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Controls Concepts for Next Generation Reuseable Rocket Engines

Carl F. Lorenzo, Walter C. Merrill, and Jefferey L. Musgrave
Lewis Research Center
Cleveland, Ohio

and

Asok Ray
Pennsylvania State University
University Park, Pennsylvania

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Carl F. Lorenzo, Walter C. Merrill and Jefferey L. Musgrave
NASA Lewis Research Center
Cleveland, Ohio 44135
FAX: (216) 433-8643
Carl.F.Lorenzo@lerc.nasa.gov

Asok Ray
Penn State University
University Park, PA. 16802

Abstract

Three primary issues will drive the design and control used in next generation reusable rocket engines. In addition to steady-state and dynamic performance, the requirements for increased durability, reliability and operability (with faults) will dictate which new controls and design technologies and features will be brought to bear. An array of concepts which have been brought forward will be tested against the measures of cost and benefit as reflected in the above "ilities". This paper examines some of the new concepts and looks for metrics to judge their value.

1. Introduction

Next generation reusable rocket engines will be strongly based on the experience gained through the design, development, and operation of the space shuttle main engine (SSME). The primary problems associated with that engine have been issues of durability of the hardware in particular of the turbine blades, bearings, and thrust chamber liners as well as various propellant ducts. Further, reliability issues with engine sensors have also been a problem. Many of the problems associated with the SSME have been summarized [1]. The durability and reliability problems which were encountered in the early SSME experience drove a variety of research efforts at NASA Lewis Research Center into various controls concepts to help alleviate these problems. These research areas included topics such as intelligent control, multivariable control, and life extending or damage mitigating control. Controls derived technology may also be useful in other ways in next generation rocket engines. For example, the techniques developed for the life extending control may have great usefulness in the design of some hardware and in the engineering of the engine start-up and shut-down processes. This approach has been called the Robust Rocket Engine Concept and will be included with other control concepts covered in this paper. In addition, earlier research in areas such as analytical redundancy applied to gas turbine engines may be important in the direction of future controls for reusable rocket engines.

The selection of control concepts for the next generation reusable rocket engines will be a difficult task. A number of important issues will need to be addressed, both at the propulsion system design level and at the controls design level. These issues include, a) the suitability and readiness of the control concept to address the problem or issue for which they were designed (i.e. effectiveness); b) the benefit or impact of the concept on steady state performance, dynamic performance, weight of the engine and availability of the engine through the propulsion phase of the vehicle; and c) the cost of the concept in terms of life cycle cost, added sensors, added or actuators, weight and design impact or complexity.

This paper will present selected control concepts applicable to next generation rocket engines and for each of these describe briefly the concepts, the status of the technology with an abbreviated bibliography, the expected benefits and the known costs at this time. Further, the paper will explore broad issues in selecting which if any of these concepts will be used in the next generation engine. Finally, the paper will examine implementation issues from a high level.

2. Controls Concepts

The controls concepts discussed in this section are not all inclusive and largely represent the research thrusts in a Resuseable Rocket Engine Control by the Advanced Controls Branch at NASA Lewis Research Center over the last decade. The Intelligent Control technology also serves somewhat as an organizing (hierarchical) structure in to which the other concepts may be fit.

2.1 Intelligent Control System

Concept: A concept for an Intelligent Control System (ICS) has been proposed by Merrill and Lorenzo [2, 3] which consists of a hierarchy of variouis control and diagnostic functionalities for application to a reusable rocket engine. These functionalities include life extending control, reconfigurable control, real-time diagnostics, component condition monitoring and engine prognostics. The ICS approach requires a successful marriage between modern control and artificial intelligence. The ICS framework is shown in Figure 1. Figure 1 shows the ICS for only a single engine in a propulsion system. Figure 2 shows the engine level ICS in the context of a three engine propulsion system as in the Orbiter vehicle. The mission level control is the highest in the hierarchy and is responsible for providing vehicle thrust and mixture ratio requirements to the propulsion level control. The propulsion level control is responsible for meeting propellant utilization requirements, performing propellant tank pressure regulation (both liquid hydrogen and liquid oxygen), and giving thrust and mixture ratio commands to each engine level control meeting requirements. The engine level control is responsible for satisfying thrust and mixture ratio demand, avoiding engine conditions having a detrimental impact on hardware durability, and accommodating engine component hard/soft faults. As shown in the figure, requirements flow down in the hierarchy and status information for decision making flows up.

The real-time diagnostic system included in Figure 1 consists of sensor validation, model based failure detection, rule based failure detection, and the diagnostic expert system. These functions, described below, are all part of a real-time distributed architecture for diagnostics and are responsible for identifying and isolating any change/degradation in engine valves, sensors or components. The engine level coordinator makes alterations to the control using engine status information generated by the diagnostic system, and propulsion requirements provided by the propulsion level control. The reconfigurable controller takes requests generated by the coordinator, makes the changes gradually thereby minimizing engine transients, and computes the valve positions to achieve the requested behavior from the rocket engine. All operations at the engine level must be performed in real-time, however, high sampling requirements are necessary only for the direct control loop which is composed of sensor validation and reconfigurable control. Other operations such as decision making in the coordinator may take longer but must known and small relative to the failure development rate.

Status: For an ICS, workable framework architectures have been established [2,3,4]. The primary functionalities of multivariable control, sensor validation, failure detection, diagnostics and coordination have been demonsrtated by simulation to evaluate ICS performance. The ICS approach has been developed and applied to the SSME by simulation to evaluate ICS performance. The above functionaltities have been demonstrated to some extent by simulation [4,5,6,7]. Both the multivariable and the life extending control components will be discussed further in later sections. Simulation results for the three engine propulsion system have also been achieved and are given in [4].

As an illustrative example, a propulsion level, damage balancing control is studied. The propulsion system consists of three separate, nominally identical engines which need to be coordinated to give the desired thrust as determined by mission requirements. This coordination is accomplished at the propulsion level. Information on the thrust and the current life status of each engine are transmitted from the engine level to the propulsion level. Each of the engines has its own, independent engine control which exists at the engine control level. Each engine in the propulsion system consists of a fuel turbopump, an oxidizer turbopump, and a main combustion chamber. The turbopumps consist of a preburner, bumine, and pump. Fuel and oxidizer are burned in the preburners. The hot gas generated in the preburners drive the turbines which in turn drive the pumps. The fuel and oxidizer turbine discharge temperatures, TOT2d and TFT2d respectively, represent important indicators of engine health. A simplified life model using the temperatures to compute a relative damage rate, D, for the engine is approximated as

$$D=k_1+k_2 MAX(TFT2d-TFT2d_N, TOT2d-TOT2d_N)+k_3 F^2$$

where the k's are constants, $TOT2d_N$ and $TFT2d_N$ are the fuel and oxidizer turbine nominal discharge temperatures respectivel, and F is thrust. In a gross sense, if either of these temperatures rise above a nominal level, the engine has degraded and has less useable life remaining. The nominal discharge temperatures would be a function of the power level of the engine. Thus, if the engine runs "hot" at any power level, e.g. $TFT2d-TFT2d_N > 0$, damage will accumulate faster than the nominal damage rate.

The propulsion level control has two goals, 1) control individual engine thrusts to be equal to the vehicle thrust command, and 2) force the individual engine damage rates to be as nearly equal as possible. Here the thrust from each engine is added to give a vehicle thrust measurement for comparison with the desired vehicle thrust. Also, the damage rates are combined linearly to automatically adjust individual thrust commands to the engine level controls to achieve equal damage rate for each engine. Example results are given in Figure 3. Here, there is a requested increase in vehicle thrust at t=0 sec. to which the propulsion system responds. Additionally, it is assumed that engine #3 degrades linearly starting at $t= t_1$ such that

$$TFT2d-TFT2d_N = k\,(t- t_1) > 0$$

where k is a constant. Between t_1 and t_2, the control achieves equal damage rates for each engine while maintaining the vehicle thrust level. This is achieved by a downthrust of engine #3 and an upthrust of engines #1 and #2. At $t = t_2$ engines #1 and #2 are at their maximum thrust levels and the degradation of engine #3 can no longer be mitigated without reducing the vehicle thrust level. Therefore, between t_2 and t_3 engine #1 and #2 thrust levels remain constant and the #3 damage rate increases beyond the #1 and #2 levels. At t_3 the mission commanded vehicle thrust is reduced and the propulsion level implements the reduction using only engine #3, the engine displaying the highest level of life usage, until t_4 where the damage rates are again equal. Between t_4 and t_5 the decreasing vehicle thrust command is implemented by thrust reductions in all three engines that result in equal damage rates. At t_5 engine #3 is at its minimum thrust and can no longer be downthrust. Since the engine continues to degrade, for each event in the simulation scenario, the propulsion level coordinator commands the individual engine thrust levels to values that minimize engine wear rate and risk, as defined by the damage rate model, within the mission level and engine level constraints.

Results achieved in the area of diagnostics include failure detection using model-based algorithms, expert systems and neural networks. The detection of actuator faults using model based algorithms was demonstrated [8]. An expert systems approach was used to detect problems in the seal systems of the high pressure oxidized turbopumps [9]. Finally, a neural network has been developed to validate sensor information and identify sensor faults [10].

Benefit: An ICS will extend engine life and allow useful, degraded peformance in spite of component failures of a reusable propulsion system, which may include multiple engines. This is accomplished by intelligent control of engine operation to achieve mission objectives while minimizing flight maintenance and maximizing engine life and performance.

Cost: The increased capability of the ICS will require improved algorithms and additional instrumentation and improved actuation hardware.

Assessment: Currently, most of the ICS primary function could be incorporated into a next generation propulsion system. Due to the inherent modularity of the ICS, a building block approach could easily be adopted. Modules representing additional functionality or addtional capability within a function, such as coverage of additional faults, can be added as time and cost permit. 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.

2.2 Multivariable Control

Concept: Control systems for liquid propellant rocket engines have focused on single loop control designs to date. The strengths of this approach are simplicity in design and implementation, low sensing requirements and familiarity. However, multivariable control design offers much greater opportunity for accurate control of the engine cycle in a liquid propellant rocket engine.

Rocket engine control is inherently a multivariable problem because both mixture ratio and chamber pressure must be accurately controlled simultaneously using two or more valves which regulate the amount of fuel and the amount of oxidzer entering the combustion process. Moreover, propellant control valves are often available to regulate the cooling flow around the main combustion chamber and nozzle. Additional valves may be added if independent control of critical temperatures is necessary to reduce the risk of a redline shutoff during off-nominal conditions [17,18]. Multivariable design methods provide the necessary coordination between flow control valves to meet closed loop specifications using some subset of the sensor suite. In a mulitvariable setting, the peformance specification may be very sophisticated and include rate limits and energy constraints on propellant control valves, command following of critical engine parameters which correspond to peformance and life, and minimum robustness criteria to handle sensor noise, off-nominal operation and inaccurate modelling.

Status: Both LQG/LTR and H-infinity multivariable design methods have been applied at NASA Lewis to the Space Shuttle Main Engine (SSME) for closed loop control. A design method using LQG/LTR was developed for the servo-compensator and applied to the SSME for tracking commands of chamber pressure, mixture ratio and high pressure fuel and oxidzer turbine discharge temperature [7]. Simulation of the SSME MVC has been conducted using the non-linear real-time engine model developed by Rocketdyne for testing SSME controller hardware [19].

Several software tools are now available for computer aided design of control systems and are complete with block diagram-like modelling, design, analysis and real-time code generation features. Multivariable control has never been more acessible for application to liquid propellant rocket engine control. However, several challenges remain in developing practical multivariable rocket engine controls. Valve hysteresis and saturation are difficult problems to handle in a multivariable setting and require complicated schemes to maintain stability with a subsequent loss of performance guarantees. Loss of valve effectiveness under reduced flow conditions results in extremely nonlinear behavior over the entire operating envelope. Difficulty in placing sensors and actuators due to the harsh environment result in non-minimum phase zeros for example. Detailed nonlinear transient models are necessary for control law development and can often be quite different from the models required for hardware in the loop evaluation. The above list is by no means exhaustive but presents some of the important issues to be addressed in developing a practical mulivariable rocket engine control.

Benefit: Multivariable control is particularly well suited to rocket control because the engines are traditionally open loop stable with few changes in power level. Consequently, a relatively small number of linear design points will be required to provide accurate control over the operating envelop. The thrust profiles are well defined a priori and limited in number allowing for optimization to minimize component damage and maximize performance. The control problem falls naturally into a servomechanism framework for command following of critical engine parameters for enhanced engine life without a loss in engine performance.

To illustrate, a multivariable design method [17] is applied to the SSME for closed loop control from 65% power to 100% or rated power. The control objective is extended from control of chamber pressure and mixture ratio to include the discharge temperatures of the high pressure oxidizer and fuel turbines. Toward this end, an additional valve is added to regulate the fuel flow between the fuel and oxygen preburners of the staged combustion cycle (ie. the oxidizer preburner fuel valve). Hence, the oxidizer preburner oxidizer valve, the oxidizer preburner fuel valve, the fuel preburner oxidizer valve and the coolant control valve are used to provide command tracking the aforementioned engine parameters [17].

Benefits of the multivariable design and the additional actuator are shown in Figure 4. Each figure represents a region of controllability of both the high pressure fuel turbine discharge temperature (TFT2d) and the high pressure oxidizer turbine discharge temperature (TOT2d). The data in each figure is generated using the real-time rocket engine model [19] with a single design point (rated power) linear multivariable control (MVC) developed in [17]. The upper limit on the region of controllability is computed for each given power level by selecting a setpoint for TFT2d and then increasing the command for TOT2d until under damped oscillations occur in any of the controlled parameters. A similar procedure is used to generate the lower bound for each of the power levels.

Figure 4a shows the region of controllability of the high pressure turbine discharge temperatures at rated power. The SSME redline limits are provided for reference for each high pressure turbopump. The MVC provides a fairly broad range of temperature control of the turbines at rated power. The controller is capable of taking TFT2d to redline but not TOT2d. The uncontrolled steady-state temperatures achieved with the current SSME controller (Block I control) are indicated in the figure. The Block I temperatures fall along the minimum temperature curve for the turbomachinery. This is not surprising since the engine is optimized for rated power operation. The MVC provides the opportunity for sliding along this minimum temperature curve to change the temperature distribution accross the turbopumps. Figure 4b shows a similar analysis at the 80% power level. The uncontrolled steady state temperatures with the Block I control are several hundred degrees above the minimum temperature curve for the turbomachinary suggesting that the temperature could be reduced at this power level if desired. Recall that no scheduling of the MVC is required in the results shown as a single point design is used from 65% power to 100% power. Finally, at 65% power (minimum power) a similar region of controllability is generated as shown in Figure 4c. The uncontrolled temperatures results from the Block I control are nearly in the center of the region suggesting considerable flexibility in the temperature distributions accross the turbmachinery. More work is needed to determine an operating strategy based upon this added capability for the SSME across all power levels. Additional flexibility may be realized if multiple point control design are used in conjunction with a scheduling policy

Cost: The development of a multivariable control for rocket propulsion requires detailed models of the engine cycle. An expanded control objective for the engine requires analysis and testing to fully understand the pros and cons of the operating strategy and its effect on the engine system from an engine performance and durability perspective. An expanded control strategy will result in a more complex control law which is harder to validate, implement and typically requires a faster sampling rate. More sensors and actuators may be desired and could adversely affect the overall system reliability if algorithms for sensor fault and actuator fault accommodation are not included in the control architecture.

Assessment: Multivariable control has matured to the point where application to complex problems is tractable and cost effective. A diversity of algorithms are available which address a broad range of issues involved in the development of algorithms for reusable rocket engine control. Software tools are available which allow rapid prototyping and generation of real-time code to simplify the implementation process and provide a straight-forward means to track the code. However, implementation issues remain which must be addressed such as actuator saturation, gain scheduling and controller discretization.

2.3 Life Extending Control

Concept: The fundamental idea of Life Extending (or Damage Mitigating) Control (LEC) [11,12,13] is that the amount of damage accumulated at critical points in the propulsion structure during transient operation may be substantially reduced by careful control during these periods. The philosophy is to feedback the damage rates at critical points in the propulsion system, say at the turbine blades and cooling jacket walls and through nonlinear optimization to use that information to minimize damage at these points while simultaneously maximizing dynamic response. Two types of damages are considered for the reuseable rocket engine, fatigue/fracture and creep. To incorporate fatigue/ fracture requires a continuum time base damage theory as opposed to the traditional cyclic based damage laws.

Status: The above concept has been developed in some detail for application to reuseable rocket engines (SSME-like). Continuum fatigue damage models suitable for controls studies have been developed [12,14]. Optimization methods have been applied to detailed non-linear simulations. The studies to this point have been primarily open loop. That is, valve position sequences to take the engine through a step change in thrust have been optimized for minimum damage and maximum response. These studies have been done based on fatigue damage only [15], with fatigue and creep damage [16] and all with various levels of initial damage. The state-of-the-art does not allow direct sensing of damage, however, research [14] has shown a strong non-linear relationship between local stress and damage rate. This stress level, through an appropriate non-linear filter, can be used as a damage rate feedback.

Benefit: Results for a commanded step increase in thrust for a reuseable rocket engine considering O_2 & H_2 turbine blade fatigue damage only [15] are shown in Figure 5. The results show the unconstrained (non optimized) accumulated damage through the transient to be three or more times that achieved with LEC. The reference paper details how these results were achieved. When creep damage is included similar transient gains can be shown. However, creep damage during the steady part of the mission may dominate. Current research efforts are directed to achieving improved results while shifting from an open loop to a closed loop control structure.

Cost: Aside from engineering costs, the primary operational cost for LEC is increased computation. This assumes that stress will not be directly measured but inferred from a structural estimator and further that damage rate will be calculated from inferred local stress and temperature. The alternative would be increased sensing. The cost in the design phase is the current requirement to use nonlinear optimization for at least part of the controller design. Current research efforts may simplify or eliminate this requirement.

Assessment: With modest additional research to simplify implementation, LEC can be ready for use for next generation reuseable rocket engines. While it is difficult to predict in advance where the critical damage locations will be, it is probably a safe assumption that turbine blade roots and thrust chamber cooling jacket walls will continue to be problematic. Experience has shown that a control that minimizes damage at these points will likely reduce damage generally in the engine.

2.4 Robust Rocket Engine Concept (RREC)

Concept: This recent concept [20] is an outgrowth of the work done on LEC. From the SSME experience it is known that much of the damage per flight is accumulated during the start-up and shut-down transients, the application of damage minimization (from LEC concept) during these periods together with design aspects can potentially yield dramatic improvements in engine durability. The design aspects include multidisciplinary optimization of the operating cycle (in a new design) as well as aero-structural optimization of critical components such as turbine blades, cooling jacket liners, etc. The approach may also include controlled or partially controlled start up and shut down transients. A high level view of the design process is shown in the flowchart in Figure 6.

Status: The concept has only recently been formulated. There have been no detailed studies performed.

Benefit: The benefits at this point are potential. Since LEC has shown the ability to reduce fatigue damage through transients to less than 1/3 of that which would normally be seen, RREC would appear to have the potential of an order of magnitude or more durability improvement. A very attractive feature of this approach is that it provides a focussed unified global approach to the design process for the engine system. That is it creates a clear measure (criterion of goodness) against which decisions to include or exclude various design features may be made.

Cost: The fundamental cost of this approach is increased computation during the design process. The evolved designs may also have mildly penalized dynamic response and propellant usage.

Assessment: The primary analytical tools are available to implement this concept; these are a useable simplified continuum damage model and nonlinear optimization tool. The issue may be industrial readiness.

2.5 Issues

Engine (and controls) designers for next generation reuseable rocket engines will be faced with the problems of deciding which if any of the above control concepts will be incorporated. As pointed out in the introduction, technology readiness, benefit and cost will drive that decision. Mission importance will also influence which technologies are applied.

Key issues that will be compared for the technologies are: number of sensors required (how much information required), what type of sensor, location in the engine, number of actuators required and their location in the cycle, and finally the computational burden. Clearly, the impact of added (or removed) components on system reliability need also be evaluated.

There is little theoretical guidance on the number of sensors and actuator required, the concepts of observability and controllability are useful but don't really do the job in a practical sense, especially for a nonlinear plant. Perhaps new or additional theory is required here. The computational burden may be estimated and reliability effects may be evaluated given component reliabilities. The effect of the control algorithms, for example Intelligent Control, on system reliability will also need to be assessed.

Sensor Requirements: There is a current thrust in aeropropulsion to reduce the numbers of sensors used for control, while at the same time the expectations from the controls system are increasing. This may be an anomalous situation.

Clearly, that feedback sensing is used at all is motivated to account for system disturbance (and load) as well as changes in the plant. These changes may come from system degradation and are assumed parametric rather than structural. There is clear need for an analytical (practical) test that can be applied to nonlinear systems or simulations that will indicate if too few sensors or sensors of too low an accuracy have been chosen. This can be time or frequency based. The test may be implemented analytically or by simulation.

The minimum sensor set needed to satisfy such a test however, may not be adequate for other aspects of control. For example, if a model based control is the approach of choice, and if the model is to be upgraded to respond to plant degradation, the sensor requirements to adequately identify the plant in the allotted time (or samplings) and over the selected operating domain may require an additional test. Further, if sensor failure is to be accommodated in a system using a method such as analytical redundancy then either more sensors or a reduced tolerance will be required. Finally, for intelligent control systems where decisions will be made by the control to accommodate physical changes in the plant a minimum set of diagnostic sensors must also be identified.

Actuator Requirements: For reusable rocket engines actuator requirements, i.e., number, location, bandwidth and resolution are usually set in a more or less ad hoc way (usually by the engine designer). Minimum actuator requirements, here number and location, are determined by the number of primary engine variables to be independently controlled. Usually this level of capability is established (or specified) during the cycle analysis phase of the engineering typically not involving the controls designer.

If this is taken as a base reference point, then the decision to add more actuators will be based on the increased functionality the actuator allows. Then a simple cost/benefit ratio analysis can guide the decision. For example, an additional actuator will allow the reduction of turbine inlet temperature and hence turbine life extension [18]. The trade-off here is relatively straight forward. As a further example, occasionally the addition of an actuator or an increase in bandwidth of an existing actuator will allow the system to operate in a domain that would otherwise be unstable. In this case associated performance gains may justify the addition.

3. Concluding Remarks

This paper has presented a cross section of current controls technology research applicable to next generation reusable rocket engine control. The areas discussed grew out of the NASA Lewis effort to respond to durability problems experienced in the space shuttle main engine. The concepts covered include: Intelligent Control, Multivariable Control, Life Extending Control, and a concept for engine start-up and shut-down called the Robust Rocket Engine Concept. The paper has assessed the status, benefits and costs of the various concepts and has exposed key issues which will likely decide which of these concepets will be applied in next generation engines.

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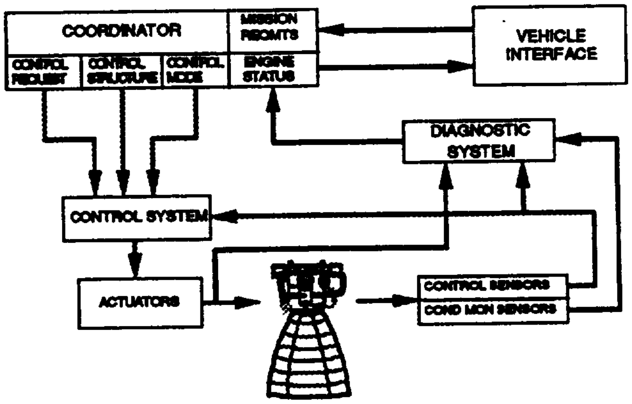

Figure 1 Intelligent Control Functional Framework

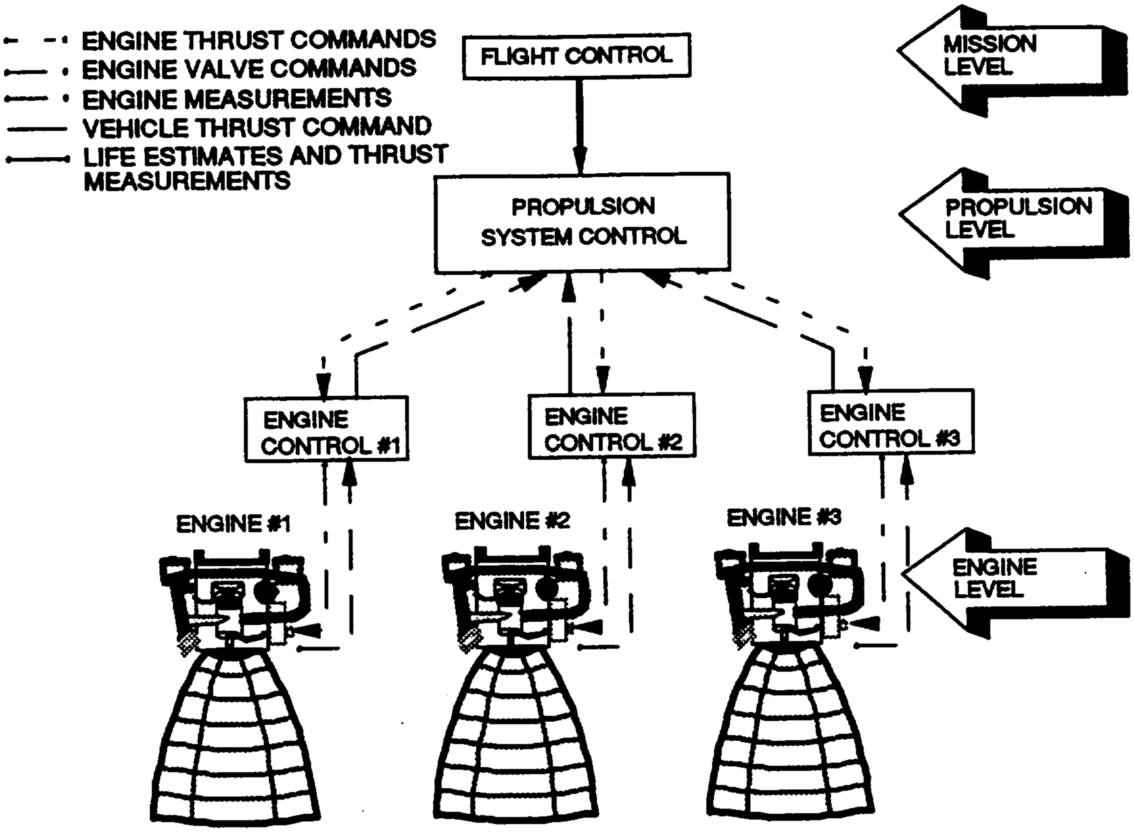

Figure 2 Hierarchical Propulsion Control System

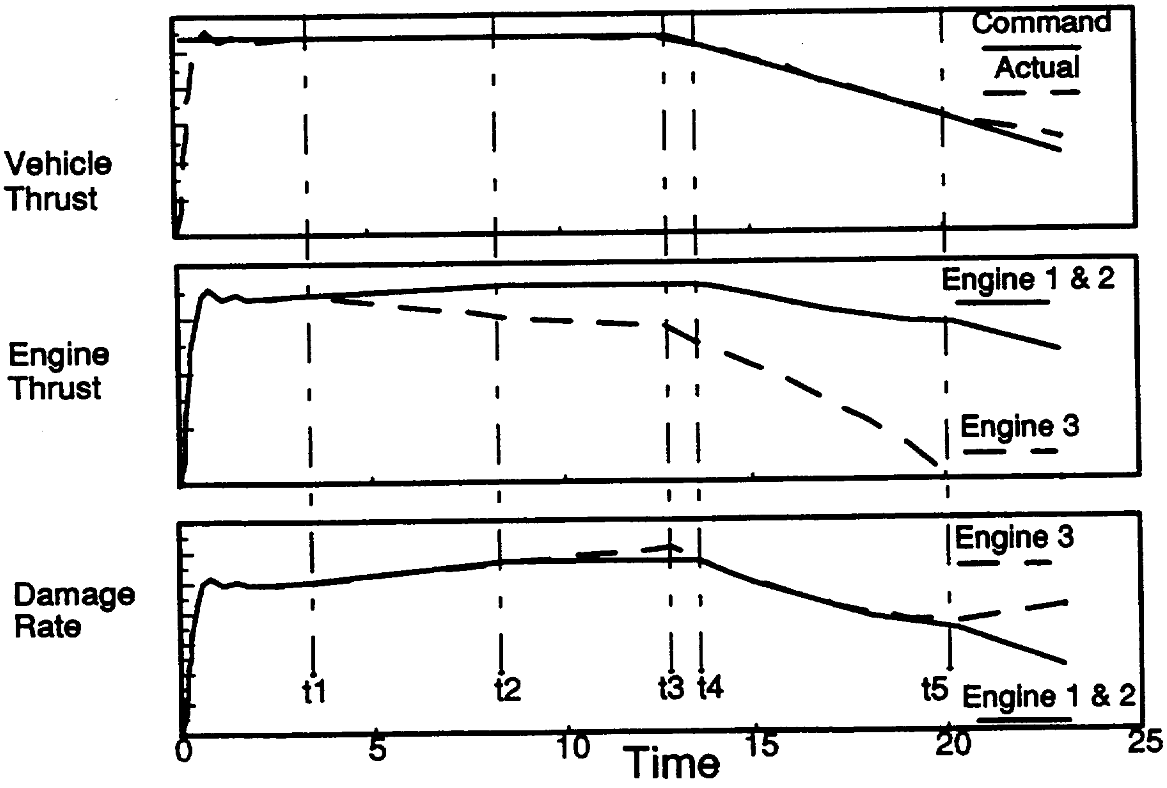

Figure 3 Results for Propulsion Level Intelligent Control

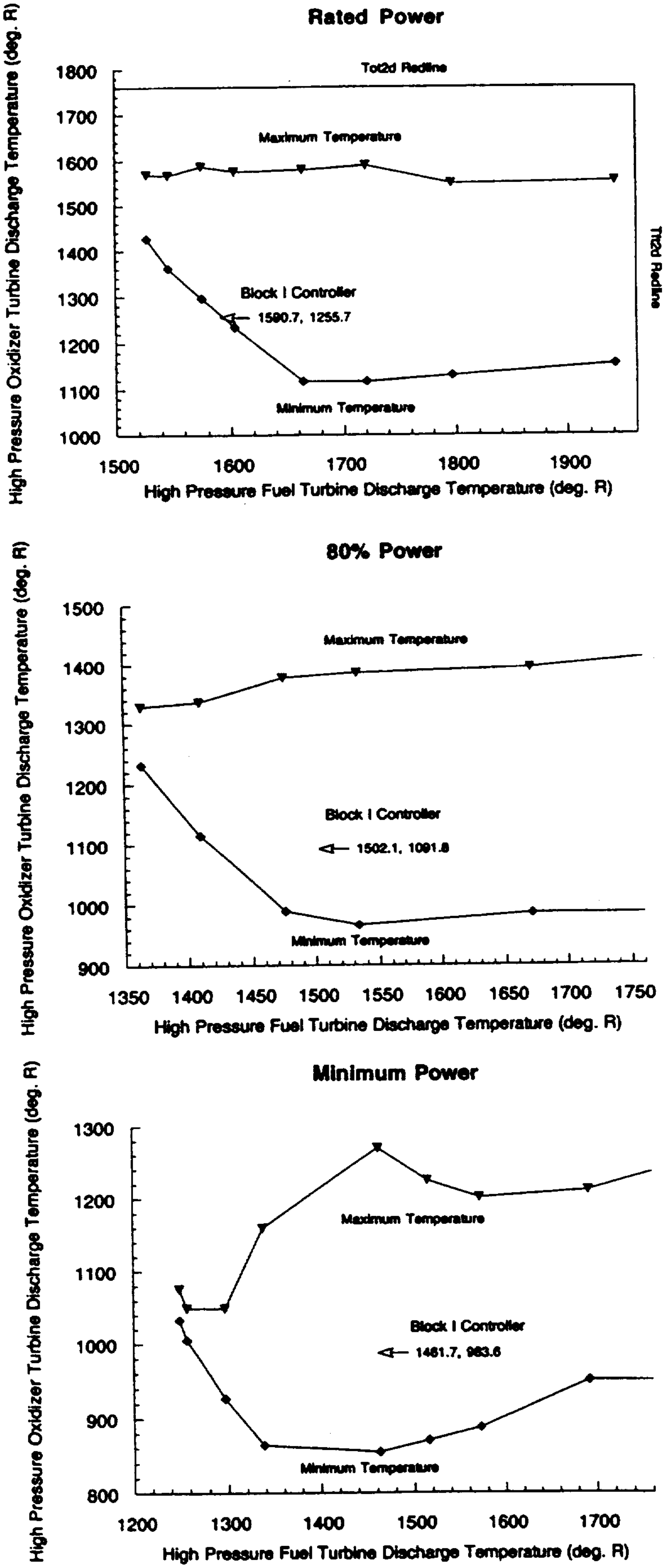

Figure 4 Regions of Turbine Discharge Temperature Controllability

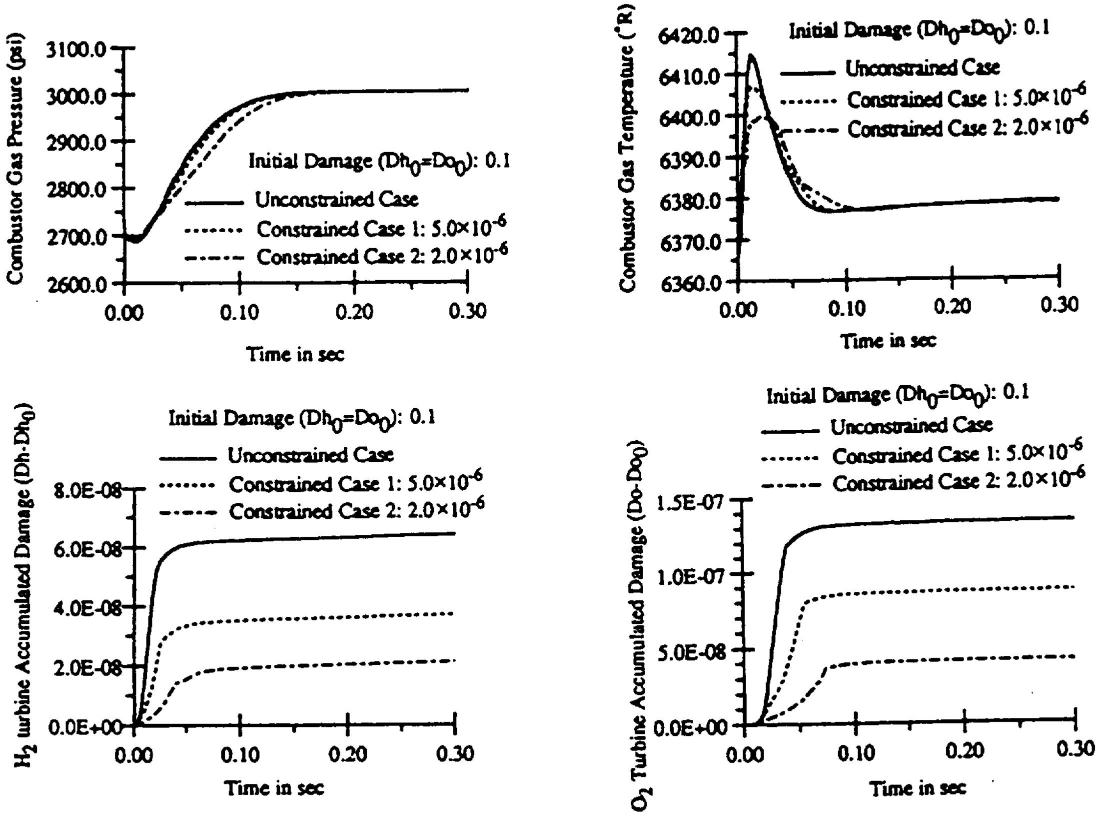

Figure 5 Reusable Rocket Engine Life Extending Control Results

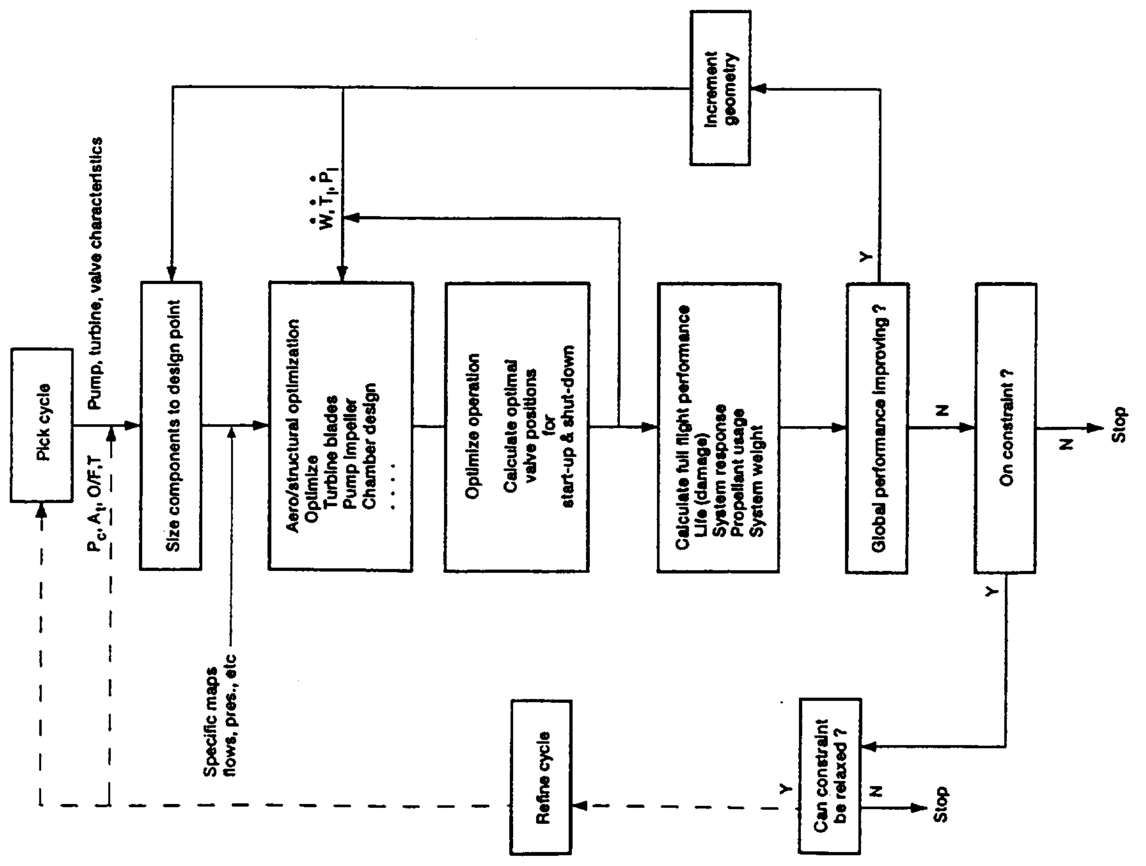

Figure 6 Rocket Engine Multidisciplinary Design Optimization Flow Chart

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Carl F. Lorenzo, Walter C. Merrill, Jefferey L. Musgrave, and Asok Ray

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

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Three primary issues will drive the design and control used in next generation reuseable rocket engines. In addition to steady-state and dynamic performance, the requirements for increased durability, reliability and operability (with faults) will dictate which new controls and design technologies and features will be brought to bear. An array of concepts which have been brought forward will be tested against the measures of cost and benefit as reflected in the above "ilities". This paper examines some of the new concepts and looks for metrics to judge their value.

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