APPLICATION OF ADVANCED CONTROL TECHNIQUES
TO AIRCRAFT PROPULSION SYSTEMS

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# CONTROLS FOR ADVANCED TURBINE ENGINES

The trend in advanced aircraft turbine engine design is toward more sophisticated cycles and mechanical complexity. This is done primarily to achieve improved thrust-to-weight ratios and improved specific fuel consumption. Control system complexity has also increased due to the increase in the number of engine variables which must be scheduled or controlled. Hydromechanical controls are rapidly being replaced by full-authority digital electronic controls in order to handle the added computational burden. The digital computer, however, does allow more sophisticated control algorithms to be used. In this paper, two Lewis Research Center sponsored programs will be described which involve the application of advanced control techniques to the design of engine control algorithms. Multivariable control theory has been used in the F100 MVCS (multivariable control synthesis) program to design controls which coordinate the control inputs for improved engine performance, and it presents a systematic method for handling a complex control design task (fig. 1). Methods of analytical redundancy are aimed at increasing the control system's reliability. The F100 DIA (detection, isolation, and accommodation) program will be described, which investigates the uses of software to replace or augment hardware redundancy for certain critical engine sensors.
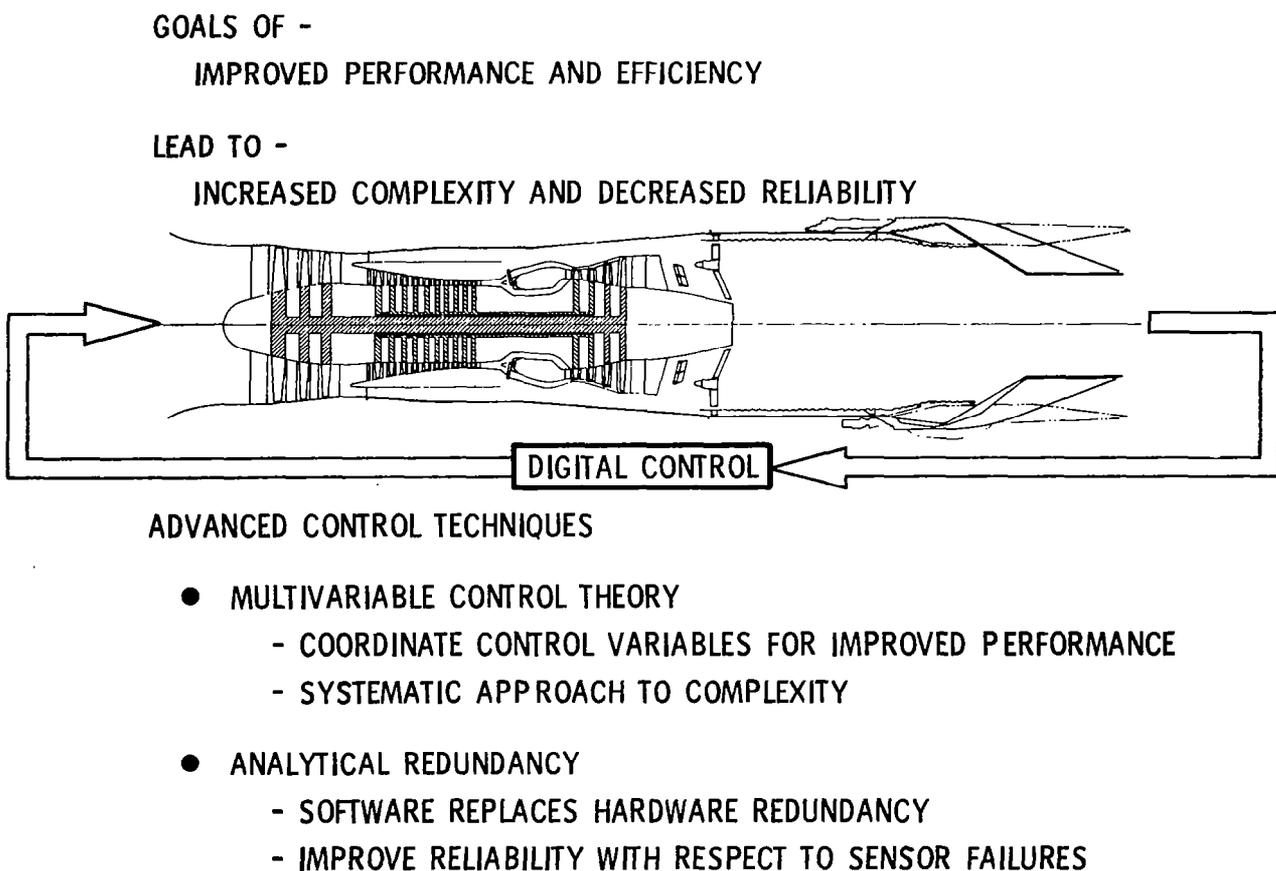
GOALS OF -

IMPROVED PERFORMANCE AND EFFICIENCY

LEAD TO -

INCREASED COMPLEXITY AND DECREASED RELIABILITY

DIGITAL CONTROL

ADVANCED CONTROL TECHNIQUES

- MULTIVARIABLE CONTROL THEORY
    - COORDINATE CONTROL VARIABLES FOR IMPROVED PERFORMANCE
    - SYSTEMATIC APPROACH TO COMPLEXITY

- ANALYTICAL REDUNDANCY
    - SOFTWARE REPLACES HARDWARE REDUNDANCY
    - IMPROVE RELIABILITY WITH RESPECT TO SENSOR FAILURES

Figure 1

The interrelationship of the two programs is depicted in figure 2. Activity in applying multivariable control methods to engine controls began in the mid 1970's (refs. 1 and 2). Motivated by these early results, a comprehensive program (F100 MVCS) was begun to demonstrate the benefits of using control theory to design a full envelope control for an F100 engine and to verify the design with both simulated and actual engine testing. Figure 2 shows the NASA LeRC facilities which were used in performing the evaluations of the MVC logic. The facilities consist of 1) a research-type control computer on which the control algorithms are programmed, 2) a real-time (hybrid) simulation of the F100 engine, and 3) an altitude test cell in which a full-size engine can be run. The F100 DIA program, which is now beginning the evaluation phase, built upon early theoretical work (ref. 3) in analytical redundancy as applied to flight control systems. The F100 MVCS control forms the basis for the control logic used in the DIA program, with sensor failure DIA logic being incorporated with it to produce the overall control. As in the MVCS program, the DIA logic will utilize the LeRC facilities for overall performance evaluation.
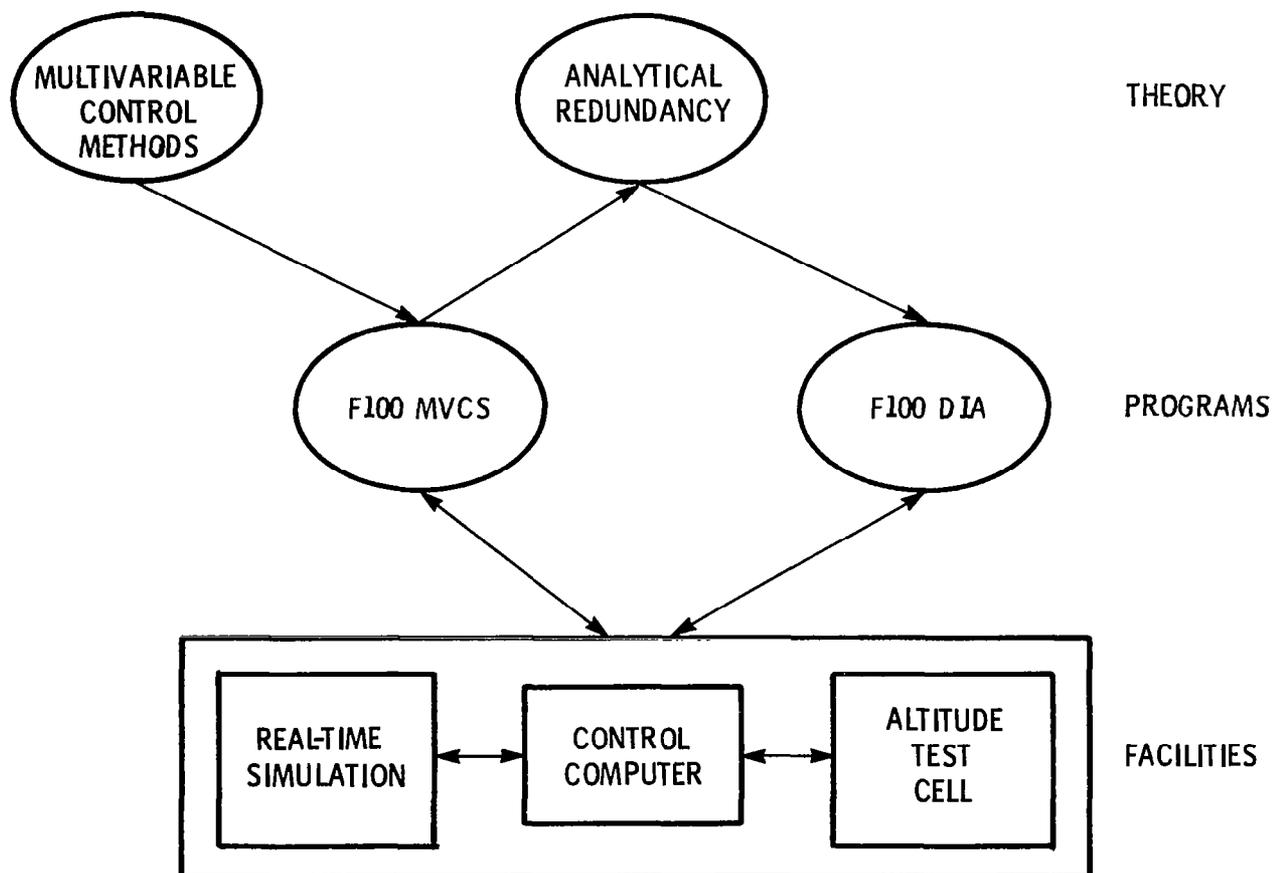
Figure 2

## F100 MVCS PROGRAM PARTICIPANTS

Figure 3 shows the organizations involved in the F100 MVCS program and outlines the activities involved in the various phases of the program. The contracted portions, funded and monitored jointly by NASA LeRC and the Air Force Wright Aeronautical Laboratories, were carried out by Pratt and Whitney Aircraft (P&WA) and Systems Control, Inc. (SCI). The overall program objective was to demonstrate the benefits of using linear quadratic regulator (LQR) synthesis procedures in designing a practical multivariable control system that could operate a turbofan engine through its operating envelope. P&WA provided a digital simulation of the F100, a set of linear design models, and performance criteria on which the design was based. SCI conducted the overall multivariable control design, which was then evaluated by P&WA on the digital engine simulation. NASA LeRC programmed the control logic on a research control computer and evaluated it using its real-time hybrid F100 engine simulation. Upon successful evaluation with the simulation, NASA conducted full-scale altitude tests to verify proper operation throughout the engine's flight envelope. References 4 to 7 document in detail the complete program
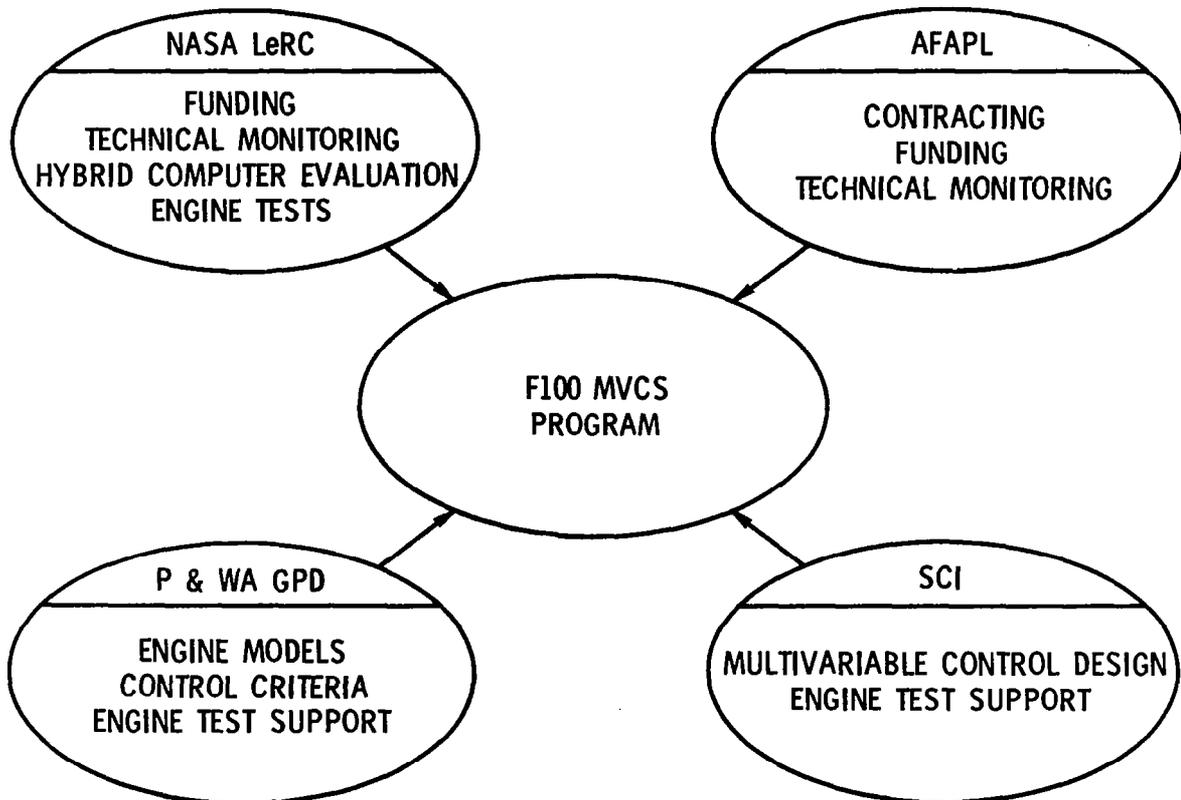


Figure 3

The LQR-based control logic was designed to meet the following criteria. Primarily, the logic must protect the engine against surge and maintain speeds, pressures, and temperatures below maximum limits. Airframe-engine inlet compatibility requires adhering to minimum burner pressure limits and maximum and minimum airflow limits at certain flight conditions. The control must keep thrust and specific fuel consumption within tolerance for specified engine degradations. The engine must accelerate and decelerate rapidly and repeatably and must remain stable in the presence of external disturbances. The basic structure of the F100 multivariable control logic is shown in figure 4. The five manipulated engine inputs are fuel flow, exhaust nozzle area, inlet guide vanes, compressor variable geometry, and compressor exit bleed airflow. Primary sensed engine outputs are fan speed, compressor speed, main burner pressure, afterburner pressure, and fan turbine inlet temperature. Basic components of the control are: 1) reference point schedules and transition control logic, which produce desired state and output and approximate control vectors, 2) gain schedules, which produce feedback matrix elements as functions of flight conditions, 3) proportional and integral control loops which produce acceptable steady-state and transient engine behavior without operating limit exceedance, and 4) engine protect logic that places absolute limits on engine inputs to assure safe operation in the test cell despite sensor or logic failures.
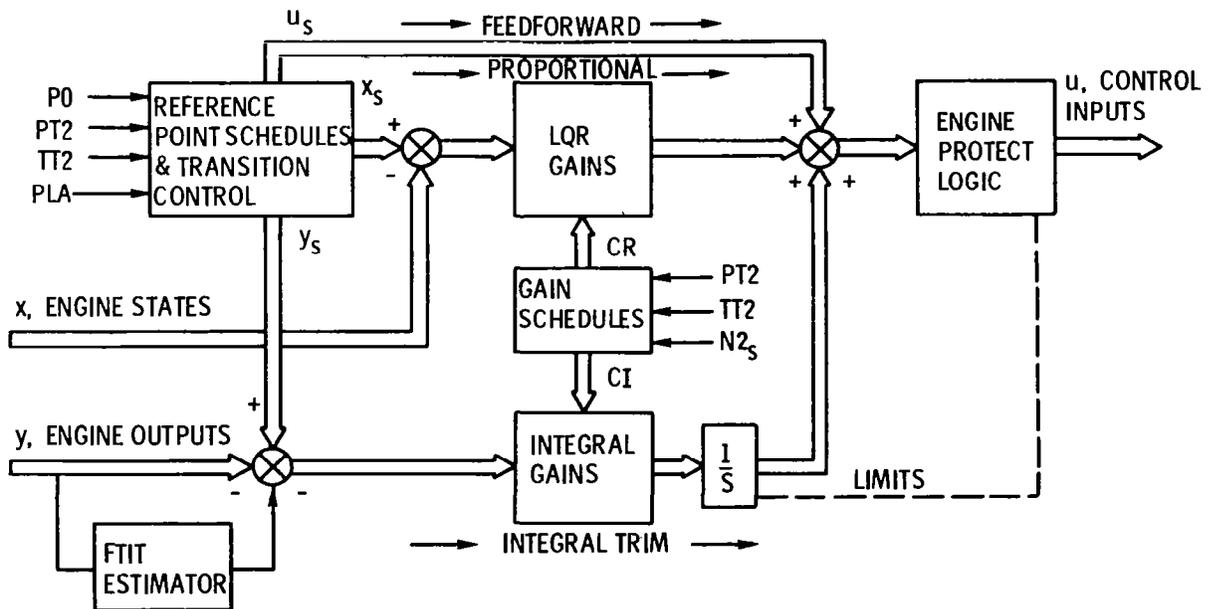


Figure 4

## CONTROL SYSTEM SCHEMATIC FOR ALTITUDE TESTS

The MVC logic shown in figure 4 was programmed in fixed-point ASSEMBLY language on a 16-bit minicomputer and debugged while controlling the LeRC real-time hybrid engine simulation. The simulation was a nonlinear, component-level representation of the engine and included lumped-volume and rotor dynamics. It accurately represents the engine's operation across the entire flight envelope. After completion of the hybrid evaluation, the same logic was used to conduct the altitude test evaluation, as shown in figure 5. Bill of material (BOM) hydromechanical engine actuators were modified to allow input of electrical commands from the minicomputer, and suitable research sensors were provided for feedback signals. Portions of the BOM control system were retained to serve as backup control and for engine start-up. A complete steady-state and transient evaluation was performed over the entire flight envelope. The LQR-based control logic performed well at all conditions. In addition, the real-time simulation was used periodically during the altitude tests for rapidly solving any logic problems encountered. The modular interface system between the computer and simulation or engine greatly facilitated this mode of operation.
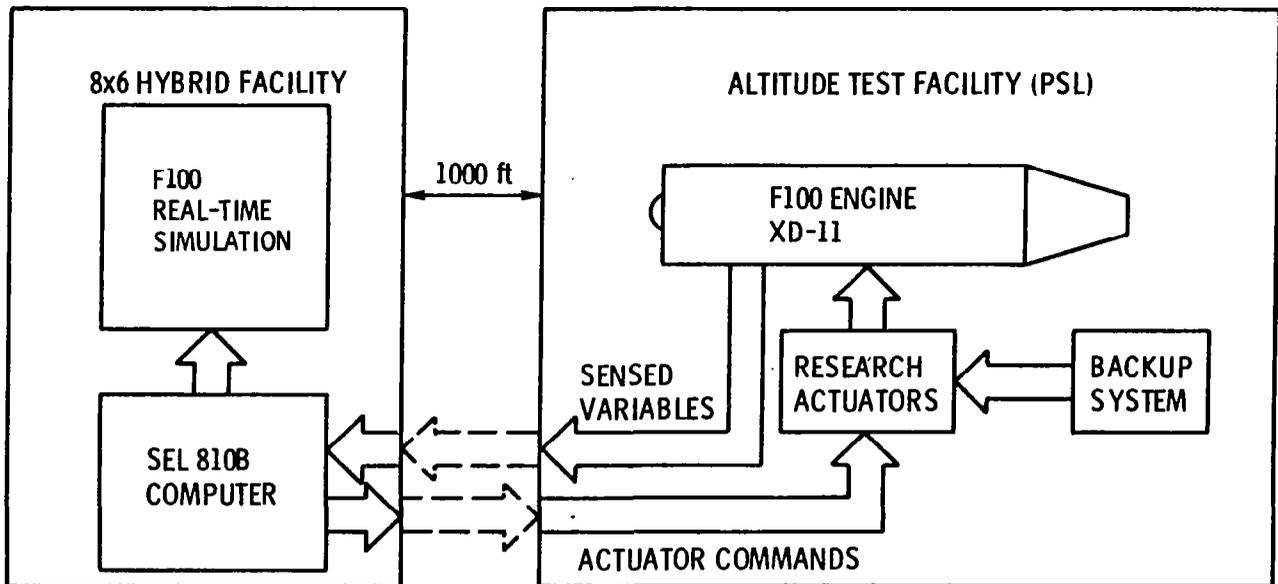


Figure 5

## TYPICAL F100 MULTIVARIABLE CONTROL PERFORMANCE IN LARGE PLA TRANSIENT

Figure 6 shows an F100 engine transient response test performed during the alti-
tude tests at a simulated altitude of 10,000 feet and Mach number of 0.6. The
input is a power lever angle step (snap) from 50° to 83° (maximum, non-after-
burning). This transient caused a number of MVC logic functions to be exercised:
transfer from fan speed integral control to fan turbine inlet temperature (FTIT)
limit control, regulator and integral control gains being varied as functions of
compressor speed, use of the FTIT estimator output, and control of the exhaust
nozzle area to control fan discharge $\Delta P/P$, a fan air flow parameter. Initially,
the control maintains the desired engine operating point by keeping fan speed and
fan discharge $\Delta P/P$ on desired schedules. During the transient, engine outputs
generally follow their desired trajectories. Fuel flow is modulated to keep FTIT
at or near its allowed limit during the initial portion of the transient. At
steady state, the logic has closed down the nozzle area and trimmed fuel flow so
that both fan speed and fan discharge $\Delta P/P$ are on schedule. This transient was
one of over ninety performed using the multivariable control, with inputs being a
wide variety of PLA trajectories, afterburner ignitions, and flight condition
excursions. The MVCS program demonstrated that digital engine controls can be
successfully designed using techniques based on LQR theory. As demands for engine
performance lead to engine designs which have larger numbers of control variables,
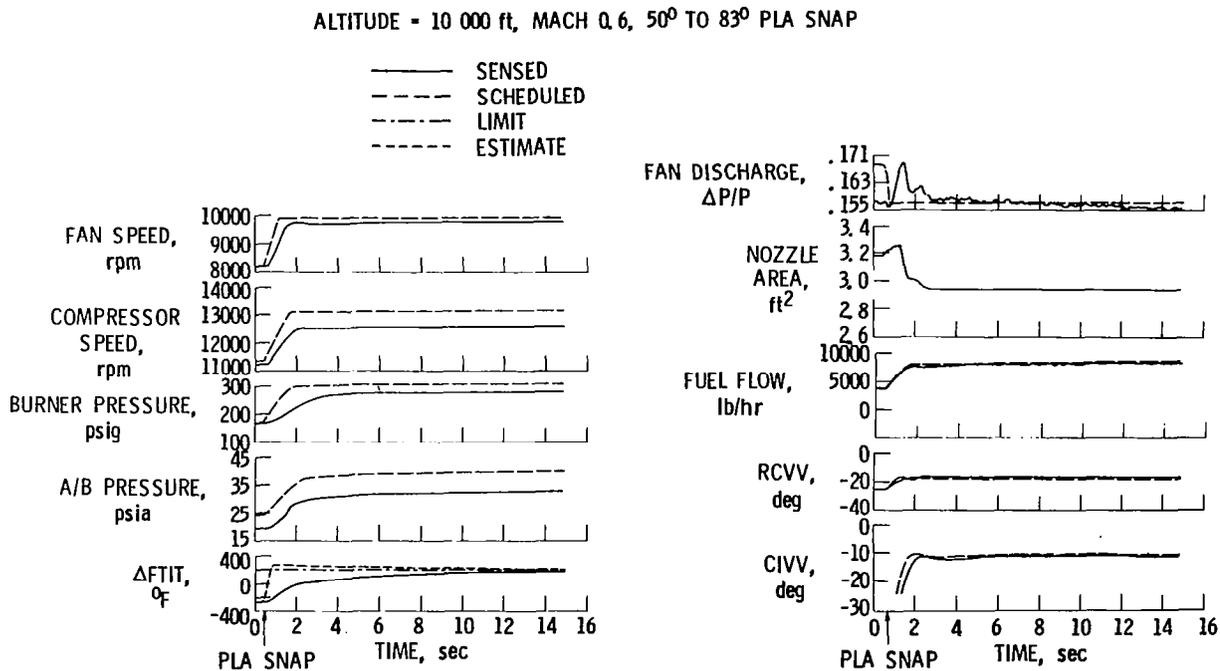LQR methods will be increasingly useful for algorithm design.



Figure 6

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# AESOP – INTERACTIVE COMPUTER-AIDED CONTROL SYSTEM DESIGN

A tool that was developed at Lewis and used during the F100 MVCS program to verify and update the contractor's multivariable control designs was the AESOP computer program (Algorithms for EStimator and OPtimal regulator design). An interactive program which solves the LQR and Kalman filter design problems for time invariant systems, it is an outgrowth of an earlier batch program LSOCE (ref. 8). As shown in figure 7, the user typically accesses AESOP by using a light pen to select desired AESOP functions from a menu displayed on a terminal screen. Available functions fall into the categories shown: open-loop system analysis (controllability, observability, eigenvalues, etc.), LQR and Kalman filter design, system response to noise inputs (both open- and closed-loop system covariance matrices), system transient responses (open and closed loop, for step and initial condition inputs), and transfer functions and frequency responses (system poles, zeroes, and generation of open- and closed-loop Bode plots). Graphic output can be produced either at the terminal screen or plotted off-line. AESOP also aids the user by checking the validity of requested function sequences. A user's manual has been prepared (ref. 9).
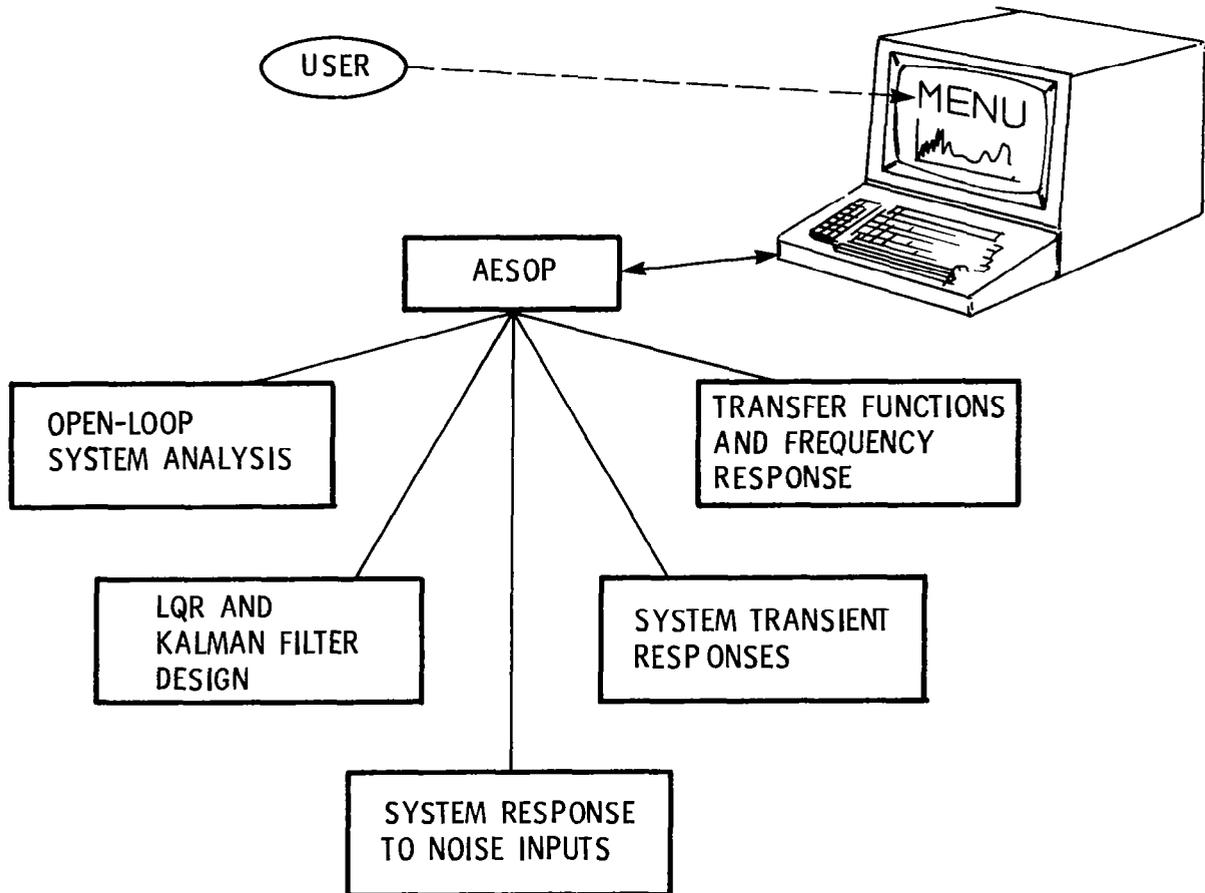


Figure 7

The relative immaturity of digital electronics compared to hydromechanical controls has raised concerns with respect to control system reliability. Past studies have shown that the least reliable parts of a digital electronic engine control system are the sensors. For this reason, as a follow-on to the F100 MVCS program, the F100 DIA program (sensor failure detection, isolation, and accommodation) was initiated to develop algorithms for enhancing digital control system reliability by using analytical redundancy. The general concept of analytical redundancy in the context of an engine control system is illustrated in figure 8. Assume that the reliability of turbine inlet temperature sensor $T_4$ is insufficient to meet mission-reliability goals. The normal procedure (hardware redundancy) would be to add two additional temperature sensors and voting logic to determine if and when a sensor has failed. The analytical redundancy approach is to incorporate a model of the engine which relates $T_4$ with other sensed engine variables (for example, $P_4$ and N). The model is then used to generate an estimate of $T_4$ which can be used with a statistical testing procedure to detect and isolate a $T_4$ sensor failure. Once a failure has been detected, the estimate can be used to replace the failed sensor and allow acceptable but possibly degraded control performance. In the F100 DIA program, contractors P&WA and Systems Control Technology (SCT) have: 1) quantified sensor failure types and frequency of occurrence, 2) determined the relative criticality of various failures, and 3) developed a sensor failure DIA algorithm for the F100 engine (ref. 10).

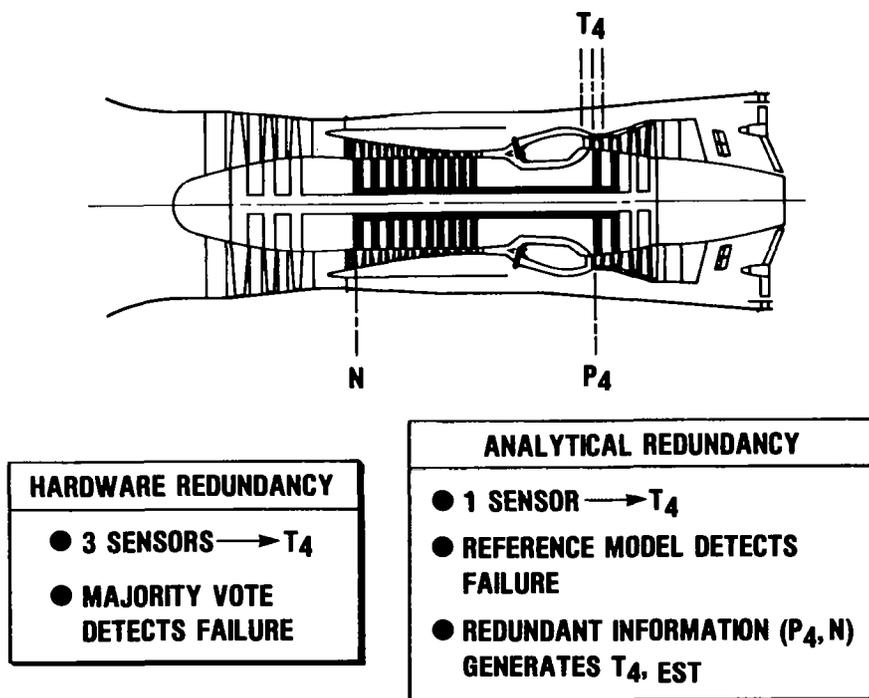**PRINCIPLE— REPLACE HARDWARE REDUNDANCY WITH ANALYTICAL REDUNDANCY**



| HARDWARE REDUNDANCY |
|---|
| ● 3 SENSORS ⟶ $T_4$ |
| ● MAJORITY VOTE DETECTS FAILURE |

| ANALYTICAL REDUNDANCY |
|---|
| ● 1 SENSOR ⟶ $T_4$ |
| ● REFERENCE MODEL DETECTS FAILURE |
| ● REDUNDANT INFORMATION ($P_4$, N) GENERATES $T_{4, EST}$ |

Figure 8

## SENSOR FAILURE DETECTION, ISOLATION, AND ACCOMMODATION CONCEPT

The structure of the F100 DIA logic and the manner in which it interfaces with the
MVC logic are shown in figure 9. The two portions of the DIA logic are an on-line
state estimator and detection and isolation logic. The estimator incorporates an
accurate, full envelope model of the engine which is updated in real time. Esti-
mator residuals are continuously monitored by the detection logic, and if a failure
is detected, isolation and accommodation algorithms are initiated. During normal
unfailed conditions, an estimate of state x is fed to the LQR gain portion of the
multivariable control and the integrally controlled engine output variables y are sent
directly to the integral control portion. This insures that any possible bias in
the estimate of y will not cause a shift in the desired engine operating point.
Once a failure has been detected and isolated, the on-line estimator is reconfigu-
red to exclude the bad sensor, and an estimate of the failed sensor signal is sent to
the integral control. Due to the modular design of the MVC logic, the only change
required after addition of the DIA logic was to eliminate the FTIT estimator, a
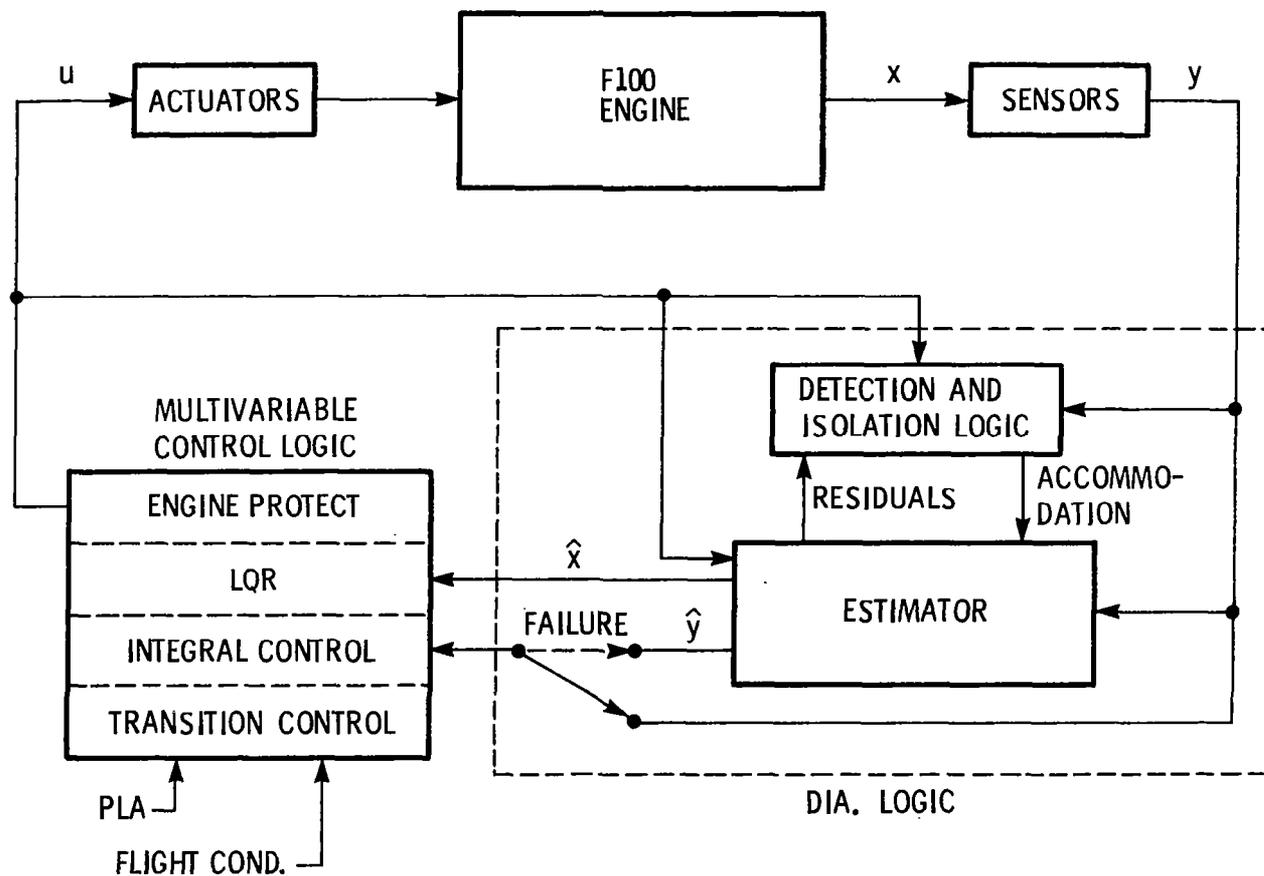task now taken over by the DIA logic.



Figure 9

The specific algorithm used by the F100 DIA logic begins with the generation of residuals for each of five engine measurements using an estimator which is designed to work with all sensors present (fig. 10). Detection and isolation algorithms are different, depending on whether a hard (out-of-range), sudden within-range shift) or soft (slow drift, slowly increasing noise intensity) failure is being detected. A hard failure is detected (and isolated) by simply comparing the sensor residual against a threshold. A soft failure is detected by computing the weighted-sum-squared of all residuals for N past observations and comparing that value against a threshold. To isolate a soft failure, a generalized likelihood ratio hypothesis test is performed, using residuals computed by a bank of five "off-line" estimators, to compute which sensor is most likely to have failed. Each of the five off-line estimates has one sensor input left out. The accommodation procedure consists of reconfiguring the on-line estimator by changing the gain matrix and omitting the bad sensor signal from its input plus resetting of the estimator's initial conditions. The F100 DIA logic has been successfully evaluated on a detailed non-real-time engine simulation while coupled to the MVC logic. The logic has been coded for a Lewis-developed microprocessor-based computer control facility and will subsequently be evaluated while controlling a real-time hybrid simulation.

(1) GENERATE RESIDUALS WITH ON-LINE ESTIMATOR

(2) DETECT FAILURE

    - HARD  :  RESIDUAL  >  THRESHOLD

    - SOFT  :  WEIGHTED SUM-SQUARED RESIDUALS (WSSR)  >  THRESHOLD

(3) ISOLATE FAILURE WITH GENERALIZED LIKELIHOOD RATIO TESTS

    - HARD  :  ON-LINE RESIDUAL TEST

    - SOFT  :  OFF-LINE USING BANK (5) OF ESTIMATORS

(4) ACCOMMODATE FAILURE

    - RECONFIGURE ON-LINE ESTIMATOR TO EXCLUDE BAD SENSOR

    - REINITIALIZE ESTIMATOR

Figure 10

## SENSOR FAILURE DIA LOGIC IMPLEMENTATION

The Lewis computer control facility being used in conjunction with the F100 DIA program is based on an Intel 8086 16-bit microprocessor and replaces the minicomputer facility used during the F100 MVCS program. It includes both an interface unit which allows information interchange between a simulation or an engine and a monitoring unit which displays and records information during a test. Figure 11 shows the basic configuration of the facility for implementing the DIA logic. Rapid control update requirements led to the use of two microprocessors, one for the control logic and one for the DIA logic, which communicate through interrupts and transmit data over a multibus. Specialized D/A and A/D allow communication with the engine, also through the bus. The timing diagram in figure 11 shows the subtasks performed by each processor and the inter-processor interrupt timing. The MVC processor processes the sensed inputs and sends an interrupt to begin the DIA processors's detection algorithm. Both processors then operate in parallel until the Kalman filter (estimator) has updated the state estimates, at which time an interrupt from the DIA processor allows the estimates to be used by the MVC processor in the multivariable control calculations. The DIA processor then searches for a possible soft failure, and only if detected, begins the isolation calculation, requiring the updating of five additional Kalman filters and the use of the GLR algorithm. Languages used in programming the logic were both ASSEMBLY language and FORTRAN with special machine language procedures developed for certain time-critical tasks.
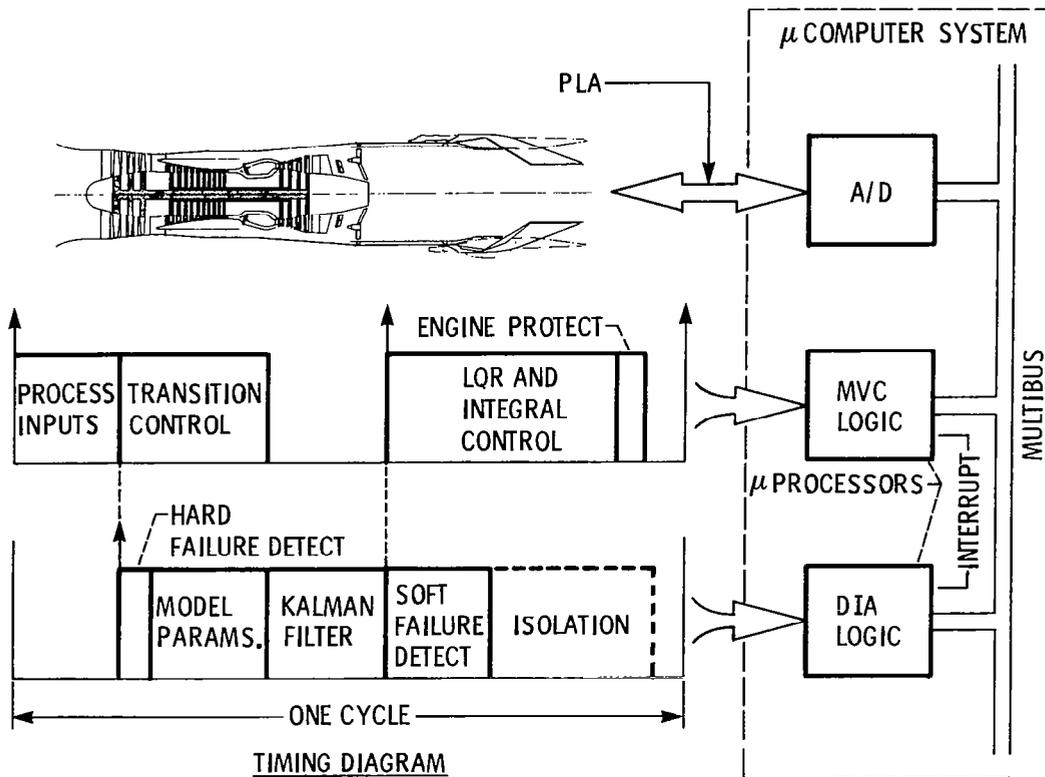


Figure 11

Advanced control related activities which are or will soon be underway at LeRC are outlined in figure 12. The F100 DIA logic will be evaluated on a real-time engine simulation throughout the flight envelope and will then be tested in the LeRC altitude facility. An operating-point control design will be performed for the F100 engine using an alternate frequency-domain method (the multivariable Nyquist array) and compared to the existing MVC design. Also, the use of modern robust control methodology to design engine controls will be investigated with an eye toward decreased sensitivity to modeling errors and simplified control algorithms. Contracts have just been awarded to investigate how best to incorporate robustness into the initial design of sensor failure DIA algorithms. Finally, in-house computer-aided control design capability (such as the AESOP program) will be enhanced so as to be better able to interactively design and analyze multivariable control and failure detection algorithms for future propulsion systems.

# FUTURE EFFORTS IN ADVANCED PROPULSION CONTROL

- EXPERIMENTAL EVALUATION OF DIA LOGIC

- MNA - LQR DESIGN METHOD COMPARISON

- ROBUST CONTROL DESIGN APPLICATION

- ROBUST SENSOR DIA LOGIC

- ENHANCED INTERACTIVE CAD FOR PROPULSION CONTROL SYSTEMS

Figure 12

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