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Prepared for the
24th Joint Propulsion Conference
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SUMMARY

E-4256

An intelligent control system for reusable space propulsion systems for future launch vehicles is described. The system description includes a framework for the design. The framework consists of an execution level with high-speed control and diagnostics, and a coordination level which marries expert system concepts with traditional control. A comparison is made between air breathing and rocket engine control concepts to assess the relative levels of development and to determine the applicability of air breathing control concepts to future reusable rocket engine systems.

INTRODUCTION

The objective of this paper is to describe a proposed Intelligent Control System (ICS) for reusable space propulsion systems for future launch vehicles. Here we define an ICS to be a control system that has coordination and execution levels and is based upon the principle of increasing precision with decreasing intelligence (ref 1). An ICS for reusable space propulsion systems has the potential to produce enhanced performance with increased reliability, durability, and maintainability. These improved control systems will incorporate a broad intelligence to accomplish these goals. This will require a marriage between modern control theory and the emerging area of artificial intelligence. In this paper the authors suggest an approach for the design of intelligent control systems for a variety of future propulsion systems. However, to make the ideas explicit the discussion will emphasize the only operational version of a reusable rocket propulsion system, the Space Shuttle Main Engine (SSME). The SSME durability experience will serve as the basis for new life extending control capabilities through improved diagnostics.

The proposed framework for an intelligent control system will consist of a hierarchy of various control and diagnostic functionalities. These functionalities include life extending control, adaptive control, real-time engine diagnostics and prognostics, component condition monitoring, real-time identification, and sensor/actuator fault tolerance. Artificial intelligence techniques will be considered for implementing coordination, diagnostics, prognostics, and reconfiguration functionalities.

First the paper will present a justification for the use of Intelligent Control Systems (ICS) for reusable rocket engine control. Next, the author's vision of the structure and functionality of this control will be presented. Finally, some of the significant technical challenges to successful implementation of an ICS for reusable rocket engines will be given.

NEED - REUSABLE ROCKET ENGINE CONTROL REQUIREMENTS

The philosophy behind rocket engine control system design has been that simpler is better. This contemporary philosophy has the effect of minimizing weight and acquisition cost and maximizing reliability. For expendable propulsion systems this is certainly a desirable approach. However, reusable rocket engines present a different and more challenging operational environment. Multiple start-stop cycles cause thermal gradients with high thermal strains per cycle. High steady-state operating stresses create large inelastic strains. High dynamic loads induce high cycle stresses. Although the Space Shuttle Main Engine (SSME) has been a reliable propulsion system, it has not demonstrated originally predicted levels of usable life (ref. 2).

To extend the useful life of a reusable propulsion system, an approach that includes the effect of the control design on maintenance costs, engine life, performance, and mission objectives dictates a control with additional intelligence (hence functionality). This additional capability may be achieved through improved algorithms and additional instrumentation and improved actuation hardware. It is anticipated that the cost of the additional complexity inherent in this additional capability will be more than offset by decreased life cycle cost.

Since many future rocket engines will be reusable, the technology and experience base that exists in the design, operation, and maintenance of reusable, airbreathing gas turbine engine control systems for commercial and military aircraft will be useful in developing an appropriate reusable rocket engine intelligent control system. One example would be a more extensive use of actively controlled critical variables (or their estimates) versus a reactive "red line/pink line" approach. A comparison of the operational environments for the turbomachinery of air breathing and rocket engines is given in table I. Note that the environments are similar except for the thermal transient environment, which is about 100 times more severe in the rocket engine, and the useful engine life, which is about 1000 times less in the rocket engine. In spite of the fuel difference it is concluded that these rapid thermal transients are a strong contributor to reduced rocket engine useful life. These transients occur during start-up and an active, closed-loop strategy has the potential to reduce these high thermal transients. Of course, increased start-up time to achieve more usable life has to be traded against the additional fuel burned and the resultant impact upon mission objectives.

In figure 1 the trend in control complexity for some airbreathing gas turbine engines is presented. Also, plotted on the figure is the SSME. From the figure it is seen that the SSME has substantially fewer control measurements and effectors than current airbreathing engines. It should also be noted that the SSME, consisting of four turboshafts, three combustors, and very complex flow paths, is considerably more complex than current air breathing engines. Additionally there are two phase flow, flow phase changes, and substantial heat exchange to complicate operation. The SSME is roughly two to three times more complex than the typical turbofan engine for example. Yet, the SSME has fewer control measurements and control effectors than current air breathing engines. Also, the environment of a rocket engine is orders of

magnitude harsher than airbreathing engines. Consequently, the usable component life of the SSME engine is orders of magnitude less than for airbreathing engines.

A more detailed comparison of the control systems for air breathing and rocket engines is shown in table II. The significant differences here are the start and stop strategies, and the use of multimode, active control for engine protection rather than a red line shutdown approach. Some work has already shown that improved control modes for the SSME, such as an advanced closed-loop control mode for turbopump preburner mixture ratio control, would help reduce thermal gradients for longer turbine blade life and reduce mixture ratio excursions for better turbine efficiency and increased thrust.

VISION FOR REUSABLE ROCKET ENGINE INTELLIGENT CONTROL

The need for improved control for reusable rocket engines has been discussed in the preceding section. Since it is clear that a transfer of technology from airbreathing engine control will be beneficial, the approach to development of an ICS would build on state-of-the-art airbreathing engine control technology to develop a broad system intelligence suitable for reusable space propulsion systems. Also, the approach would use SSME durability experience as a basis for a new life extending control capability and to expand capabilities for diagnostics and condition monitoring. Finally, an ICS design should be demonstrated by simulation and eventually on a test bed engine.

The author's particular vision of the framework of an ICS to meet these needs is given in figure 2. The framework provides a rational, top-down basis for the incorporation of system intelligence through the hierarchical integration of the control functional elements. This hierarchy integrates functionalities at the execution level such as the high-speed, closed-loop (traditional control) controller, engine diagnostics and adaptive reconfiguration with a top level coordination function. The top level coordination function serves to interface the current engine capability with the other engines in the propulsion system, the vehicle/mission requirements, and the crew. It modifies controller input commands and selects various control reconfiguration modes to resolve any conflicts between objectives.

The ICS Execution Level

As stated above the execution level of the ICS would consist of the high-speed control, the engine diagnostics, and adaptive reconfiguration. Each of these elements is described.

The high-speed control. - This portion of the ICS supplies the traditional fuel control function. As seen in figure 2 the high-speed control receives its input commands from the coordinator. Also the coordinator would signal changes in the various control modes of the high-speed controller in response to detected engine failures or to changes in mission objectives. In the SSME three modes are employed to control the engine. Two modes give open-loop start-up and shut-down capability. In the third mode, called the main stage mode, two closed-loops are used to control main combustion chamber pressure and an estimate of mixture ratio. In the ICS several additional control modes would be incorporated. Two new modes would be included that would extend

engine life through closed-loop control of engine start-up and shut-down. In the ICS not only would the main combustion chamber pressure and mixture ratio variables be controlled in main stage, but also the mixture ratios (and therefore turbine inlet temperatures) for the two preburners. Additionally, alternative modes would be included to limit maximum temperatures in the turbo-pumps. Also considered would be modes that would (1) accommodate the control reconfiguration selected by the intelligent coordinator due to failure detections, and (2) actively control engine operation to diagnose or predict component failure.

Diagnostics/prognostics. - The ability to obtain a diagnosis for the cause of incorrect engine operation and to obtain a prognosis of an impending component failure will greatly enhance engine safety, improve operability, and significantly reduce operational cost. Mission success potential will also be improved by using prognostic information to alter engine operation to conserve the remaining life of a failing component. ICS control systems will incorporate this kind of intelligence to accomplish these goals. The major requirement of this intelligence will be the capability to diagnose system failures, to predict impending failures, and to actively respond to these diagnoses and predictions in real-time. The diagnostic capability will take advantage of previous engine test and flight experience as well as human diagnostic experts familiar with the engine. The prognostic capability will be based upon current life and durability work in both space and airbreathing propulsion and a broad increase in condition monitoring instruments and interpretive analysis.

Not only does the ICS consist of a hierarchy of functions, but the diagnostic system is also seen as an intelligent hierarchy. This is shown in figure 3. Here the diagnostic execution level consists of several highly decentralized or independent subsystems, called condition monitors, where the first level subsystem inputs are the various engine measurements. The first level outputs are used by the next higher level and the failure accommodation control. These outputs would be more informationally dense than the subsystem inputs. Subsystem inter-communication would be minimized. Examples of these subsystem functions in the first level would include (1) sensor/actuator/valve fault detection (ref. 3), (2) directly diagnosable or prognosable component failures, (3) other time critical detection algorithms, and (4) specialized signal processing (e.g. power spectral density calculations for accelerometers or pattern recognition algorithms). Intermediate levels, if required, would consist of interconnections or groups of small, lower level subsystems. Intermediate level subsystems would be grouped by similar function, physical subsystem such as hydraulic system of LOX system, or geographical location. Finally, the top, or coordination, level would consist of a single, centralized system which would yield a diagnosis of failure mode cause or a prognosis of available component life. The top level would include the capability for reasoning from (1) experiential knowledge of the engine, (2) structural information, (3) functional information, (4) physical laws, and (5) and lower, execution level outputs.

Reconfiguration and adaptation. - Reconfiguration will be required to modify the control structure in response to diagnostic and detected fault information. Control reconfiguration will maintain a safe and graceful degradation of performance from fully operational status, to reduced operability, to a

shutdown condition. Reconfiguration will require that the control be simultaneously cognizant of both the engine operational requirements and status as well as the vehicle mission objectives and status. Adaptation will be required to adjust engine operation to small changes or degradations in component performance. Adaptation will require the identification of engine dynamics to define engine changes for use in the adaptive control law and for use in the diagnostic system.

The ICS High Level Intelligence

The ICS top level will consist of the coordination control. Coordination (high level intelligence) will be required to ensure safety and mission objectives while arbitrating the potentially conflicting requirements of optimum performance and durability. Also, the coordinator will integrate the control system with those of other engines in a multiple engine propulsion system. It is anticipated that Artificial Intelligence (AI) techniques will be useful in the design of the intelligent coordinator to integrate the required functionalities. The requirements for this top level of the control hierarchy include integrating vehicle mission goals and their criticality with engine status as determined by the diagnostic subsystem, the reconfiguration subsystem, and the adaptation subsystem. The high level intelligence will then be designed to use this information to deduce the appropriate control mode. Control mode would be selected based upon detected failure modes or changes to propulsion objectives. Examples of modes designed for different propulsion objectives include a maximum thrust mode, a propulsion utilization mode, and life extension mode. Once a mode is determined, the high level intelligence will generate the appropriate controller requests. The controller requests are the specific information used by the high-speed engine control loop to effect the desired engine performance, for example desired engine chamber pressure or desired mixture ratio.

As the coordinator of the major decisions between vehicle, engine, crew, and ground, the high level system intelligence will autonomously implement time-critical decisions and request authority on nontime-critical decisions. Nontime-critical decisions would be made by crew or ground personnel between flights or firings or during a flight if possible. This will allow the crew and ground personnel a high level interface to the engine control.

One example of a decision that the coordinator would make would be to modify the main chamber mixture ratio for propellant utilization or to preserve hardware. Another decision would be to change control modes due to a faulty actuator, an impending component failure, or a ground or crew request in response to a changing mission objective. A final example would be a decision to change the engine operating condition within a mission profile to avoid excessive vibration at a critical speed or speed, pressure, and temperature limits.

THE CHALLENGE - IMPEDIMENTS TO INTELLIGENT SYSTEM CONTROL

Although the benefits to be gained by the application of an ICS to future reusable rocket engine systems are impressive, the challenges to successful implementation of such a control are great. Not the least of these is that an ICS prototype must successfully demonstrate all of the above mentioned functionality in a time frame consistent with real-time operation of the rocket

engine. Many intermediate steps for successful demonstration will be required. One step would include modeling engine failure and life modes for simulation and design. These models would also incorporate start and stop dynamics as well. Another step would be the successful design of the coordinator itself, and successful integration of a host of subsystem processors into a functioning unit. This last step would include the integration of the symbolic processing expected in the top levels of the control or the diagnostic system with the numeric processors expected at the execution levels of these systems. Once the functional demonstration is complete, it must be conclusively evident that the costs associated with the additional instrumentation, actuation, control computers, and control software will be more than offset by a reduction in life cycle cost.

The authors' recognize that the use of expert system based decision making in real-time will require significant advances in artificial intelligence. Advances required include improved computing times, realistic hardware, and improved software. Faster hardware devices are becoming available almost daily to improve computing times. Also, new approaches to solving the tree-based decision algorithms of expert systems are being investigated. Also symbolic processors are now becoming available as computer board-level products suitable for integration into traditional computer control systems. Additionally, some method of verifying and validating the software for such a highly integrated and intelligent control must be found.

CONCLUDING REMARKS

The authors' vision of an ICS was presented. This vision included a distributed, hierarchical control which embodies a high degree of intelligence. The need for such a capability was presented. The impressive functionality of an ICS was shown to be predicated upon the active use of additional instrumentation and actuation. Some of the more significant challenges to the successful demonstration of an ICS for reusable rocket engines were presented.

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TABLE I. - AIR BREATHING AND ROCKET ENGINE ENVIRONMENT COMPARISON^a

Item	Rocket engine turbine	Air breathing engine turbine
Turbine inlet temperature, °F	1540	2600
Blades cooled	No	Yes ^a
Blade metal temperature, °F	1500	1500 to cruise 1650 to takeoff
Rotor tip speed, ft/sec	1850	1850
HP/rotor blade, hp	500	600
Material	Superalloy-Mar-M 246	Superalloy-Mar-M 246 RE 120
Start time, sec	0.5 to 3	30, Typical
Stop time, sec	0.1 to 0.5	30, Typical
Thermal transients, °F/sec	3000 to 8000	50 to 100
Start-stop cycles	0.2 to 55	2400
Useful life, hr	0.1 to 7.5	8000

^aTable courtesy of Rockwell International, Rocketdyne Division.

TABLE II. - ENGINE CONTROL SYSTEMS COMPARISON

Engine control systems	
Space Shuttle Main Engine	Turbofan
Open-loop start/stop Programmed value sequencing	Closed-loop start/stop N and T ₄ feedback Control of temperatures and pressures Avoids instabilities
Closed-loop main stage Two control loops Single mode operation 1. Thrust/implied mixture ratio control Red line temperature shutdown	Closed-loop operation Four control loops Four mode operation 1. Thrust/fuel consumption 2. Thrust/temperature limit 3. Thrust/minimum air flow limit 4. Thrust/maximum pressure limit
Single-loop, noninteractive control design	Multivariable interactive control design with turbine temperature estimation

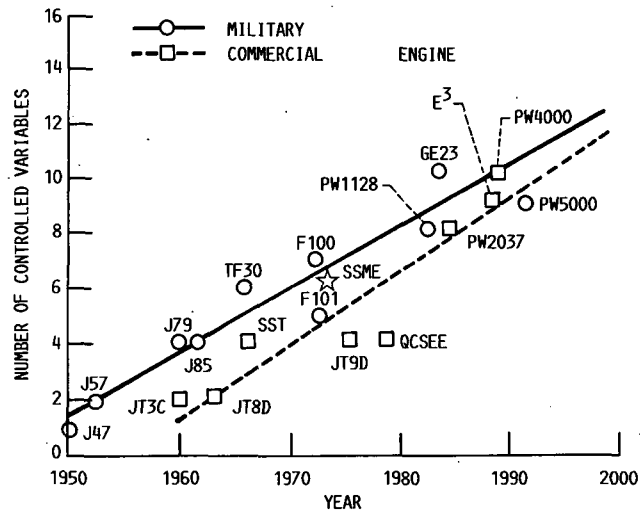


FIGURE 1. - TRENDS IN CONTROL COMPLEXITY FOR AIRCRAFT TURBINE ENGINES AND SSME.

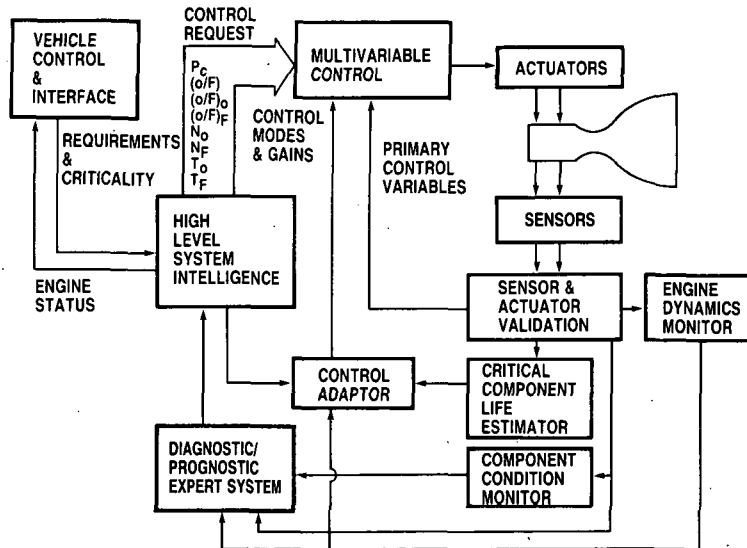


FIGURE 2. - REUSEABLE SPACE PROPULSION INTELLIGENT CONTROL SYSTEM FRAMEWORK.

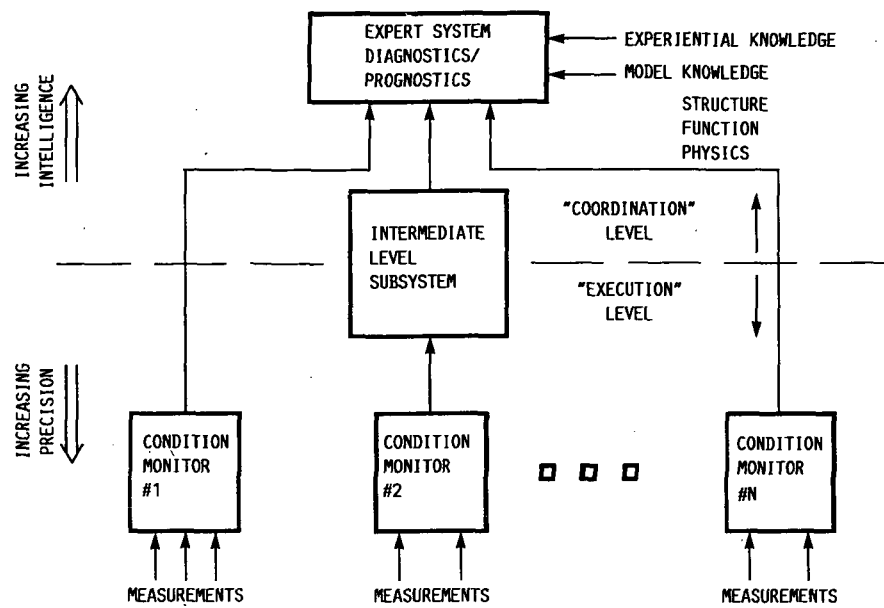


FIGURE 3. - DIAGNOSTIC/PROGNOSTIC SYSTEM HIERARCHY.



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