PROPULSION CONTROLS

A LOOK INTO THE FUTURE

Ronald D. Hackney
Pratt & Whitney Aircraft Group
Government Products Division

SUMMARY

Increased system requirements and functional integration with the aircraft have placed an increased demand on control system capability and reliability. To provide these at an affordable cost and weight and because of the rapid advances in electronic technology, hydromechanical systems are being phased out in favor of digital electronic systems. The transition is expected to be orderly from electronic trimming of hydromechanical controls to full authority digital electronic control.

INTRODUCTION

Alvin Toffler in his book *Future Shock* said — "We're all aboard a train which is gathering speed, racing down a track on which there are an unknown number of switches leading to unknown destinations. Most of us are in the caboose looking backward."

This can be expecially true for the propulsion control where there are at least two outside influences, engineers, directing the train. These are the airframe and electronics industries. The airframe industry provides requirements. The electronic industry provides technology.

Future propulsion system controls will be highly reliable full authority digital electronic with selected component and circuit redundancy to provide the required safety and reliability. Redundancy may include a complete backup control of a different technology for single engine applications. The propulsion control will be required to communicate rapidly with the various flight and fire control avionics as part of an integrated control concept.

Development of the technology for advanced control systems will continue to evolve in the ongoing progression from hydromechanical controls to prime reliable digital electronic control systems for advanced aircraft in the late 1980's and 1990's. Part of this technology progression has already taken place with programs supported by government and industry. Two such programs have been the Full Authority Digital Electronic Control (FADEC) program and the Integrated Propulsion Control System (IPCS) program. The FADEC program engine tested advanced technology control hardware. The IPCS program has developed and tested an integrated inlet/engine/nozzle integration concept in the F-111 aircraft. A planned NASA program, Integrated Aircraft Control Technology, will develop a dedicated F-15 flight test vehicle for integrated aircraft/propulsion control research.

CURRENT TECHNOLOGY

An early step at Pratt & Whitney Aircraft was the use of a limited authority supervisory digital electronic control and a full function hydromechanical control unit for the F100 engine. This combination allowed the realization of some of the benefits of digital electronic controls while maintaining the proven reliability of the hydromechanical control.

The F100 afterburning turbofan, illustrated in Figure No. 1, is representative of current high technology engines. The F100 is a low bypass ratio, twin-spool, axial flow, augmented turbofan engine. The control, basically hydromechanical with digital electronic trim, sets performance by controlling the inlet guide vanes, compressor variable stators, compressor bleeds, main burner fuel, augmentor fuel and exhaust nozzle area. As the engine/control system is reaching maturity, the electronic trim control reliability and responsibility is increasing dramatically. In fact, current digital electronic reliability exceeds that of the hydromechanical. This same kind of supervisory system is currently being developed for advanced JT9D and JT10D commercial engines. A full function hydromechanical unit is included in these control systems to provide the confidence necessary to introduce digital electronic controls into commercial service.

TECHNOLOGY EVOLUTION

Hydromechanical systems are being phased out in favor of the more capable electronic systems. An orderly transition is expected over the next ten years as illustrated in Figure No. 2. First generation electronics — Electronic Engine Control (EEC) — act as a trim on the F100 hydromechanical control. Second generation electronics — Digital Electronic Engine Control (DEEC) act as a full authority control, but utilize a hydromechanical backup control. Third generation electronics — Full Authority Digital Electronic Control (FADEC) — provide primary and backup control.

The major obstacle to universal acceptance of electronic systems is their relatively high failure rate while operating under severe environmental stress. Simple engines can be controlled by hydromechanical devices that have demonstrated much higher reliability than current electronic computation devices. However, as computational complexity increases, the reliability of hydromechanical devices decreases more rapidly than that of the electronic devices. The electronic control system is projected to be more reliable than hydromechanical systems for the engines of the 1980's.

Several research and development programs are being conducted to evaluate the reliability of full authority digital electronic systems when subjected to the environment of JT8D and JT9D engines. For mid-term transport applications, a dual channel approach is being evaluated to provide acceptable system failure accommodation. A single channel full authority Digital Electronic Engine Control (DEEC) in combination with a limited capability hydromechanical backup control is being developed for advanced F100 engines. A full authority digital electronic control was also tested for an integrated inlet/engine/nozzle system in F-111 aircraft under the Integrated Propulsion Control System (IPCS) program.

Further development of electronic control technology is being conducted under the Navy Full Authority Digital Electronic Control (FADEC) program. The Pratt & Whitney Aircraft FADEC design features two processors in one box, selected redundancy, parameter synthesis, and built-in-test to provide a high degree of fault tolerance. Advanced component technology used in the Pratt & Whitney Aircraft FADEC design is based upon projections for production of a control system in the mid-1980 time frame. For example, both central processors will be implemented with three very large scale integration (VLSI), silicon-on-sapphire (SOS) complementary metal-oxide semiconductor (CMOS) devices. This degree will represent a significant technology improvement over an existing 11 chip LSI CMOS processor design, and indicates the rapid trend toward greater packaging density, higher reliability, and improved computational capability.

Another program being conducted as part of NASA's Energy Efficient Engine (E^3) program is identifying control technology areas requiring development. Programs like FADEC and E^3 should continue because as automatic controls become more commonplace in the consumer market, industrial research will focus more on that need and less on the special needs of the aerospace industry.

Electronic control system reliability will be enhanced by electronic controls with internal fault detection, parameter synthesis, and switching logic that will transfer data and control functions for fail-operational performance. Electronic controls today are structured around a multi-chip processor. The cost of this processor will continue to drop as more complex architecture and instructions are included on each chip. As illustrated in Figure No. 3, cost per calculation is decreasing at a 50% per year rate. A significant improvement in reliability will also follow with development of a single chip microprocessor and the associated reduction in external circuit connections.

As illustrated in Figure No. 4, a propulsion control system is not just an electronic box, but consists of many other varied components which are optimized as a system to meet the system goals. It is important to continue technology development for all components of the complete propulsion control system to make possible the optimization of performance, weight, cost, reliability, maintainability and other operating benefits. Important hardware considerations include the advanced output interfaces, advanced sensors, control system environment, integration, and electronic and component reliability.

Further research is required on advanced output interface devices which can be incorporated into actuation systems to provide interfaces that are more compatible with digital computers. An example of such an interface is the pulse-width modulated solenoid, developed for a fuel metering valve under the NASA Digital Output Interface (DOI) program. New sensing devices for propulsion system parameters should be developed that are compatible with digital controls and will reduce the input interface hardware requirements.

Optical communication has been proven feasible and cost effective for aircraft use by the ALOFT study and demonstration program. Presuming that immunity from electromagnetic interference is necessary, optical data links that are suitable for use in the engine environment must be developed. Figure No. 5 illustrates some potential advantages of optical communication. Also, alternate interface configurations such as multiplexing of feedback signals to the control unit and locating power switching elements away from the computer control unit need to be pursued.

Electronic component reliability is adversely affected by increasing temperatures. Therefore, it is necessary to provide cooling to the digital electronic control unit. For engine mounted control systems, this cooling may be provided by flowing fuel through passageways in the control unit. This approach may not be adequate at the elevated ambient and fuel temperatures encountered during supersonic flight. Therefore, research into alternate cooling approaches should be conducted.

System integration of the propulsion and airframe would benefit from cooperative programs in which airframe and engine manufacturers consider: (1) supplying data from the aircraft central air data computer to the propulsion system controls; (2) supplying electrical and hydraulic power with acceptable characteristics from the aircraft power systems to the propulsion system controls; (3) configuring the control system and intersystem communication links to accommodate such problems as lightning strikes, EMI, and common mode failures; and (4) design of the control system to minimize damage resulting from engine fires.

A single channel digital control with selective component and circuit redundancy will result in a system of minimum cost and complexity, but requires considerable substantiation to ensure that acceptable reliability levels will be obtained without the use of redundant channels or backup control configurations. Technology advances are therefore required in the area of digital electronic components to provide continuing improvement in system reliability. Design studies are also required to determine how to utilize advanced technology components and features such as selective redundancy and fault tolerance logic to optimize the control system reliability. An Air Force sponsored program, "Digital Electronic Control System Reliability," has a goal to establish the definition of a Full Authority Fault-Tolerent Electronic Engine Control (FAFTEEC) system that has significantly better reliability than any of the electronic or hydromechanical alternatives and still maintains performance, cost and weight advantages. Figure No. 6

illustrates the goals of this program. Selected redundancy will be utilized to minimize mission cost/effectiveness.

Software development areas include propulsion and flight controls integration and the application of advanced control methods. Because of the flexibility and logic programming capability of full authority digital electronic controls, a number of sophisticated control functions can be incorporated which will promote efficient propulsion system operation, reduce pilot workload, improve safety of operation, potentially reduce fuel consumption, and make the control system less sophisticated for the user. For advanced supersonic transport and fighter aircraft applications, further technology development is required in the area of integrated aircraft/inlet/engine/nozzle control modes. Control algorithms should be investigated to improve the logic capability of the digital control instead of implementing hydromechanical control logic in electronic boxes. Technology development would also be desirable for performance seeking controls and integration with Engine Condition Monitoring functions. Performance seeking logic can be implemented on-line to provide improvements in propulsion system and aircraft system performance through optimization of control variable settings. The software capability of the propulsion control can be used to provide data to an engine condition monitor which analyzes the mechanical health and component efficiency of the engine to provide early identification and prevention of problems, thereby reducing operating and maintenance costs.

Closed loop test benches like the one illustrated in Figure No. 7 will be utilized to verify hardware and software concepts even before engine definition. As illustrated, a hybrid computer can simulate the aircraft and the engine components that "turn and burn" — compressors, burners, turbines, augmentors, etc. Control components are driven such that "real" engine operation is simulated.

INTEGRATION

The design of propulsion systems has traditionally been based on the primary objective of maximizing steady-state performance of the total vehicle. New aircraft designs and technology advancements are giving designers a great range of aerodynamic and propulsive capabilities for interactive/integrated force controls. This requires that the configuration be visualized in terms of concepts such as force production, force distribution and force management. Force production incorporates aerodynamic propulsive interactive force systems such as in-flight vectored thrust, in-flight reversed thrust, jet flaps and external blown flaps. Force distribution includes advanced concepts such as relaxed static stability, canards and maneuver flaps. Force management includes features such as flight propulsion control, coupling systems, maneuver load control, direct lift control, direct side force control, energy management and energy maneuverability.

Figure No. 8 illustrates a few potential next generation aircraft. These aircraft will dynamically blend the control functions of the weapon system. An example would couple flight control, propulsion control and laser tracker control to the weapon fire control with the object being to maximize aiming precision or target range. Performance seeking control actions could be supervised by the mission control system. Algorithms could be selected to maximize range, minimize time-to-target or maximize flight time. Contributing systems (flight, propulsion, navigation) could optimize performance while simultaneously observing subsystem limits. Research to define these blended control modes will require cooperative "team" studies to assure that each subsystem is properly represented and modeled with adequate fidelity.

CLOSING THOUGHT

The technologies supporting control system evolution draw from a wide variety of disciplines. While some of these disciplines are paced by progress within the aerospace community, most of them are now heavily influenced by the demands of the consumer industries.

As automatic controls become more commonplace in the consumer market, industrial research will focus more on that need and will respond less to the special needs of aerospace products. Although some consumer products and techniques will be adaptable to our needs, the net effect will be a requirement to expend more research dollars for aerospace specialty items.

Research money alone will not, however, reverse the current trend of specialty industries to ignore or reject the aerospace market. Within these industries we see a rare consensus between the "managers" and the "innovators" that aerospace products are not worth the trouble. In addition to a low profit margin, the managers see a poor return on the investment of time and limited innovative talent. This reinforces their natural desire to constrain the innovations and react only to the consumer market. The innovators are not stimulated because long range military missions, plans and products are not visible to them. In addition, their novel or revolutionary ideas are frequently "stonewalled" by Military Specifications.

There are many other factors involved in this problem and a solution is not obvious. Some research effort should be expended to define new planning, budgeting and procurement procedures plus new technology management methods that will encourage these specialty item subcontractors to participate in aerospace product development.

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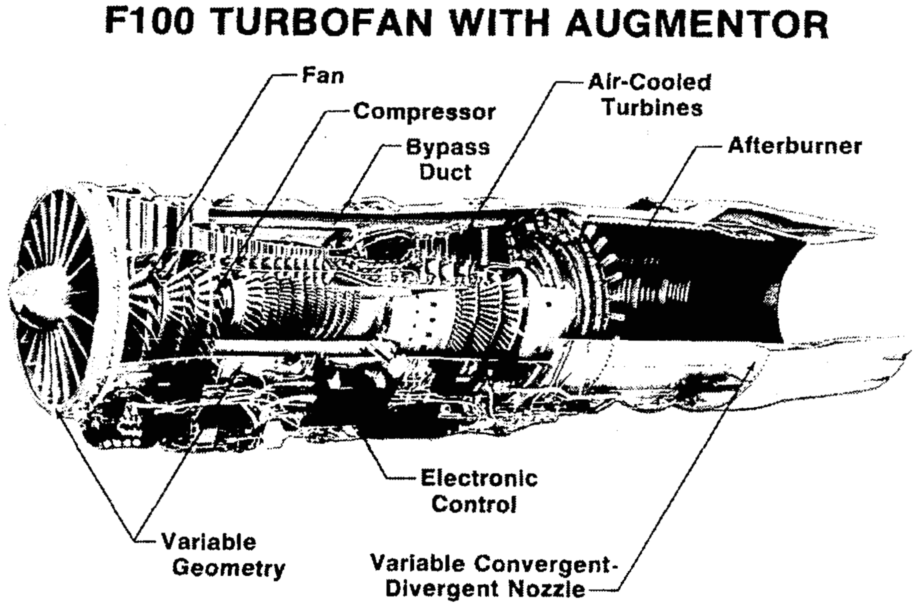


Figure No. 1

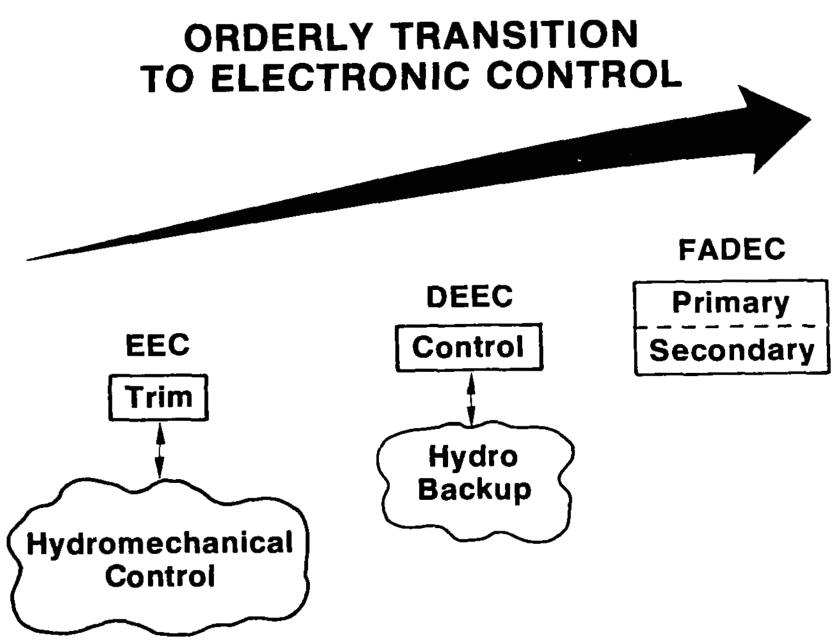


Figure No. 2

ELECTRONIC COST PER CALCULATION REDUCING 50% PER YEAR

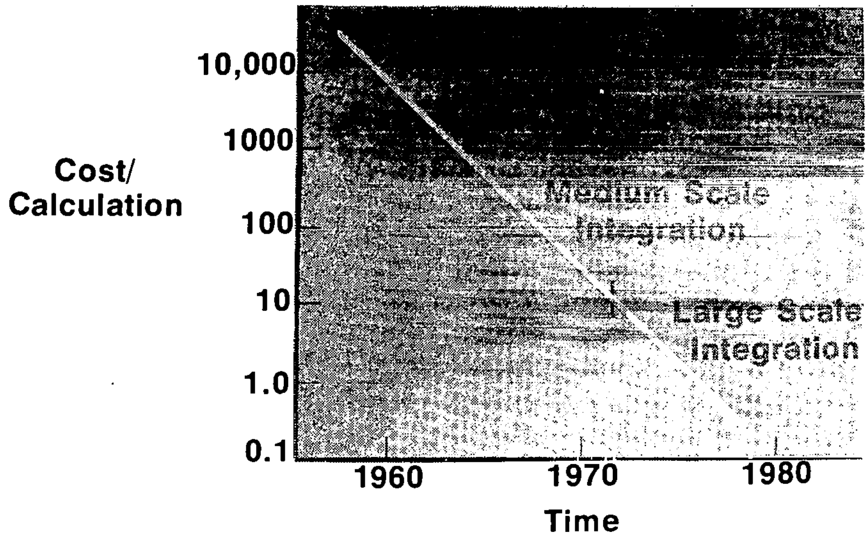


Figure No. 3

CONTROL TECHNOLOGY/GOALS

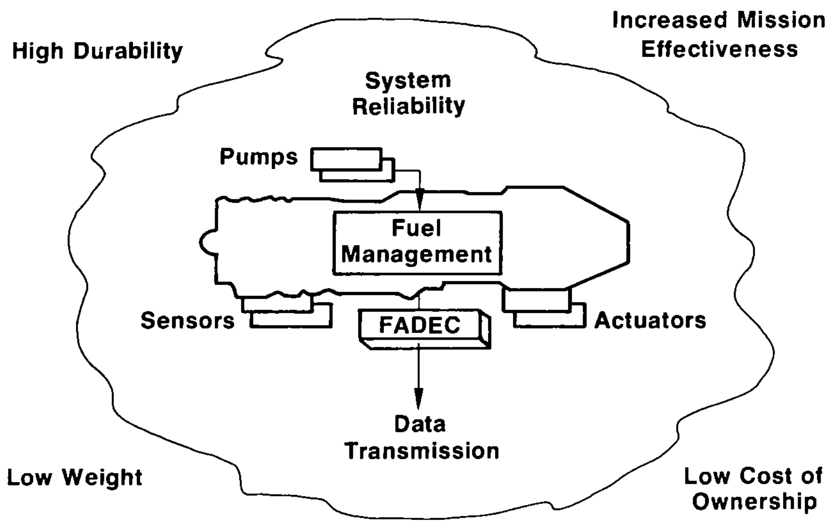
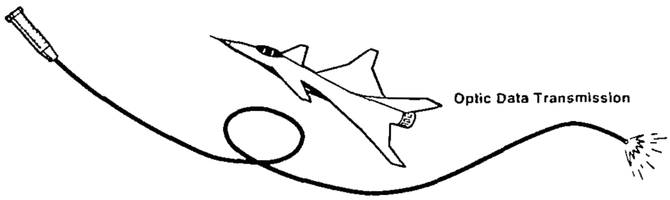


Figure No. 4

FLY BY LIGHT

Engine Cable Weight Reduced
High Data Rate
No Electromagnetic Interference



Fail Gracefully
Security - No Leakage
Direct Communication With Computer

Figure No. 5

RELIABILITY WITH REALISM

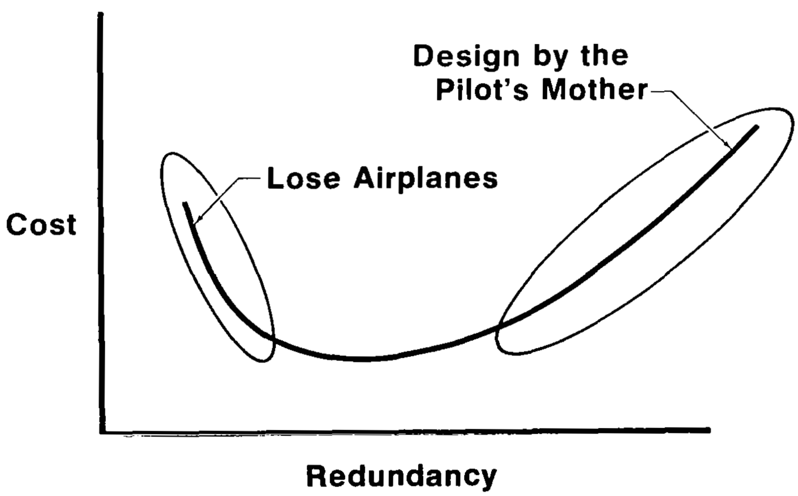


Figure No. 6

CONTROL SYSTEM DEVELOPMENT/ INTEGRATION FACILITY

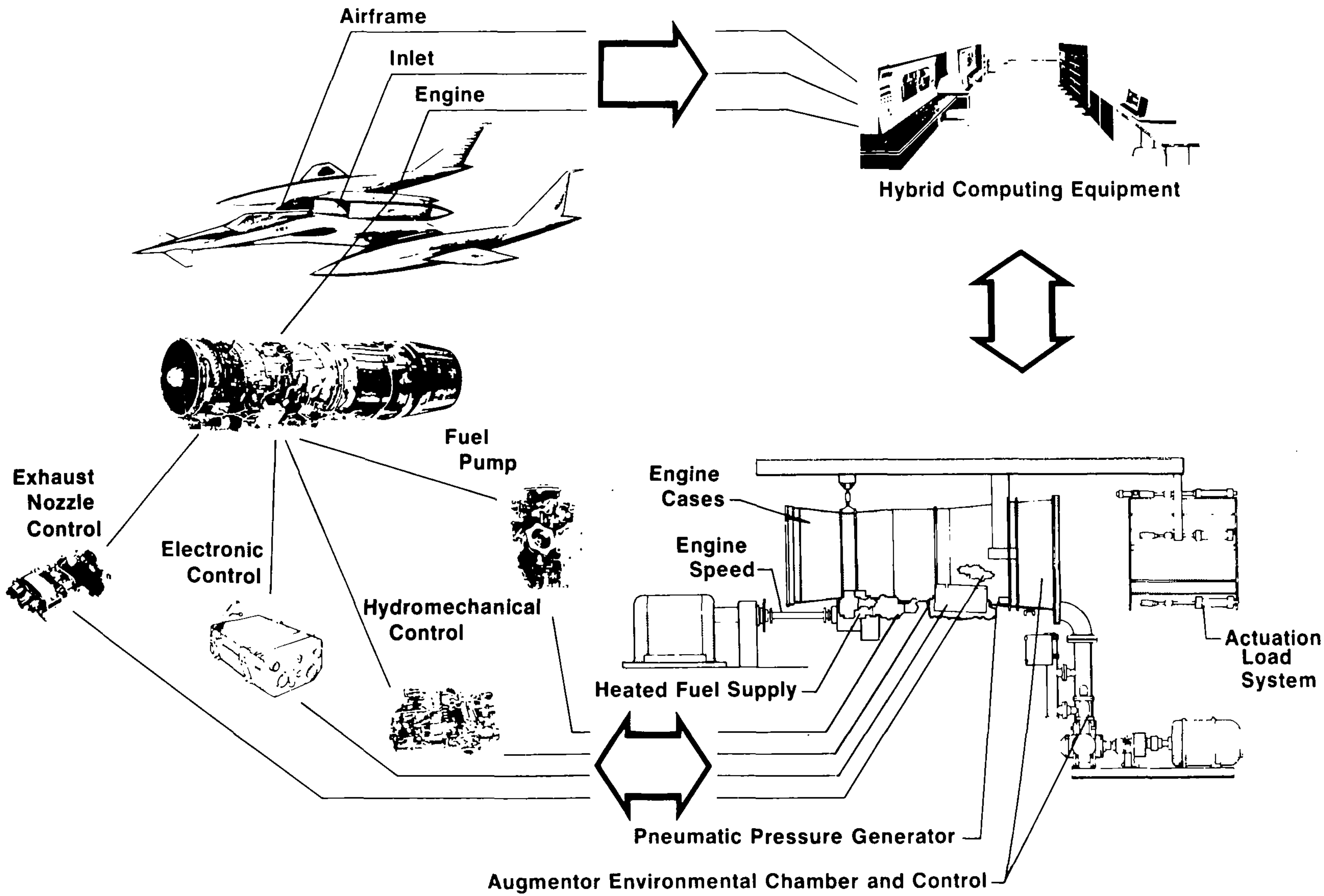


Figure No. 7

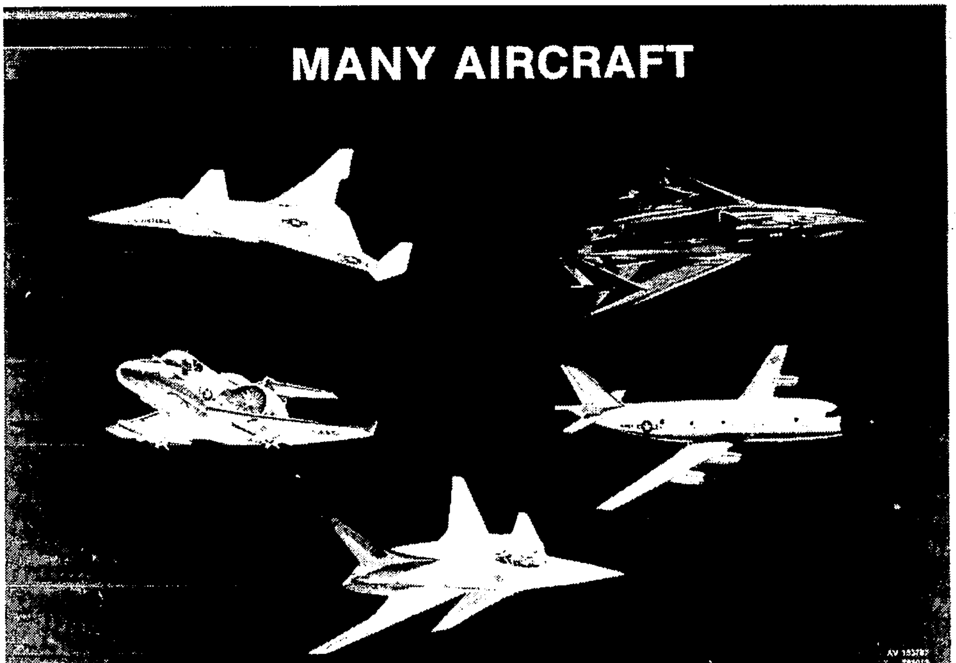


Figure No. 8