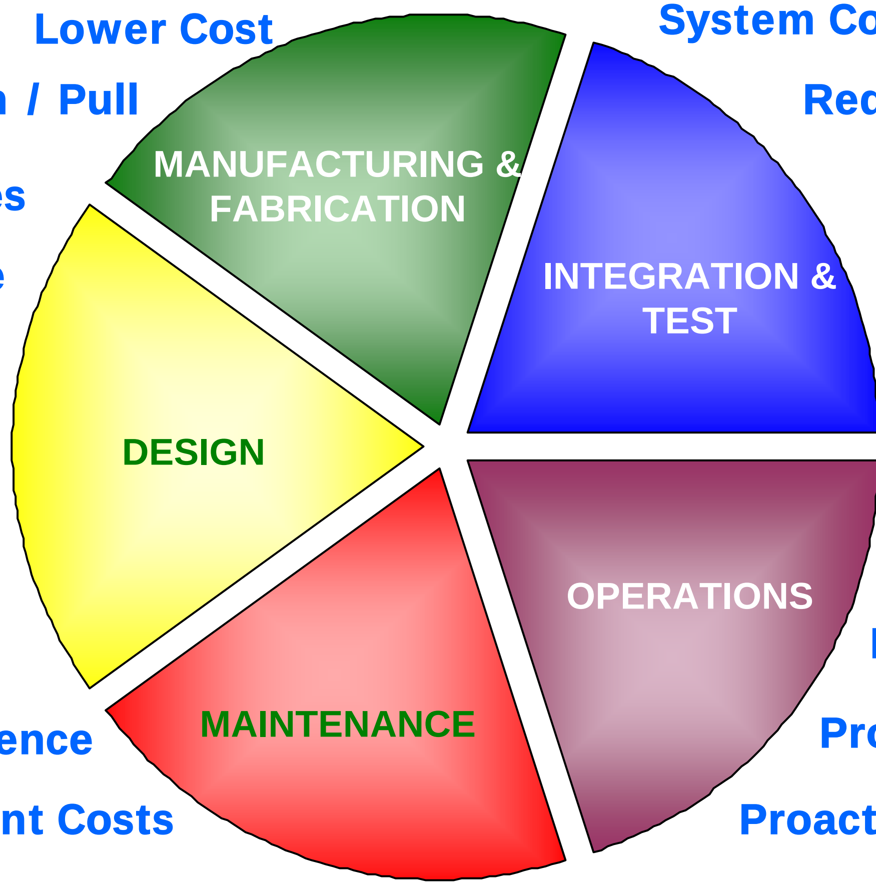
Distributed Engine Control Working Group

The main goals of the DECWG will be:

- Identify, quantify and validate **benefits** from the stakeholder perspective.
- Identify the impact of **new control strategies** on all facets of the user community; including design, fabrication, assembly, supply chain, and operations.
- Identify **regulatory and business barriers** which impede the implementation of alternate control philosophies.
- Identify existing and emerging **technologies** which can be leveraged in the aero-engine control system.
- Identify **technology barriers** which prevent the implementation of alternate control philosophies and provide guidance to industry for their removal.
- Develop an overall **roadmap** with which to guide the successful implementation of alternate control philosophies.

Motivation / Goals

Lower Cost
Technology Push / Pull
Simplify Upgrades
Add Customer Value
Time to Adapt / Add New Features
Adaptive Control / Flow Control
Reduce Weight
Mitigate obsolescence
Reduce Sustainment Costs



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

Performance, Time & Cost

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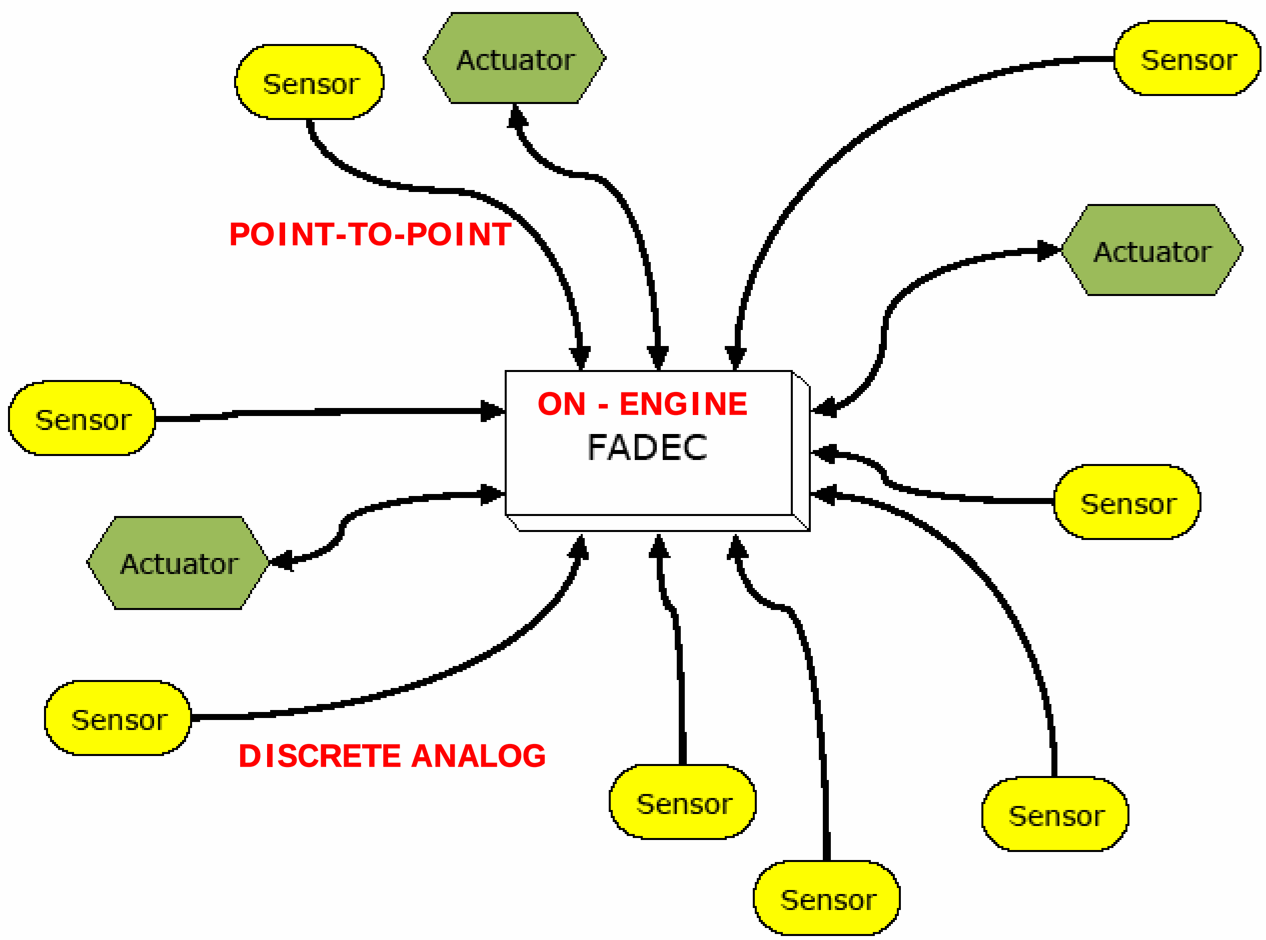
Central Control System Issues

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

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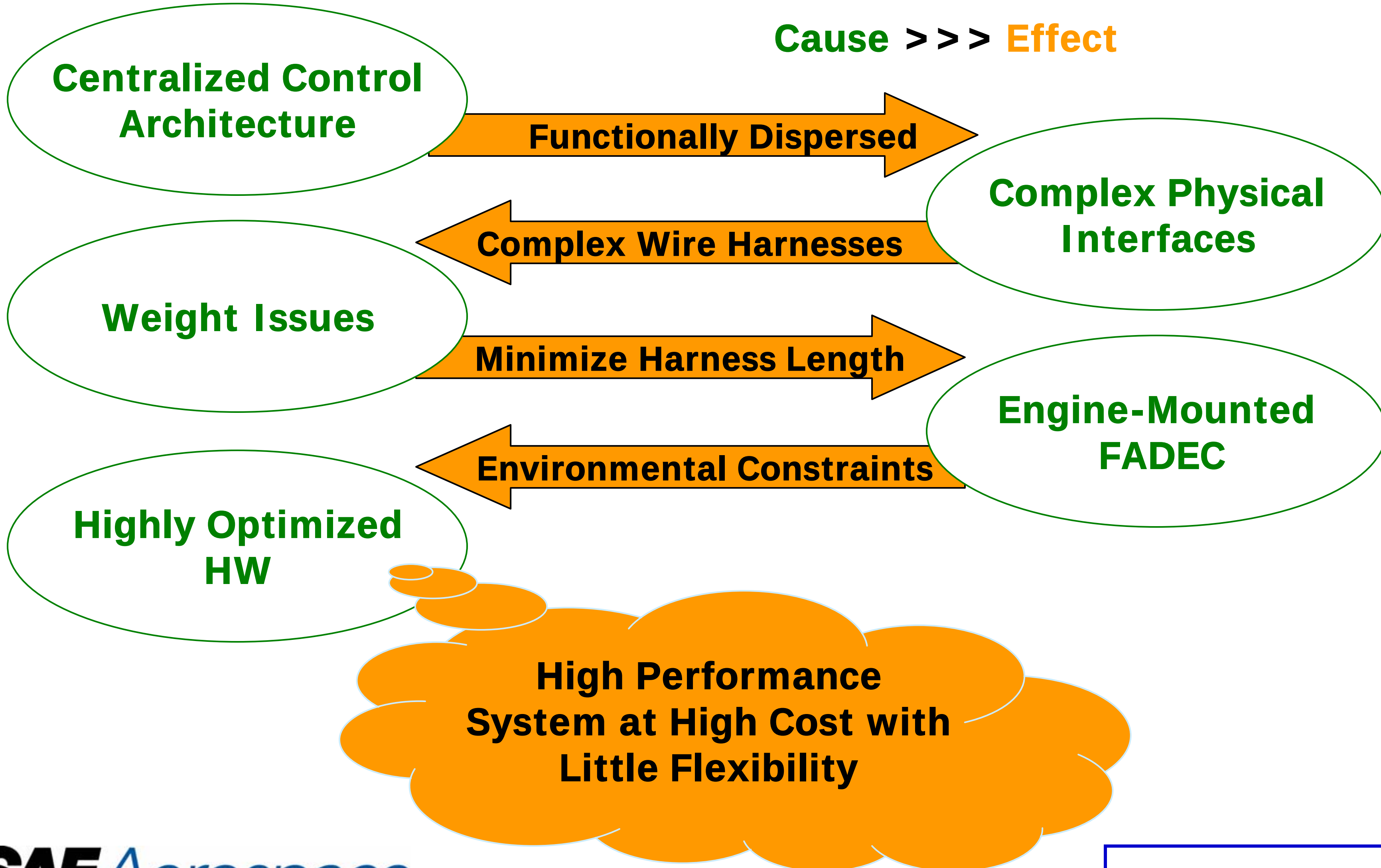
System Design Decisions



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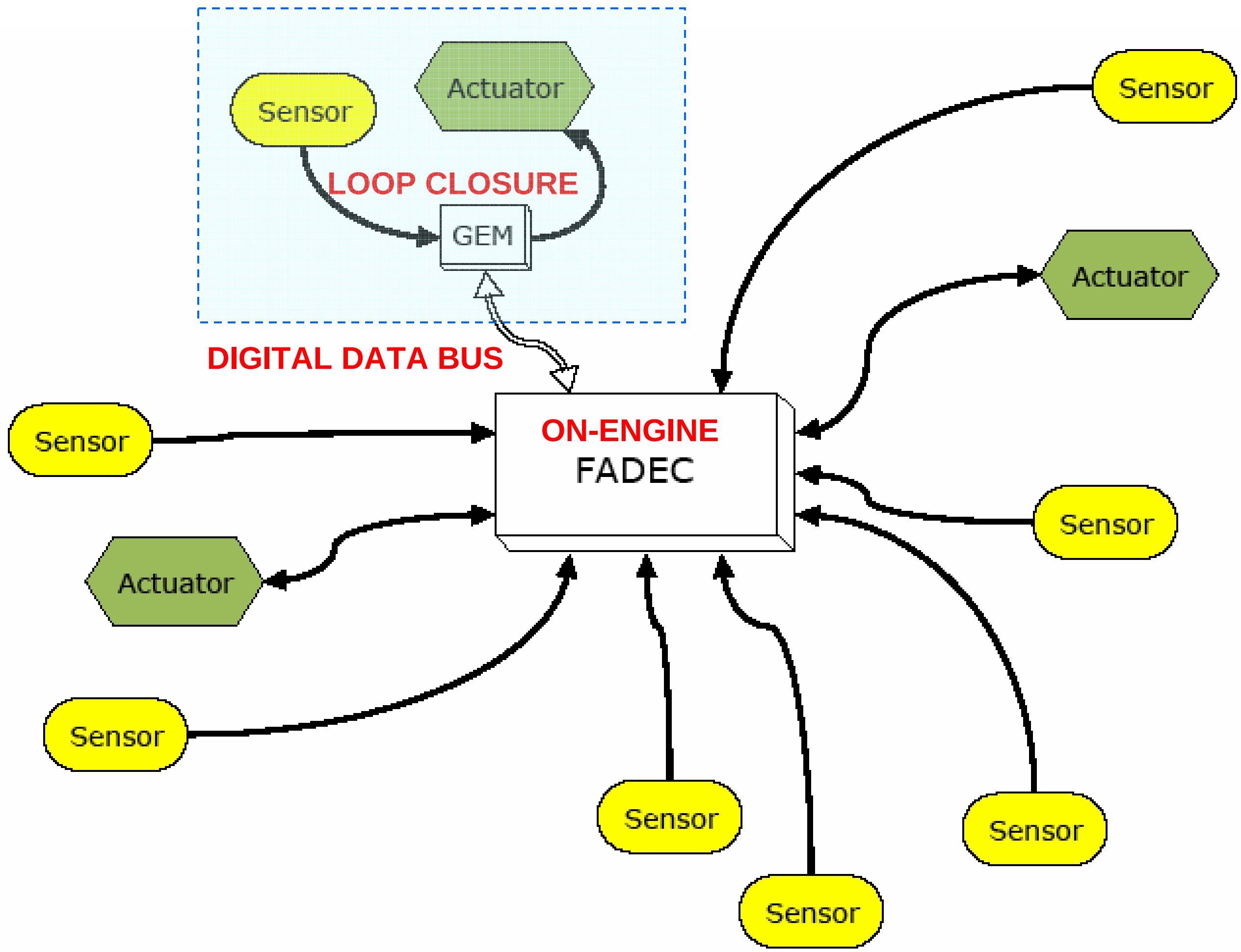
Foundational Development

- Lightweight Distributed Systems (LDS)
- *High Temperature Electronic Components (HiTEC)*
- *COntrolled Pressure-ratio Engine (COPE) Program*
- *Propulsion Instrumentation Working Group (PIWG)*
- *Versatile Affordable Advanced Turbine Engine (VAATE) Initiative*
- *NASA Glenn Research Center Initiatives*

Elements of Distributed Engine Control Technologies have been in development since the early 1990's

Transition to Distributed Control System



Harness
- Reduced Wire Count
- Simplified Mechanical Interface

FADEC
- Simple Loop Closure Off-Loaded to Controller

System
- Limited Fault Isolation
- Functional Segregation

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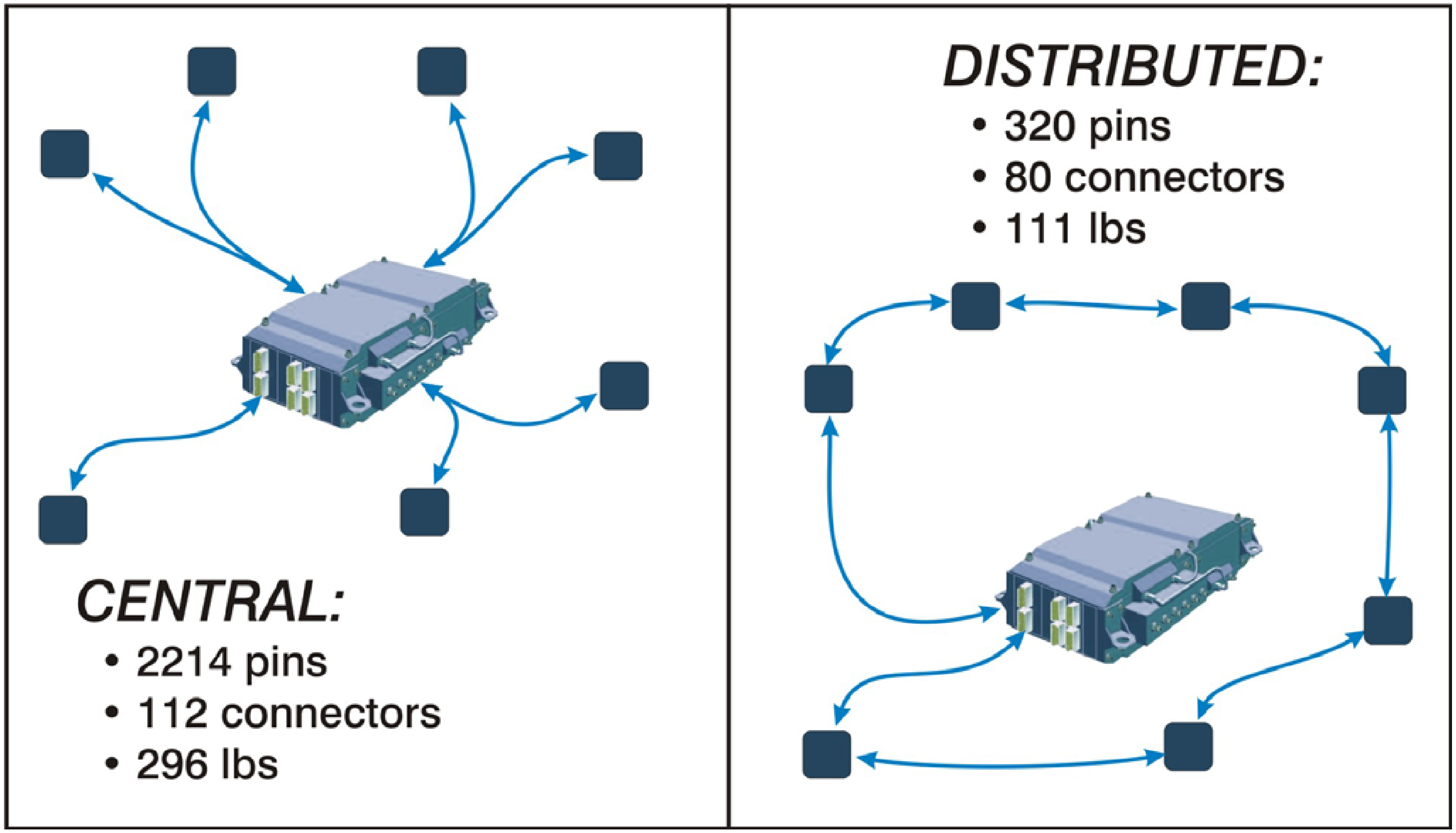
Analysis of Wiring Harness

Expected Impact of Distributed Control



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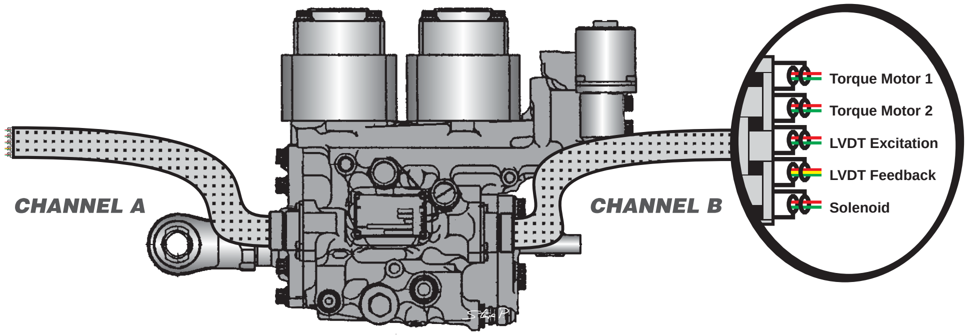
HIGH-TEMPERATURE SMART ACTUATOR

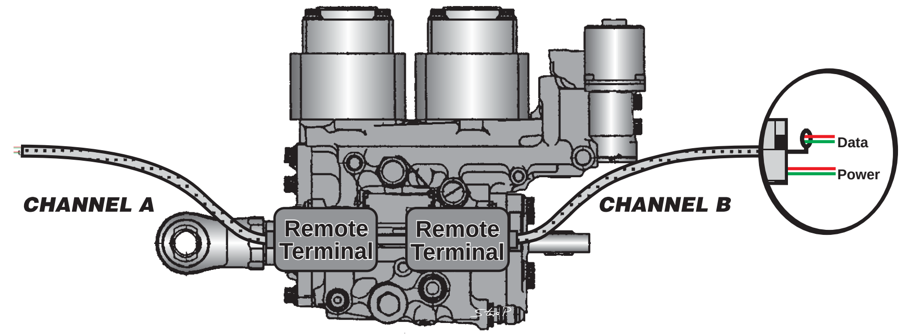
KEY COMPONENT FOR DISTRIBUTED CONTROLS

CONVENTIONAL FAN IGV ACTUATOR



CHANNEL A	11 Wires
	10 Shields
CHANNEL B	11 Wires
	10 Shields
TOTAL	42 Conductors

SMART FAN IGV ACTUATOR



CHANNEL A	4 Wires
	1 Shield
CHANNEL B	4 Wires
	1 Shield
TOTAL	10 Conductors

ADDING COMPACT ELECTRONICS MODULE TO ACTUATOR HAS SIGNIFICANT SYSTEM BENEFITS

- TOTAL WIRE COUNT INTO FADEC REDUCED FROM >500 TO 8
- FADEC COST REDUCTION OF $75K (SUBSTANTIALLY MORE IF FADEC IS OFF-ENGINE)
- FADEC STANDARDIZATION FOR MULTIPLE ENGINES (NEW FADEC DEVELOPMENT IS ~$50M)
- DISTRIBUTED BUILT-IN TEST PROVIDES NEAR 100% FAULT ISOLATION

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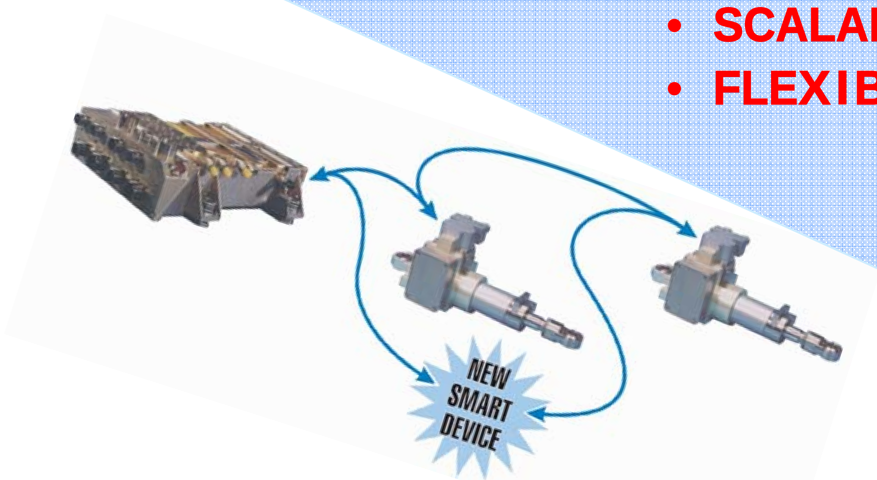
Vision for Distributed Control

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

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 .

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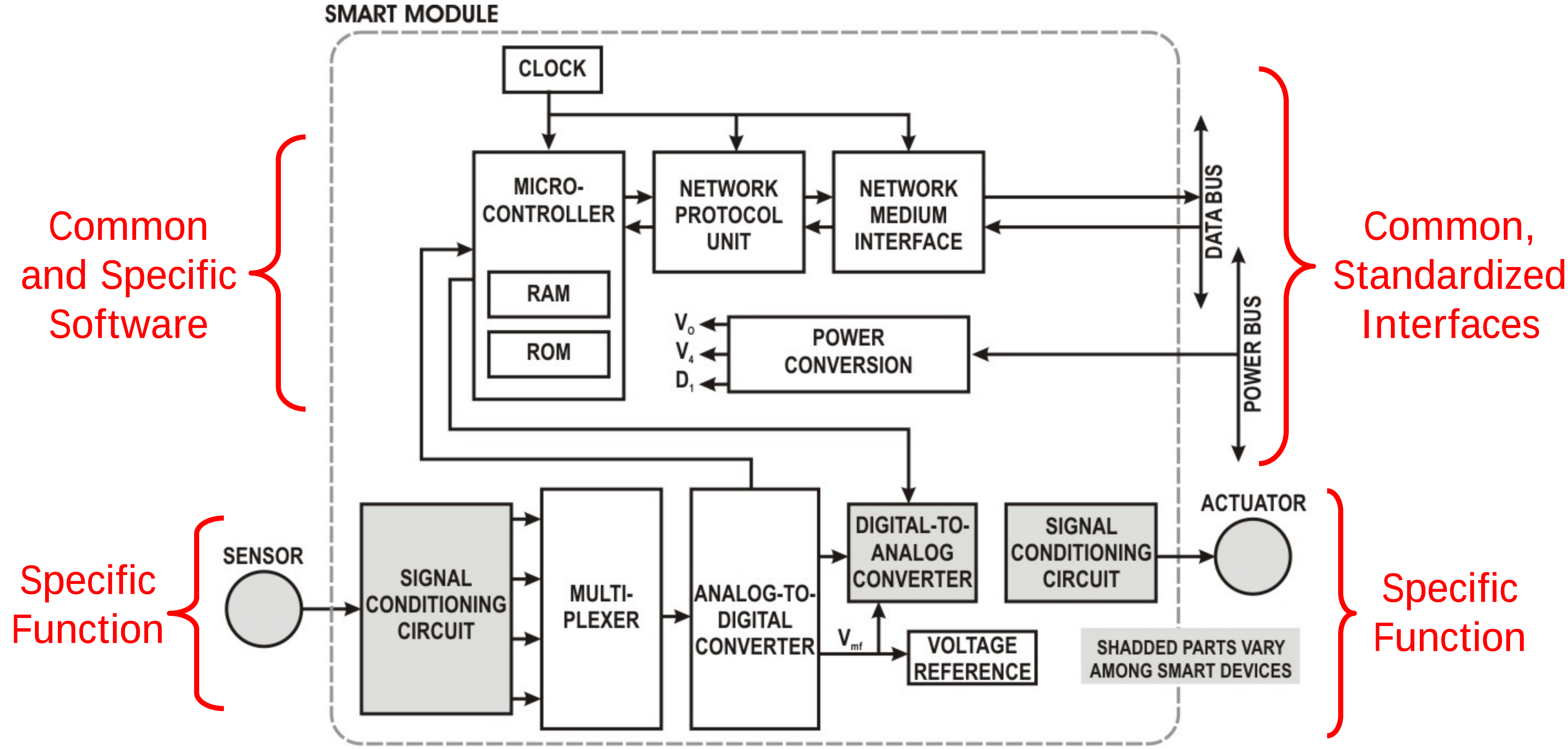
Modular Design Elements for Engine Control

In Distributed Control much of the Hardware AND Software can be reused in the system AND across engine platforms



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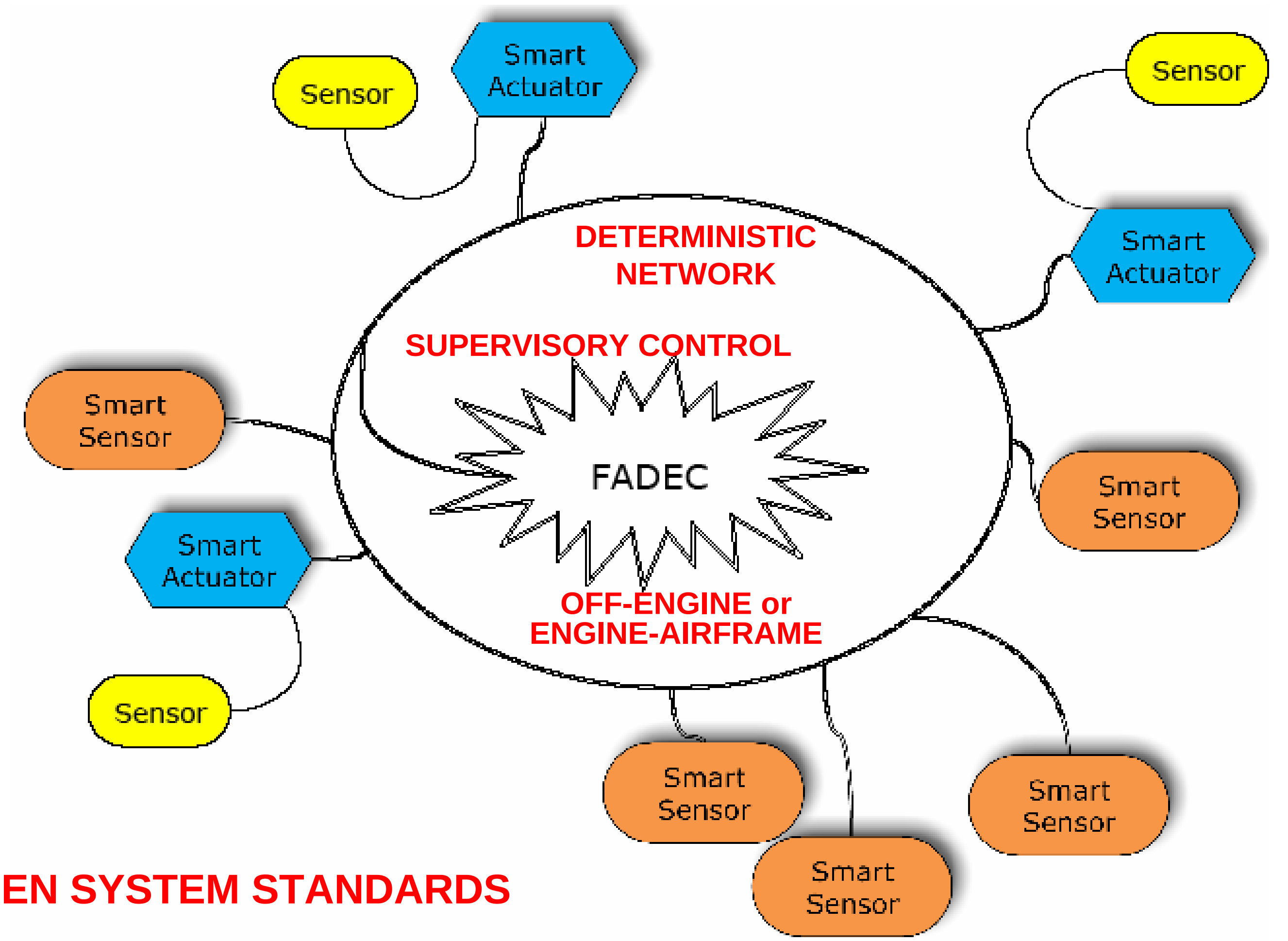
Integrated Distributed Engine Control



OPEN SYSTEM STANDARDS

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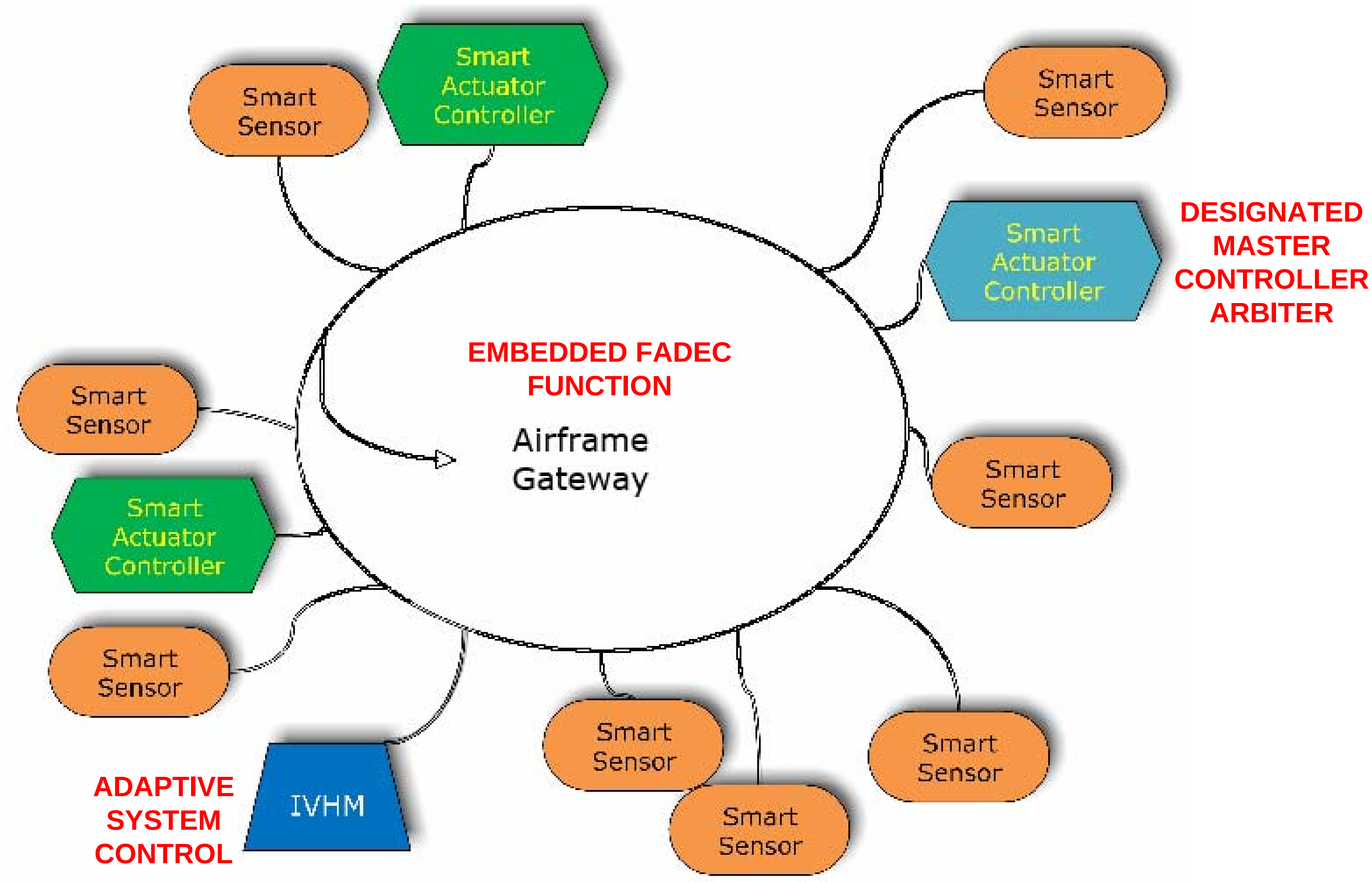
Embedded Distributed Control



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A Long Term View

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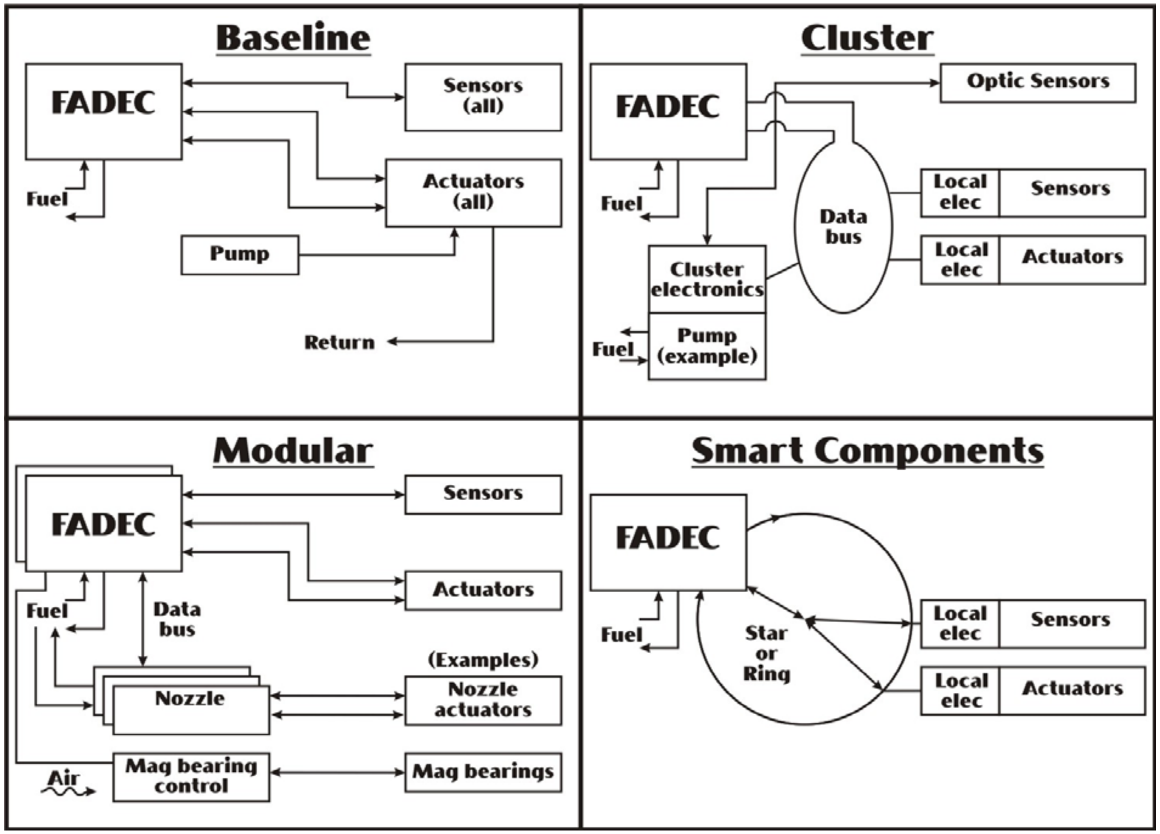
Distributed Architecture Flexibility



Distributed Architecture Does NOT Force a Specific Configuration
It Provides for the Best Choice on a Given Platform

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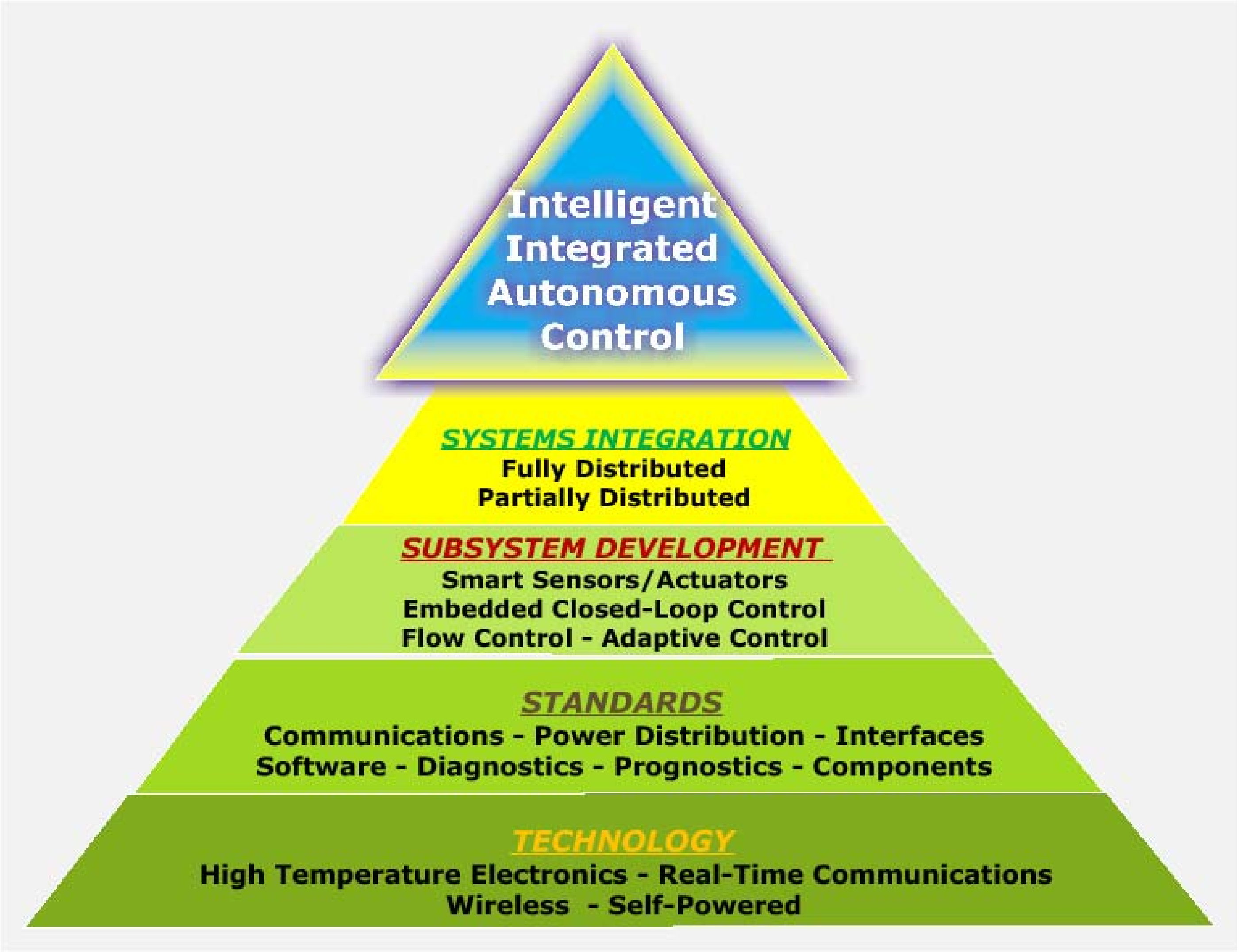
Challenges

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

Elements of the Development Roadmap



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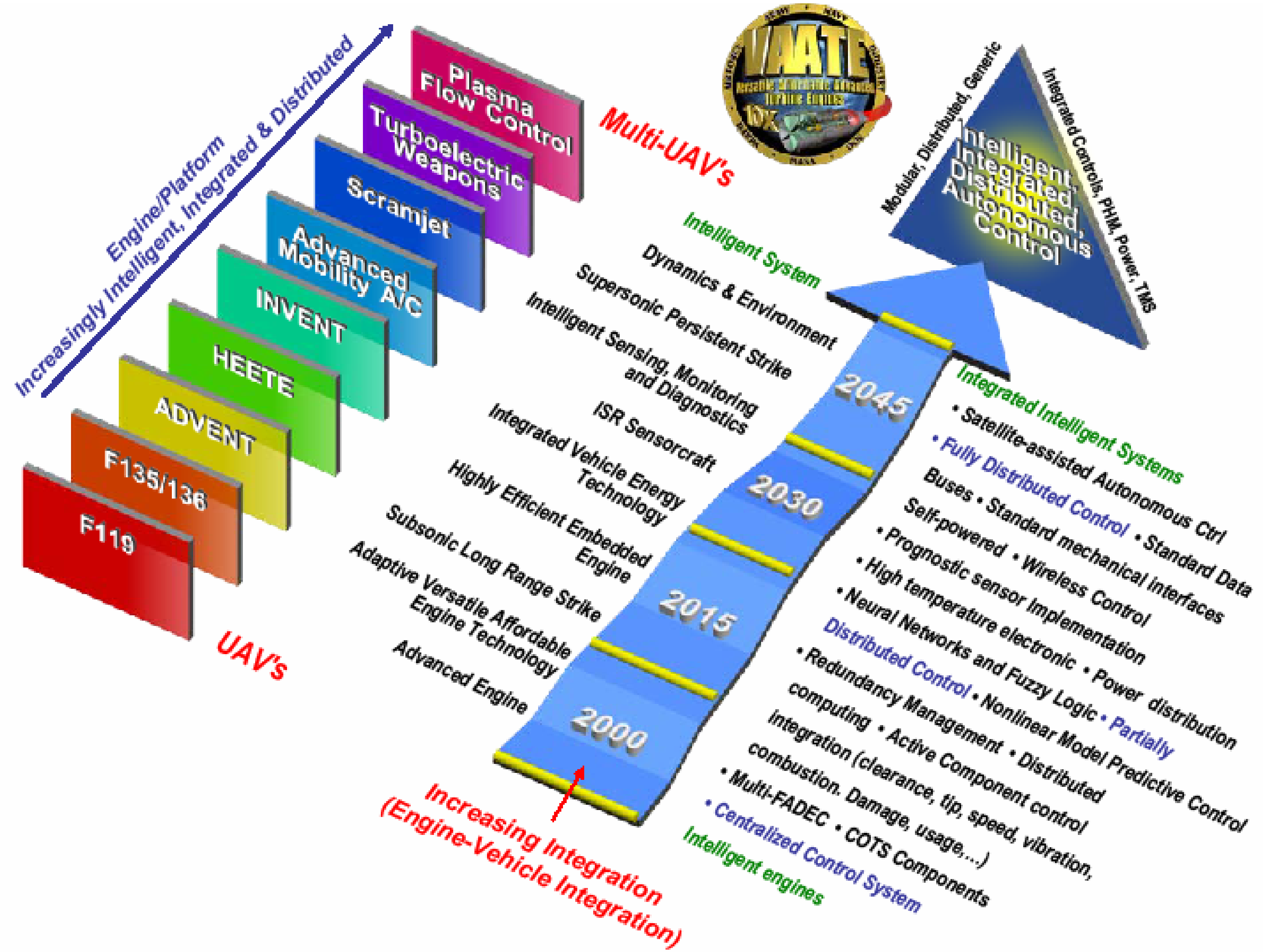
Expectations for Future Engines

CURRENT ENGINES:

- Mechanical / Structural / Aerothermodynamic design provides a fixed optimum operating point
- Large, fixed safety margins accommodate worst case deterioration and operating conditions
- Inflexible engine response to changing operational & environmental conditions
- Maximum performance compromised for wider operability
- High support costs

FUTURE INTELLIGENT ENGINES:

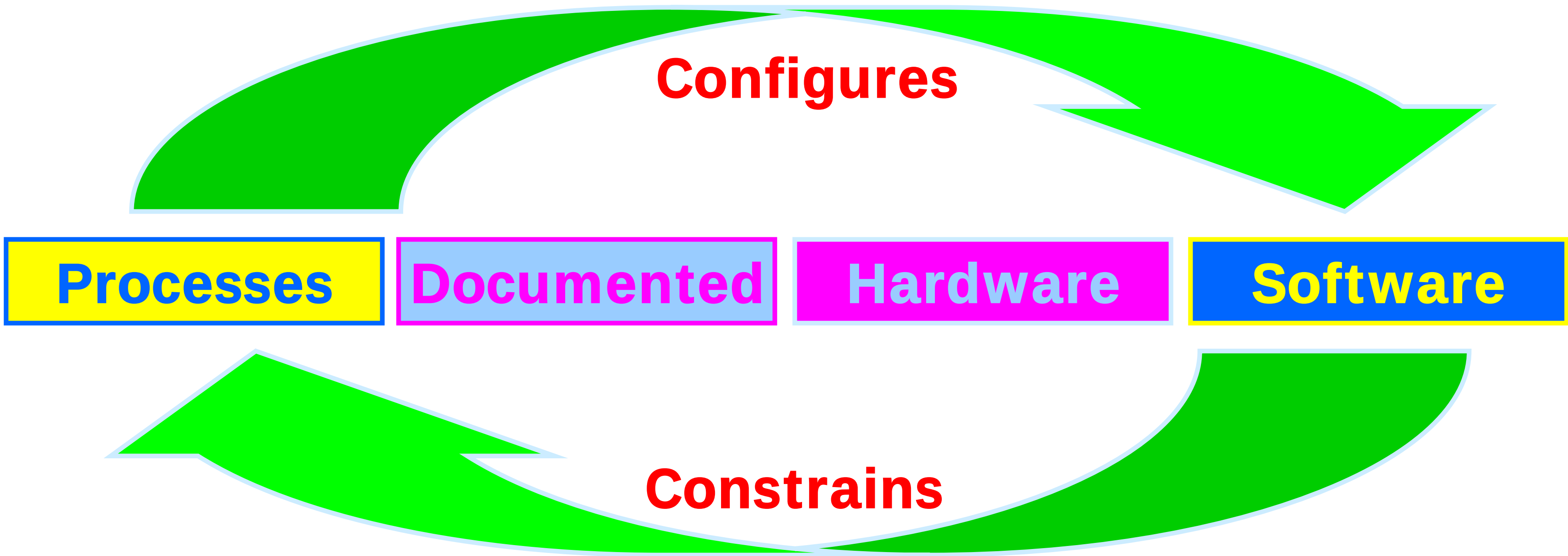
- Intelligent control maintains optimum engine operation through adaptive response to all changing conditions while maintaining safety margins
- Accommodation for internal (engine health) or external (new/changed missions) conditions
- Performance requirements met through End-of-Life
- Increased knowledge of flowpath and mechanical conditions enable optimization, self-diagnosis, self-prognosis


Engine/Platform
Increasingly Intelligent, Integrated & Distributed
F119
F135/136
ADVENT
HEETE
INVENT
Advanced Mobility A/C
Scramjet
Turboelectric Weapons
Plasma Flow Control
UAV's
Multi-UAV's
VAATE
Intelligent System
Dynamics & Environment
Supersonic Persistent Strike
Intelligent Sensing, Monitoring and Diagnostics
ISR Sensorcraft
Integrated Vehicle Energy Technology
Highly Efficient Embedded Engine
Subsonic Long Range Strike
Adaptive Versatile Affordable Engine Technology
Advanced Engine
2000
2015
2030
2045
Increasing Integration (Engine-Vehicle Integration)
Intelligent, Integrated, Distributed, Autonomous Control
Modular, Distributed, Generic
Integrated Controls, PHM, Power, TMS
Integrated Intelligent Systems
• Satellite-assisted Autonomous Ctrl
• Fully Distributed Control • Standard Data Buses • Standard mechanical interfaces
Self-powered • Wireless Control
• Prognostic sensor implementation
• High temperature electronic • Power distribution
• Neural Networks and Fuzzy Logic • Partially Distributed Control • Nonlinear Model Predictive Control
• Redundancy Management • Distributed computing • Active Component control integration (clearance, tip, speed, vibration, combustion. Damage, usage,...)
• Multi-FADEC • COTS Components
• Centralized Control System
Intelligent engines

Integrated System Design Process

Evolutionary Development Process…

Deploying COTS as much as possible …



Define and Refine the Process and Configuration Design H/W and S/W simultaneously...

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Conclusion

- Aero-engine control systems will decide the success of future aeropropulsion systems; Transforming the control system into a distributed architecture, based on open system standards, is necessary to meet the challenge.
- High temperature electronics is the enabling technology for aero-engine distributed control.
- The DECWG perceives the benefits of distributed engine control as:
  1. Reducing the size/weigh/cost of wiring harnesses
  2. Simplification of system upgrades,
  3. Distribution of computational burden,
  4. Increased robustness against faults/damage
  5. Mitigation obsolescence issues.

Questions??

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