VI - DIRECTIONS IN PROPULSION CONTROL

Carl F. Lorenzo

This section discusses research at NASA Lewis in the area of propulsion controls as driven by trends in advanced aircraft. The objective of the Lewis program is to develop the technology for advanced reliable propulsion control systems and to integrate the propulsion control with the flight control for optimal full-system performance.

CONTEMPORARY PROPULSION CONTROLS ISSUES

The primary drivers seen for propulsion control research are a continuing increase in aircraft and propulsion system complexity, increased dynamic coupling between the aircraft and the propulsion system, and a continuing need to reduce control system weight while increasing reliability.

The demand for increased functionality for future aircraft and the desire to optimize aircraft and propulsion systems as an integrated entity has led to a large increase in the physical complexity of the aircraft/propulsion systems. The new functionalities can include vertical and short-takeoff-and-landing capabilities coupled with high-speed cruise. To achieve these capabilities special-purpose aircraft are being designed with a high degree of dynamic coupling between aircraft and propulsion systems. This is a dramatic departure from traditional aircraft design where such coupling was minimized. The effect of large dynamic coupling is to increase pilot work load. Advanced controls can help alleviate the problem of pilot work load and allow optimal aircraft performance to be achieved; however, this necessitates that the unified or integrated design approach to aircraft flight controls and propulsion control be evolved.

Control weight as a percentage of propulsion system weight is significant in spite of gains made by conversion to digital systems. Previous sections of this paper have discussed our efforts in fiber optics and high-temperature electronics (using silicon carbide), which should help reduce control system weight. Further efforts are perhaps best approached by industry as part of the design process and by applying new materials technologies.

COMPLEXITY ISSUE

Airbreathing engine complexity is reflected by the number of primary control variables managed for a given engine (fig. VI-1). This is an important measure, since it indicates the number of sensors required as well as the amount of actuation, and it is a general indicator of propulsion system complexity. The trend has shown a steady increase in controlled variables over

the years. With this trend has come the use of full-authority digital elec-
tronic controllers, which have helped in dealing with the complexity issue.
The increase in control components implies a corresponding decrease in control
reliability unless specific measures are taken to deal with the issue.

DYNAMIC COUPLING

Typical of aircraft with significant dynamic coupling are supersonic
short takeoff and vertical landing aircraft (STOVL) (fig. VI-2), advanced high-
speed x-wing rotor craft, and even hypersonic aircraft where engine air capture
and aircraft pitch control are tightly coupled. Vertical lift aircraft flight
control at low forward speed and through transition are typically dominated by
propulsion control considerations. These aspects provide strong motivation for
research in the area of flight/propulsion control integration.

PROPULSION CONTROLS

Current activities of the NASA Lewis controls research program are indi-
cated as follows:

(1) Hypersonic propulsion dynamics and control
(2) Reconfigurable control
(3) Controls networking
(4) Sensor failure detection, isolation, and accommodation

The hypersonic propulsion control work includes hypersonic engine dynamic
modeling, propulsion control, and control instrumentation keyed to the NASP
technology maturation program. Dynamic models of the various NASP components
are being developed (refs. VI-1 to VI-4) and integrated into full engine models
for study of dynamic ramjet/scramjet stability and control. Several dynamic
inlet models, which include inlet unstart studies, have been implemented, and
combustor models consistent with real-time simulation have been formulated.

The reconfigurable control effort seeks to create expert system intelli-
gence which, in real time, can "redesign" a control system to account for sig-
nificant changes in aircraft or engine behavior. In this process (fig. VI-3)
an on-line recursive identifier will monitor the plant variables to detect
changes in the plant. When such a change occurs an expert system (ref. VI-5)
will be invoked to manage a control redesign using one of several design
approaches. The new design will be impressed on the plant controller. If nec-
essary, a second expert system (yet to be developed) will tune the control for
desired performance.

Efforts in controls networking aim to develop high-performance communica-
tions systems tailored specifically to distributed integrated aircraft flight/
propulsion controls. The magnitude and the time variability of network-induced
delay directly impacts control system stability. Thus, network performance,
that is, end-to-end delay as a function of offered load and communications
packet size, for various configurations has been both simulated and measured
directly from network systems for various configurations (refs. VI-6 to VI-12).
Further, to improve control tolerance of delay, the use of filters and observ-
ers, and control synchronization across the distributed control system are
being studied (refs. VI-13 to VI-16).

FAILURE DETECTION ISOLATION AND ACCOMMODATION

The Sensor Failure Detection and Accommodation program (refs. VI-17 to VI-28) strives to attain control system reliability through the application of analytical redundancy instead of hardware redundancy (multiple sensors for each measurement). Analytical redundancy uses available sensor information and reference models of the engine to detect sensor failures and to generate accurate estimates which replace failed sensor information to the controller (fig. VI-4).

Sensor failure accommodation logic has been developed that uses sensed signals from the engine and actuators together with analytical models of the engine to create (Kalman filter based) estimates of the engine parameters. These estimates (fig. VI-5) are used by the multivariable control as representing the actual engine variables. Failed sensors are detected by "hypothesis testing" a series of hypothesis filters, each of which uses all available signals but one. Likelihood statistics are generated and compared to detect the failed sensor(s). The failed sensors are then removed from the calculation of the estimates.

The sensor failure accommodation algorithm and multivariable controller are implemented (fig. VI-6) in a triple-microprocessor-based control system (ref. VI-24). The computers calculate (1) the multivariable control laws, (2) the detection and accommodation logic, and (3) the isolation logic to determine which sensors have failed. The processors are Intel 80186/80187 based hardware which allow a 40-msec update time while processing the algorithms in a high-level language (FORTRAN). This computer implementation was used to validate the detection and accommodation logic both for real-time simulations and with an actual engine.

To validate the analytical formulation and practical implementation of the sensor failure algorithm, full-scale tests were performed (ref. VI-22) with the Pratt & Whitney F-100 engine in the Lewis Propulsion System Laboratory (fig. VI-7). The tests were conducted over a wide range of altitude/Mach number conditions.

In the tests, various forms of sensor failure were electronically imposed on the control sensors. Actual engine performance in response to an imposed drift failure in the nozzle pressure sensor signal is shown in figure VI-8. Such small drift failures are very difficult to detect, and thus the time of detection is not immediate. It can be seen, however, that the actual engine thrust loss is quite small. In the figure the "sensed" variable is the signal that would be normally seen by the control. The "actual" is the "sensed" variable without the imposed drift failure, and the "estimated" is nozzle pressure as determined by the Kalman filter.

The major events are as follows: at point A, a slow drift is introduced into the sensed signal, so that sensed signal would begin to deviate at a rate of 1 psi/sec. From point A to point B, the control tries to accommodate what is going on. It senses the pressure rising and opens up the nozzle area. In response to that the actual pressure begins to fall, until a loss of control authority at point B. At that point the sensed pressure begins to deviate at the 1 psi/sec rate. At point C the logic has determined that failure has occurred and removes the faulty sensed variable, in this case, nozzle pressure,

from the estimator calculation. Then the actual signal and the estimate begin to come back together as the control returns to a normal mode operation. At point E, without sensor failure accommodation, engine shutoff occurs.

The results of the sensor failure accommodation testing on the F-100 engine are summarized as follows:

(1) High-performance failure detection (120 different failure scenarios, 11 engine operating conditions, both subsonic and supersonic conditions)
(2) Good post-failure accommodation performance (no significant loss of performance power transients with accommodated failures)
(3) Sequential failure detection and accommodation
(4) Simultaneous failure detection and accommodation
(5) Engine control with all feedback sensors failed

One hundred and twenty different failure scenarios were run. Demonstrated capabilities include the detection, isolation, and accommodation of drift, in-range step, noise, and large-scale "hard" failures. Failure testing was done at 11 Mach number/altitude operating conditions over the flight envelope. Also demonstrated was the capability to detect sequential sensor failures as well as simultaneous failures. The algorithm worked satisfactorily for all tests. Excellent post-failure control performance was demonstrated including full-range operation with single sensor failure.

As a demonstration case the F-100 engine was run with all feedback sensors failed. (The input sensors Pt_2 and Tt_2 were not failed.) Under the condition of all engine control sensors failed, the controller correctly detected each failure and accommodated all failures by using the computed estimates for all the signals. While in this condition the engine was smoothly accelerated and decelerated as shown in figure VI-9.

The NASA Lewis new thrusts in propulsion control are focused on the areas of supersonic STOVL integrated control and intelligent system control.


INTEGRATED FLIGHT/PROPULSION CONTROL

The supersonic STOVL aircraft (fig. VI-10) typifies the trend toward complex aircraft with large dynamic coupling between the aircraft and propulsion system. A NASA Lewis and NASA Ames program will develop advanced integrated controls methodologies and designs for this application. Current plans focus on the F-16 aircraft and the F-110 engine with vectorable nozzles and an ejector as the vertical thrust effector. The integration problem is to evolve controls designs and methodologies which integrate subsystem controls in a manner to achieve optimal aircraft performance. Nonlinear simulation models of both aircraft and propulsion system are being created. Linear control models will be abstracted from these to be used as a basis for control design. Validation tests at NASA Lewis will incorporate a piloted simulator and actual engine/ejector firing together with a simulated aircraft to evaluate developed control laws. Final validation is planned to be done with the NASA Ames Vertical Motion Simulator.

INTELLIGENT SYSTEM CONTROL

The block diagram in figure VI-11 indicates an expansion of the traditional control function into a broad system intelligence (ref. VI-29). This will be initially applied to reusable space propulsion systems. The inner control loop will be designed with life-extending methodologies (yet to be developed) which will combine controls technologies with those of structure and material sciences. The new interdisciplinary technology will be applied to state-of-the-art engines such as space shuttle main engine or hypersonic propulsion systems where transient effects on engine life are important, and where transient performance must be controlled.

Artificial intelligence concepts will likely be used for the highlighted functions. An on-board diagnostic/prognostic expert system will identify impending hardware failures using information from component condition monitoring instruments, and engine dynamics monitor and performance information. A high-level coordinator will determine the required remedial action; for example, change control request or if necessary invoke a control adapter that will reconfigure (redesign) the control in flight. This research is expected to greatly enhance vehicle and propulsion performance, and substantially improve life, reliability, and maintainability.
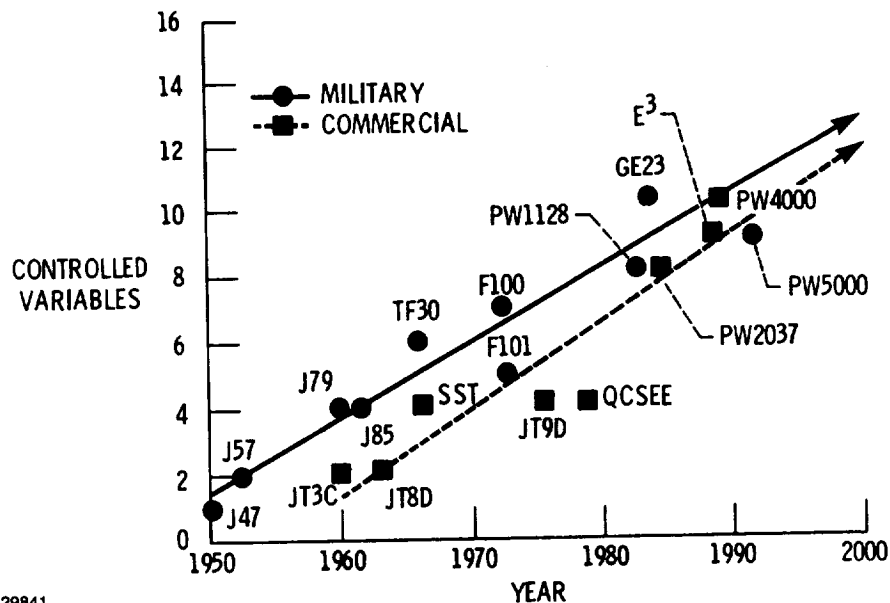
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Figure VI-1. – Trends in control complexity of aircraft turbine engines.

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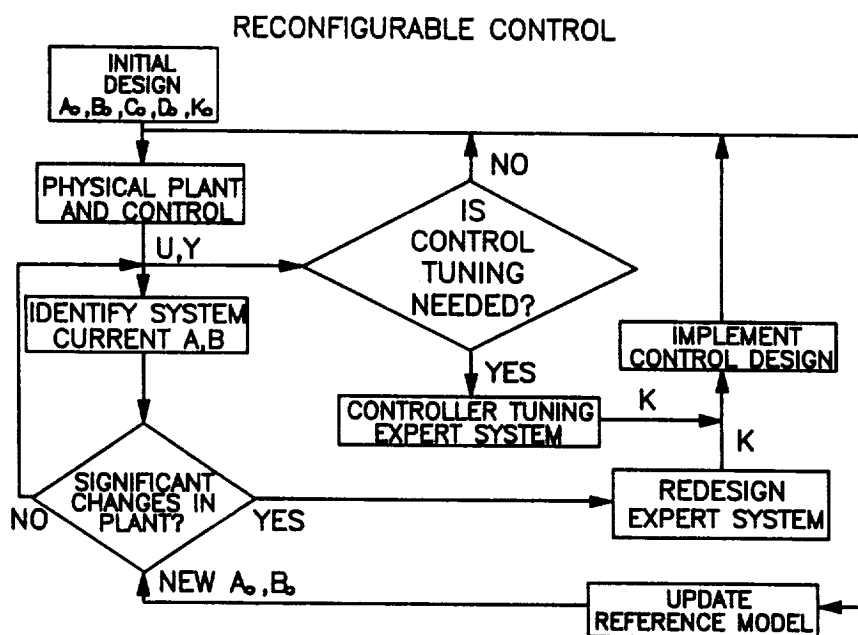Figure VI-2. – Supersonic short takeoff and vertical landing aircraft.

RECONFIGURABLE CONTROL

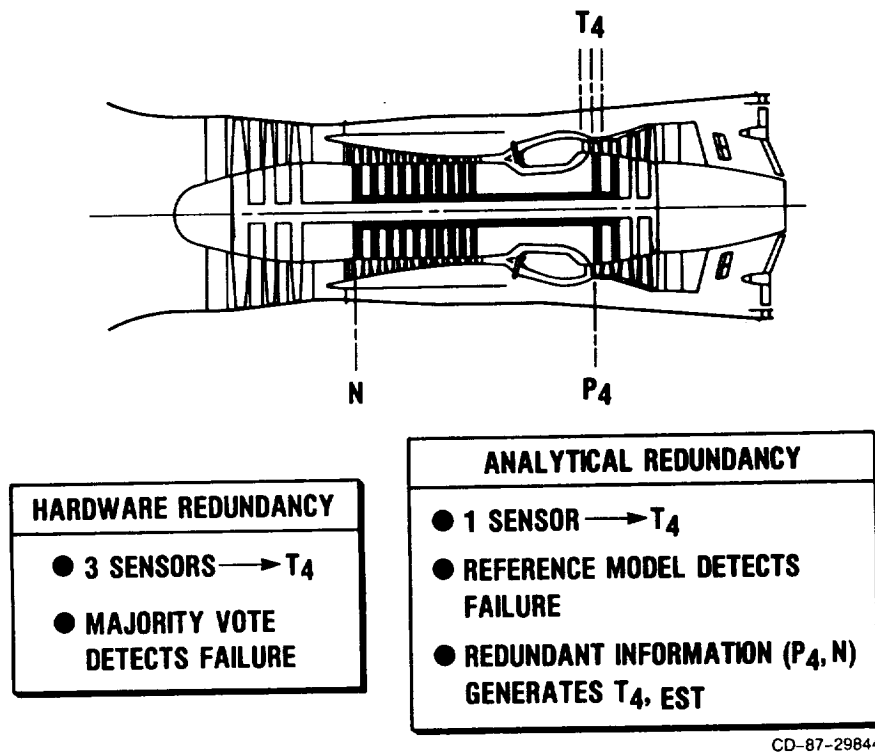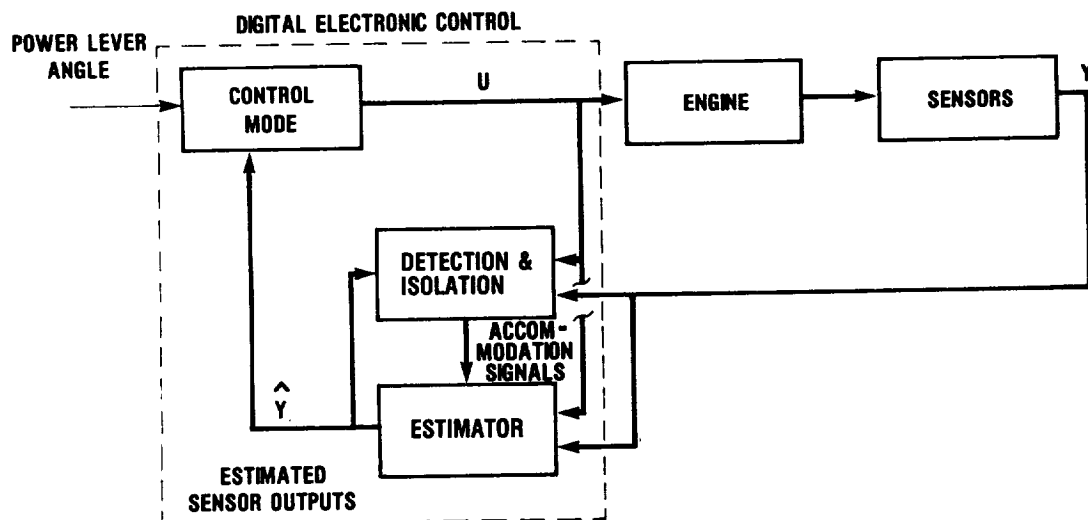Figure VI-3. – Block diagram of reconfigurable control system.

256
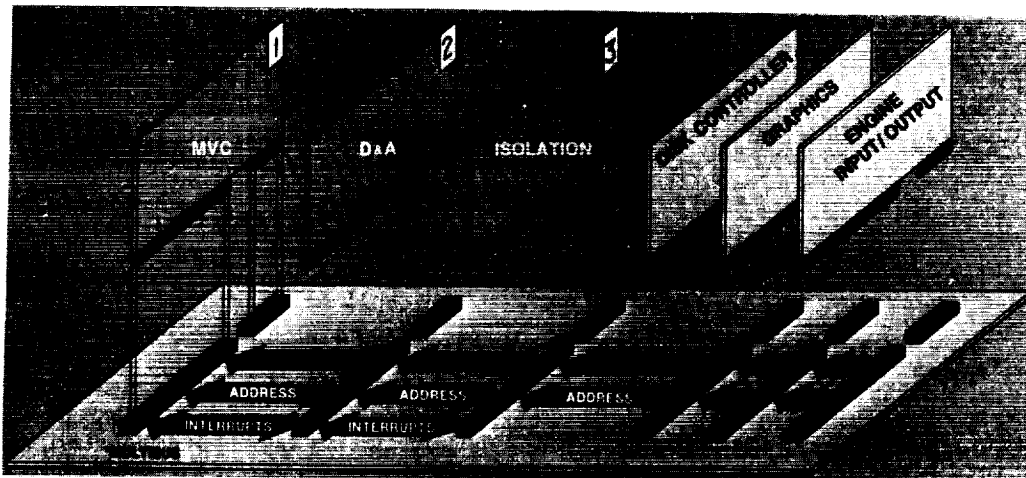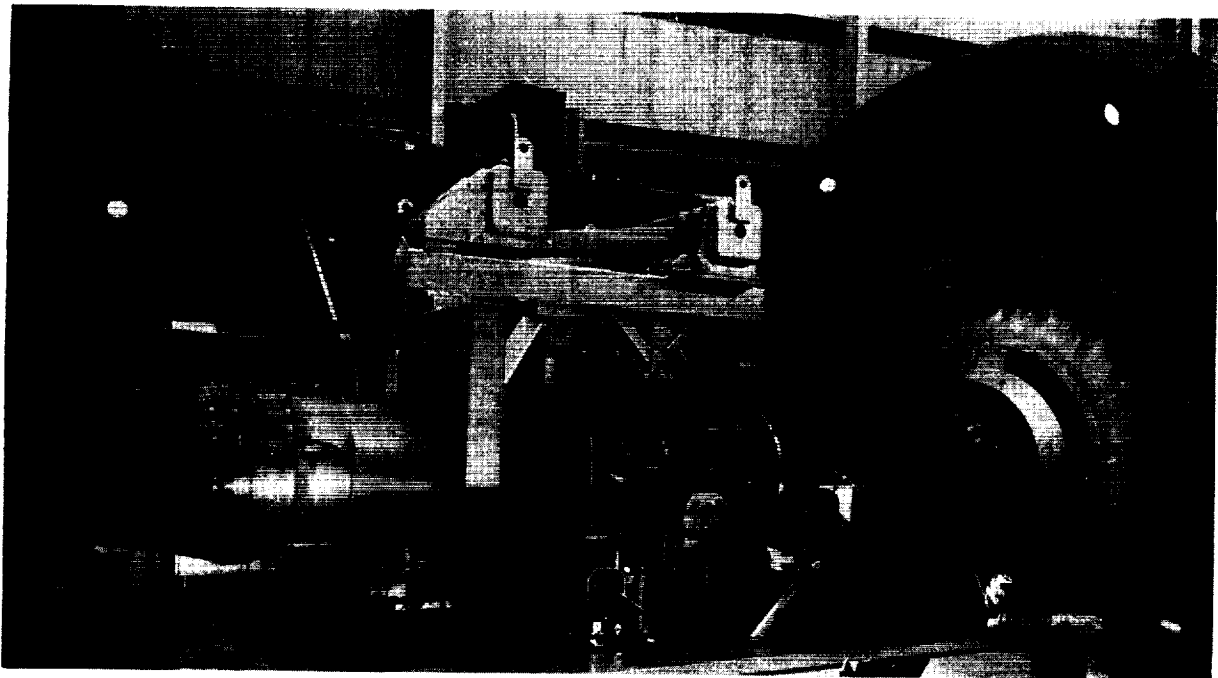
Figure VI-4. - Analytical redundancy.

Figure VI-5. - Simplified block diagram for sensor failure accommodation system.
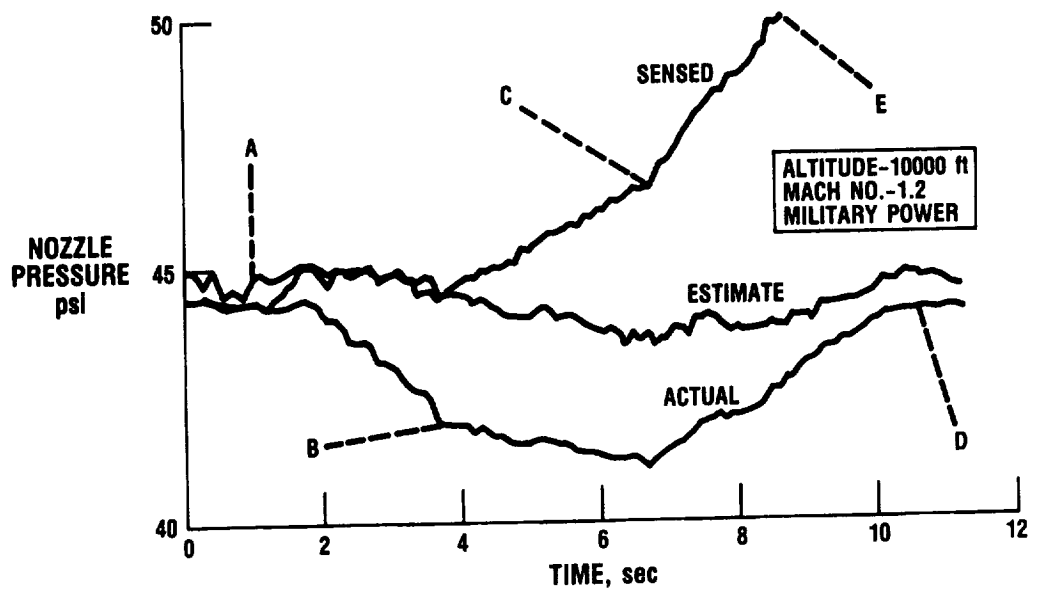
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Figure VI-6. – Hardware implementation for sensor failure accommodation system.

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Figure VI-7. – Pratt & Whitney F-100 as used in sensor failure accommodation program in Propulsion Systems Laboratory.

NOZZLE PRESSURE psi

TIME, sec

ALTITUDE–10000 ft
MACH NO.–1.2
MILITARY POWER

SENSED

ESTIMATE

ACTUAL

CD-87-29848

Figure VI-8. – F-100 engine drift failure on nozzle pressure.

FAN SPEED rpm

TIME, sec

ALTITUDE, 10000 ft
MACH NO., .6

ESTIMATE
REQUEST
ACTUAL
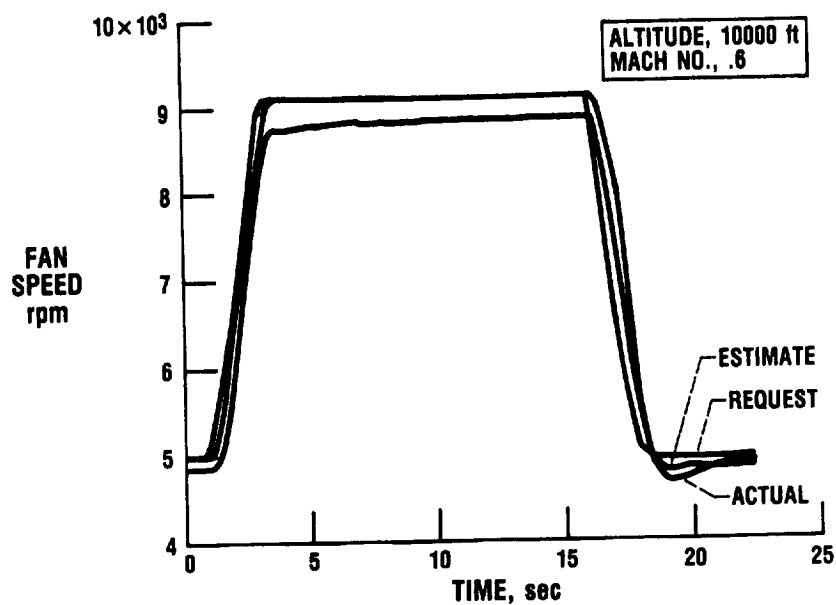
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Figure VI-9. – Engine response to throttle transient with all sensors failed.

259

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Figure VI-10. - Supersonic STOVL ground test aircraft to be used in integrated controls studies.

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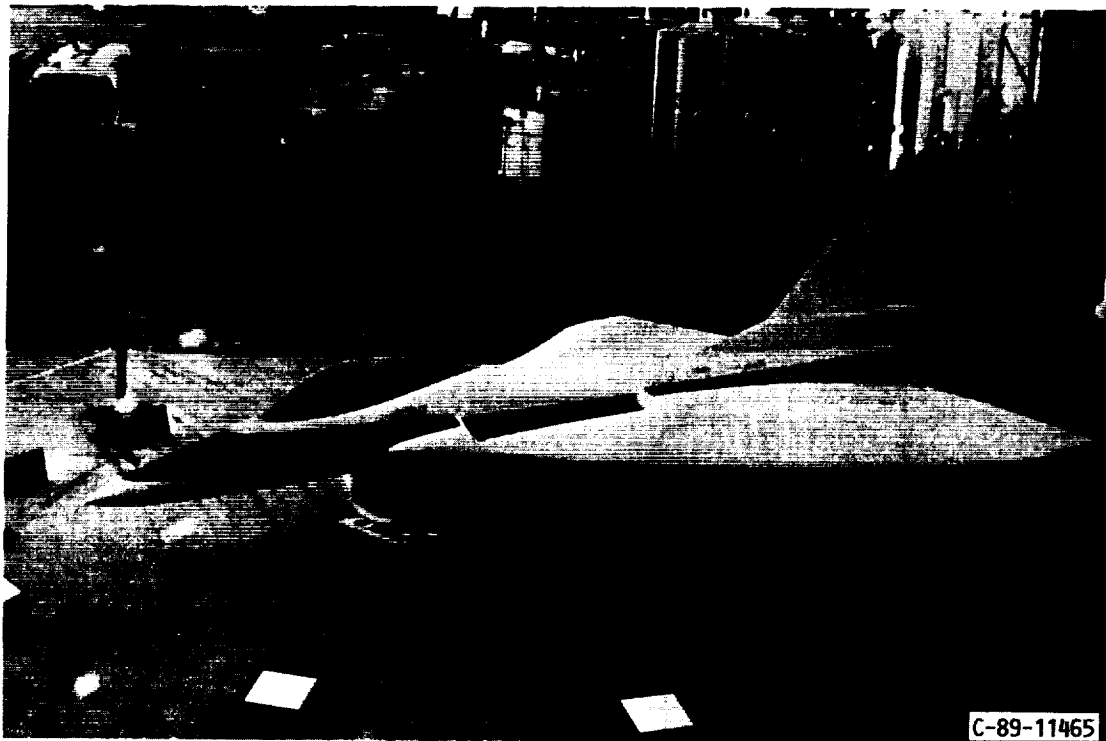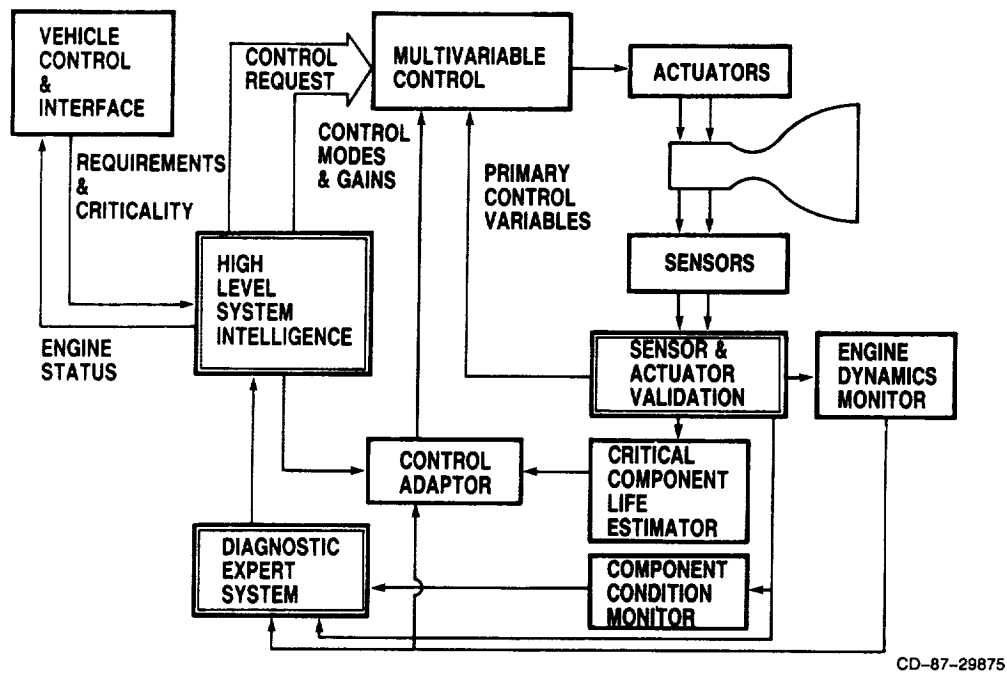Figure VI-11. - Block diagram of intelligent system control.

260

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