Digital Electronic Propulsion Control System Problems and Payoffs

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Improvements in electronic-control technology will provide reliable, cost-effective control systems to meet turbine engine requirements in the mid 1980s. The complex control requirements for these advanced engines include increased accuracy, multiple control loops, and more communication links between the aircraft and propulsion systems. The current hydromechanical control systems are not capable of handling these increased control requirements. Technological advances will make possible a control system designed around a prime reliable digital electronic computer which will meet the control requirements for the advanced engines and will eliminate the need for a hydromechanical control. Predicted benefits which will be offered by the prime reliable electronic control system include reductions in control system cost, fuel consumption, and aircraft weight.

Introduction

CONTROLS for contemporary and future aircraft propulsion systems are undergoing a revolutionary change. The two primary factors causing this change are more complex engine cycles and a substantially increased requirement for coupling the engine control with other aircraft systems. The new complex engine cycles may have several additional independent variables requiring coordinated control. In some cases the control must provide thrust management in addition to the protection functions normally provided. Other aircraft systems which are being coupled with the engine control include the inlet control, aircraft flight control, and diagnostic systems. Conventional hydromechanical engine controls, used so successfully in the past, can no longer handle the increased functions required of the future propulsion control system.

A system that appears to have the capability required of an advanced propulsion control system is centered around a digital electronic computer. This paper discusses advantages of the digital electronic control, location of the electronics relative to the propulsion system, reliability of the control system, and technological advances required to bring about a prime reliable digital electronic control system.

Problems

The types of new requirements being placed on the propulsion control systems in contemporary and advanced engines will now be discussed.

First, there is the complex propulsion cycle, wherein the propulsion plant has several more independent variables than have faced the control system ever before. The number of variables which the control system must coordinate can be up to eleven for the engine and another four or five for the inlet. For maximum performance it is imperative that all of these variables be coordinated to maintain engine performance for steady-state operation, stable and safe operation for transients, as well as to provide the fastest possible engine response to power change commands. Figure 1 shows such a propulsion system and the variables involved. As can be seen, the variables which must be coordinated include fan geometry, compressor geometry, gas generator fuel flow, perhaps turbine geometry, a core-stream exhaust nozzle, and in addition, possibly a duct augmenter and duct augmenter nozzle, and a divergent nozzle behind the convergent nozzle. Going back up front to the inlet, one sees a system of two or three ramps and probably some sort of a bypassing door arrangements. The practical limit for hydromechanical controls is five or six variables, and therefore this type of propulsion system needs a considerably more powerful computer.

In more conventional engines, particularly those used in subsonic transport aircraft, there are also new requirements for the control. One such requirement for the control is to provide multi-engine thrust management as well as the speed-governing and protection functions which have been the role of the control in the past. Thrust management requires that for a given throttle setting the engine must deliver a given percentage of the maximum available thrust as long as that throttle setting is maintained, regardless of how flight conditions or atmospheric conditions change. Figure 2 shows what the biasing schedule must look like in order to provide this function of constant-percent thrust. Note that there are several inputs making the function multi-dimensional, which is obviously something which would be impractical to implement on three-dimensional cams. A digital electronic computer can readily store these data as polynomials or as data arrays in the computer memory. In the past, the biasing functions in the hydromechanical control have been designed primarily to put the engine in approximately the right ball park as a function of flight conditions for a given throttle setting, and it was up to the crew to establish exactly what power settings they wanted in terms of the thrust-indicating parameter such as low-rotor speed or engine pressure ratio. Figure 3 shows a typical bias function employed in the hydromechanical control for a high-bypass engine. Note that it has inlet pressure and inlet temperature biases of the selected speed. Alongside of the bias curve is a figure which gives an indication of how power lever angle will vary as a function of inlet temperature for a given rating. Depending on the particular bias schedule, this variation could be as much as 40°.

Yet another new requirement for the propulsion control system is that of integration with the aircraft. As mentioned, for the complex cycles integration of the engine and the inlet controls is necessary to provide optimum performance and transient stability. Several research and development programs are currently being worked in both the military and commercial fields to integrate the propulsion system controls with aircraft controls to optimize the entire aircraft system for energy management. This effort is applicable to both transport-type aircraft where range is the significant consideration, and to fighter-type aircraft where maneuverability as well as

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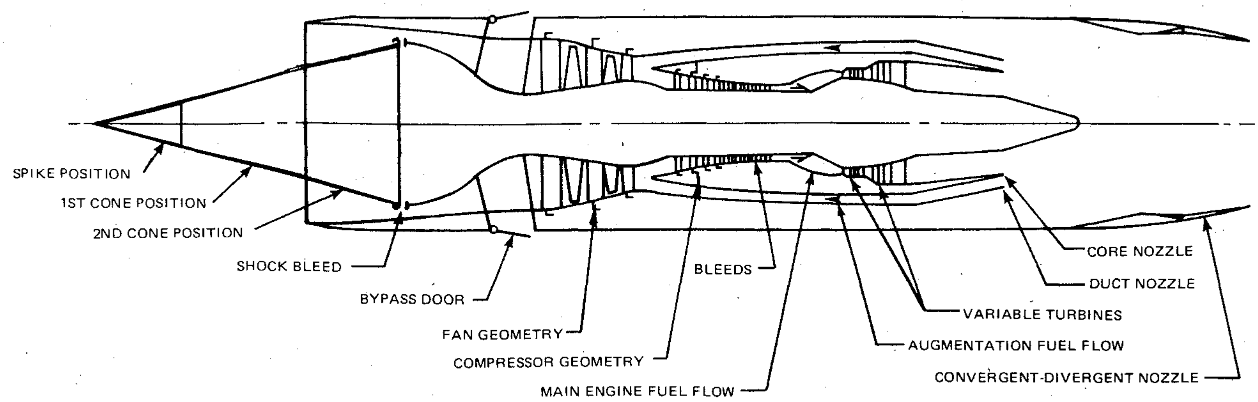

Fig. 1 Complex propulsion system.

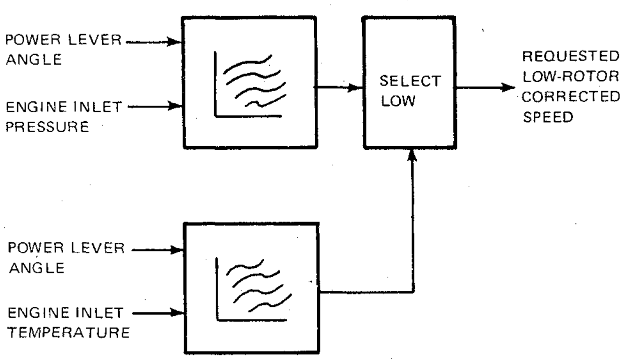

Fig. 2 Biasing schedule required to provide constant percent thrust.

range must be considered. Maneuverability improvement is obtained by generating increased side forces on the aircraft to enable it to execute highly sophisticated maneuvers. These forces can be made available, in part, from the propulsion system. Aircraft which fly at high Mach-number speeds have also shown the need to couple propulsion and aircraft controls for flight stability. In order to accomplish these objectives, it is imperative that the propulsion control and the flight control be coordinated and aware of each other's capabilities and limitations.

Another area where integration of the control is of extreme interest in future aircraft is that of propulsion-system diagnostics and condition monitoring. The degree of in-flight condition monitoring that is required depends on the application, transport or fighter. In any event, both in-flight and on-ground analyses of data obtained during flight are necessary to expedite engine maintenance and provide trending of engine characteristics so that engines can be overhauled or maintained at appropriate periods. This minimizes the cost of the maintenance and maximizes utilization of the engine and aircraft system. The role of the propulsion control in the condition monitoring function can vary considerably. As a minimum, it can provide a digital data link to a separate condition-monitoring computer and data storage system. As a maximum, it can provide some or all of the condition-monitoring computation capabilities within the control computer itself, with a data link to a data-storage system for further ground analysis and data trending.

What Type of Electronics?

As early as 1965, the question of the role of analog and/or digital electronic computers in future controls had been addressed. Predictions then and predictions since then have all favored the use of the digital computer. There are some simple reasons for choosing the digital computer. It has the flexibility and capability to store huge amounts of data in a very small package and is functionally insensitive to environment. Analog computers have a tendency to drift with time and be sensitive to temperature and other environmental changes, therefore tending to have inherently less accuracy than the digital computer. The analog computer program also cannot be readily modified once the circuit is designed, causing increases in development time and cost. When considering analog vs digital computers the questions of cost and reliability always arise. Predictions for solid-state devices which are most readily adaptable to digital circuitry show the cost of these devices being reduced by orders of magnitude over the next several years. Reliability is still a question. The key to reliability, of course, is to reduce the number of parts. Solid-state electronics is incorporating more and more circuit and logic design per chip as technology advancements are made, going from small-scale integration to large-scale integration to what is predicted to be very large-scale integration. In each step, the number of parts required in the electronic system is substantially reduced, and as a consequence, the reliability of the system goes up. The secondary reliability consideration involves both hardware design and software design. Reliability for completion of a mission, but not for maintenance actions, can be achieved through redundancy. Reliability can also be achieved by carefully thought-out software and hardware designs wherein component failures can be detected through built-in test capabilities of the computer system. Logic can be employed in the software and hardware to allow the computer to recognize problems and take alternate courses of action. This idea is termed soft failure capability. One of the primary concerns in employing electronic controls has been that a failure caused total loss of control. This must be completely avoided, and with manufacturers' projections of advancing electronic technology, the concept of marrying software and hardware logic with the very large-scale integrated circuit and hybrid circuit designs will demonstrate that soft failure capability can be practically achieved. With this technology, digital electronic controls can achieve the same levels of reliability that are experienced with current hydromechanical control systems.

Trade Studies

Control Configuration Trade Studies

A comprehensive series of trade studies has been conducted for application of the digital electronic control to both fighter and transport aircraft. These trade studies explored control configuration possibilities ranging from engine-mounted electronics dedicated to a single engine to a centralized aircraft-mounted unit for control of multiple engines. The trade studies considered control system reliability, procurement cost, life cycle cost, maintainability, dispatchability and other parameters directly affecting the selection of a control configuration. As would be expected, the general conclusion from the control-configuration is application oriented. It is interesting to note, however, that in all cases studied, the dedicated control (one control per engine) turned

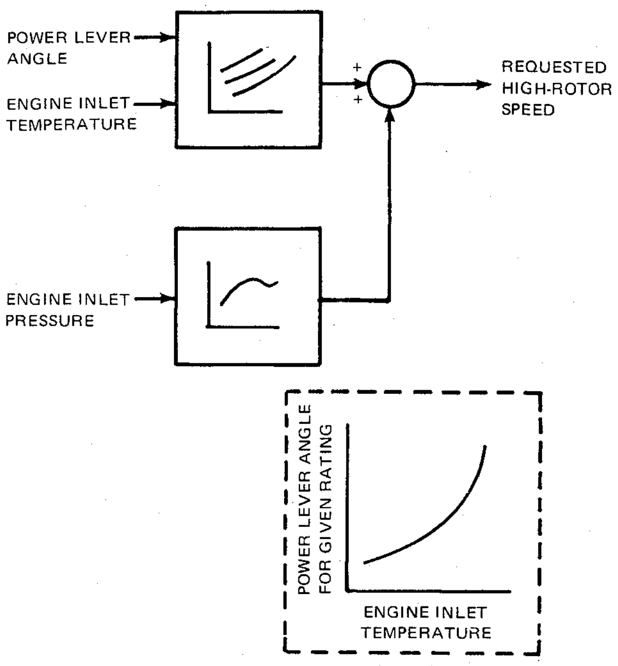

Fig. 3 Bias function for typical hydromechanical control.

out to be superior in terms of reliability and cost effectiveness in comparison with the centralized control concept.

Figure 4 illustrates the four basic systems considered in the control-configuration study. System A is the conventional hydromechanical system which is currently in service. System B is the system which integrates all of the propulsion (inlet, engine, and nozzle) controls. System C multiplexes all of the propulsion control signals and sends them to a central aircraft mounted computer, receives multiplexed commands from the computer and converts them into signals to drive the propulsion-system values and actuators. System D is the same as System C without multiplexing, so that individual wires for each sensor and each valve and actuator must be run from the propulsion-system unit to the computer and back. With the exception of the central computer control, each control was studied when mounted on the engine, in the nacelle or pylon, and in the avionics bay. In the case of the central computer, it was always mounted in the avionics bay.

As an example of the results of the trade study, some data for a subsonic transport are presented. The data showed that dedicated controls for each propulsion unit were the best approach when considering all of the factors in the study. The data also show that the control should be mounted near or on each propulsion unit. The data presented here are concerned with four types of controls based on these general findings.

Figure 5 schematically illustrates thes control systems which have been scaled to equal functional complexity. The controls are the current hydromechanical control system, an electronic control working in a supervisory capacity (supervisory control), a primary electronic control which has full control over the engine with a simpler secondary electronic control (redundant electronic control), and a single electronic control with no separate redundant control function. For these four systems, data on reliability, dispatchability, in-flight shutdown rate, and life cycle cost were analyzed. The analyses considered the four systems using current technological capability and also using projected technological capabilities for the 1985 time period.

Table 1 presents the current-technology data. With the current hydromechanical system as a base for current technology, the reliability data show the hydromechanical system is the best, considering the current state-of-the-art for electronic technology; the dispatchability data show that the supervisory control and the redundant electronic control system have better dispatchability and in-flight shutdown rates because of their redundancy features. This assumes the aircraft is allowed to dispatch with one electronic control system inoperative. If this is not permitted, dispatchability of the supervisory system becomes about equal to the base system and the redundant electronic system is worse than the base system.

A key decision is required on the dispatchability of single-engine and multi-engine aircraft with either the primary or secondary control inoperative, whether hydromechanical or electronic. A single-engine aircraft would probably not be dispatched if either of the propulsion control systems were inoperative. For multi-engine aircraft, this type of question must be answered through cooperative study by the engine manufacturer, the control manufacturer, the aircraft manufacturer, airlines, the military, and the governmental regulatory agencies involved.

With current technology, the single electronic control has excessive dispatchability delay and in-fight shutdown problems, primarily because it was assumed that failure of the electronic control without a backup would shut the engine down. On a life-cycle cost basis, all three electronic systems were shown to be less costly than the current hydromechanical control system, but considering the operational requirements as well as cost, only the supervisory control and redundant electronic control systems can be considered as reliable alternatives to the hydromechanical control if current technology is used in the systems.

Table 2 presents the data from the study based on the use of 1985 projected technology. The hydromechanical control is used as the base, and because control manufacturers are projecting no significant changes in the level of technology of the hydromechanical control over the next ten years, the base is essentially the same as the 1975 base. In all cases the electronic control system types show substantial improvements over the base system. The supervisory and redundant electronic controls are shown to have improved over their 1975

Table 1 Propulsion control system trade study—1975 technology

Control system configuration (equal complexity)	Percent increase or decrease: Maintenance requirements	Dispatch delays	In-flight shutdowns	Life cycle cost[a]
Current hydromechanical control system	Base	Base	Base	Base
Supervisory control	+20	−30 to −40[b] 0 to −10[c]	−30 to −40	−5 to −10
Redundant electronic control	+30	−50 to −60[b] +60[c]	−80	−30 to −40[b] −20 to −30[c]
Single electronic control	−10	+30	+250	−30 to −40

[a]Constant-year dollars (1974). [b]Assumes aircraft is dispatchable with one electronic system out. [c]Aircraft dispatchable only with all systems operational.

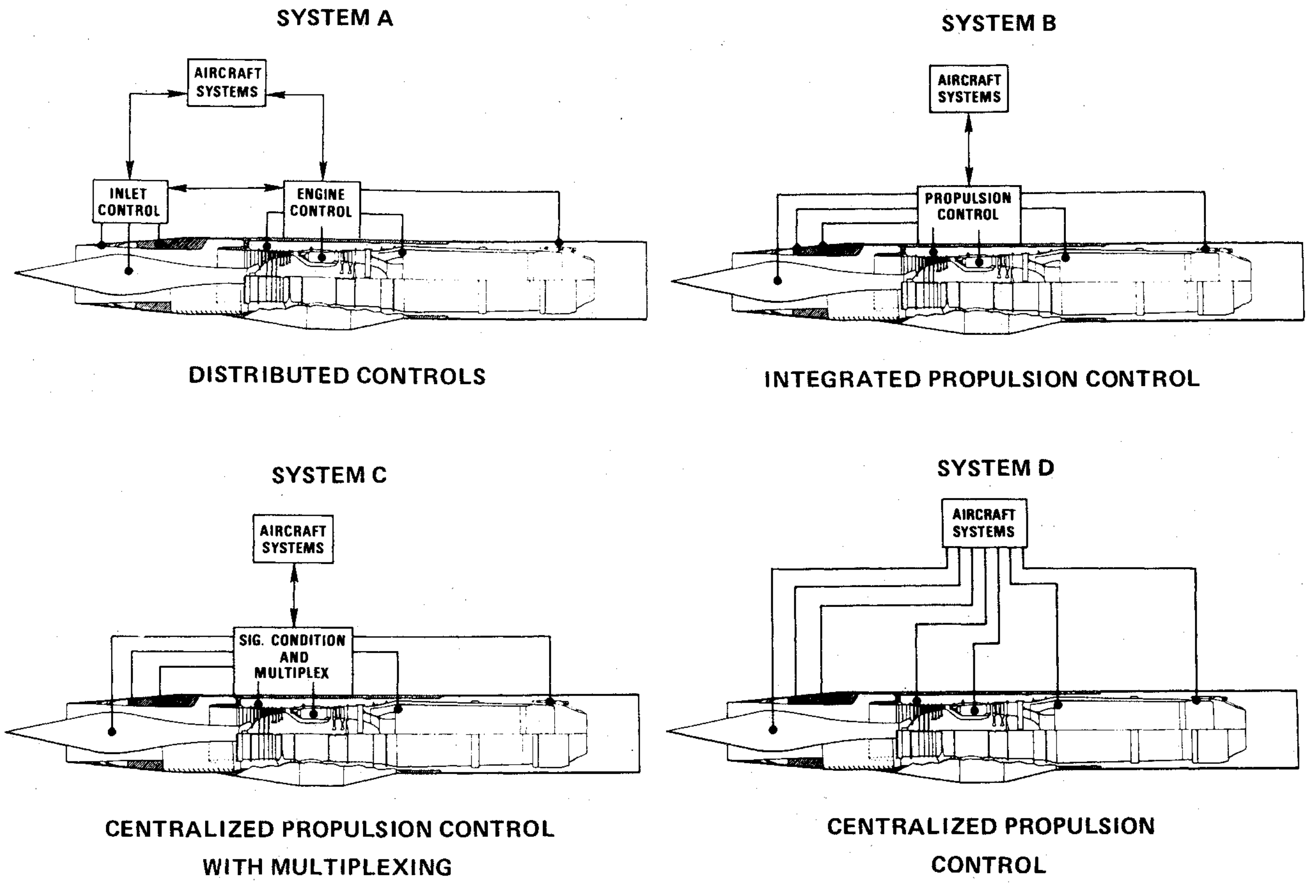

Fig. 4 Basic control system configurations studied.

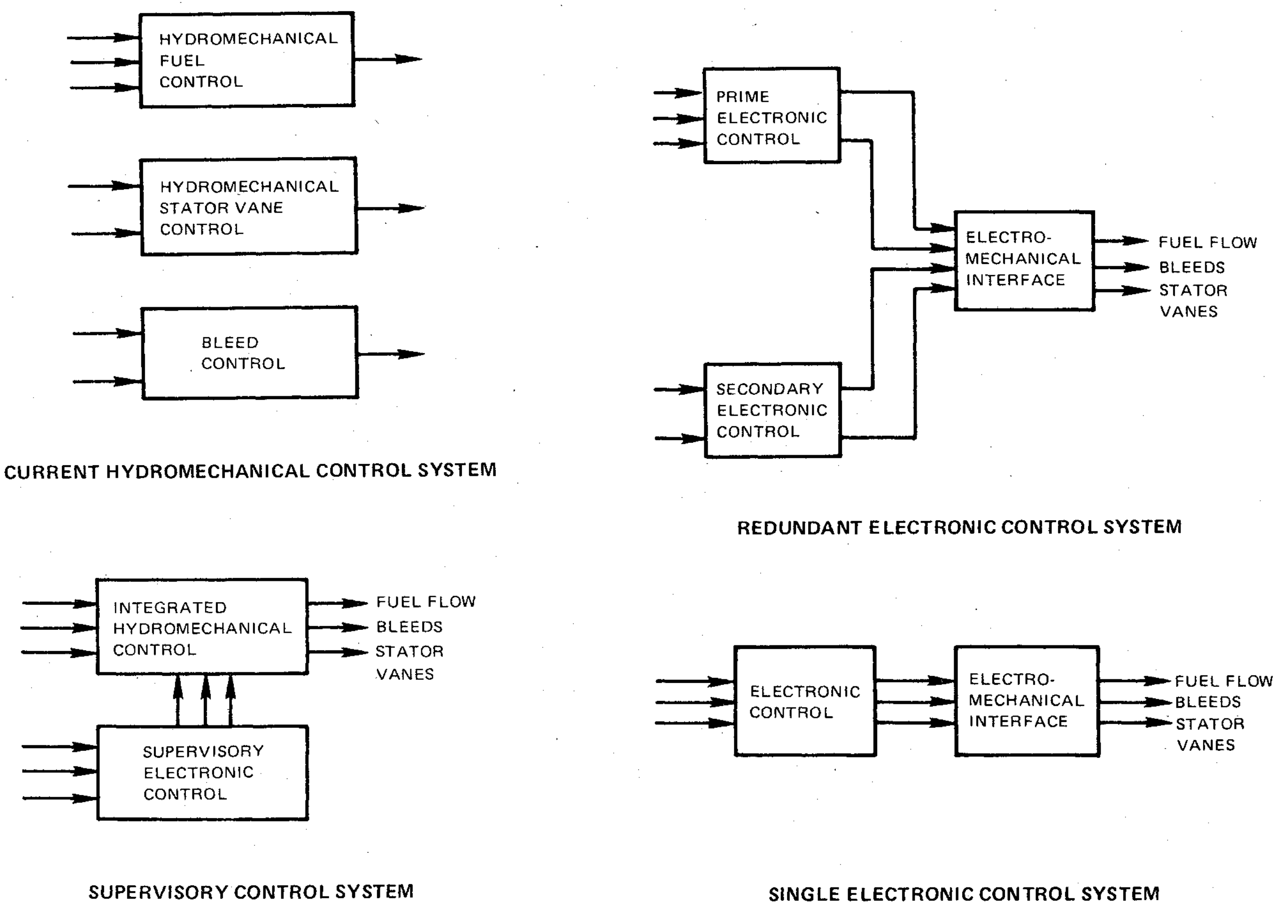

Fig. 5 Four types of controls evaluated.

Table 2 Propulsion control system trade study—1985 technology

Control system configuration (equal complexity)	Percent increase or decrease			
	Maintenance requirements	Dispatch delays	In-flight shutdowns	Life cycle cost[a]
Current hydromechanical control system	Base	Base	Base	Base
Supervisory control	−30 to −40	−30 to −40[b] −10 to −20[c]	−30 to −40	−10 to −20
Redundant electronic control	−50	−50 to −60[b] −30 to −40[c]	−80	−40 to −50[b] −30 to −40[c]
Single electronic	−50 to −60	−40 to −50	−30 to −40	−40 to −50

[a] Constant-year dollars (1974). [b] Assumes aircraft is dispatchable with one electronic system out. [c] Aircraft dispatchable only with all systems operational.

counterparts primarily because of projected improvements in electronics reliability. For the 1985 time period, the single electronic control also shows substantial improvement due to projected improvements in electronic system reliability. The single electronic control with 1985 technology has predicted reliability better than the other three systems, equal or better dispatchability, fewer in-flight shutdowns except for the redundant electronic control, and lower or equal lift cycle costs. These predicted data would indicate that the single electronic control could be considered "prime reliable." It is interesting to note that a 50% change in maintenance cost results in only a 10% change in life cycle cost, implying the strong relationship between life cycle cost and unit procurement cost.

To summarize, with current technology, the supervisory control indicates improvements over the current hydromechanical control in all categories, as does the redundant electronic control, provided dispatchability is allowed with one of the electronic systems inoperative. With projected 1985 technology, the single electronic control shows improvements that make it generally equal or better than the redundant electronic control and clearly improved over the controls in service today. Savings in weight and size offered by the single electronic control over the redundant system will tend to tip the scale in favor of the single electronic control as the choice for 1985.

Control System Cooling Trade Studies

Projections to 1985 do not particularly give any indication that the semiconductor junction temperatures will be allowed to run much higher than a limit of approximately 250°F. For purposes of extending life, which of course is paramount in achieving good reliability, it is desirable to run the electronics at a maximum temperature range of 150 to 180°F. A trade study was performed to determine the type of cooling system which would best meet this need. The results of the cooling study are not nearly as clear-cut as some of the other results we have seen. It has been established that cooling is required for electronics. Cooling can be supplied from the aircraft environmental control system as cold air, or cold fuel can be pumped from the tank directly to the electronic unit and then returned into the fuel system. It appears that for cooling, the best result will definitely be defined by the application, and the trade studies will not provide any further insight than that. Studies have shown that the incorporation of a separate dedicated refrigeration system is somewhat expensive and adds a significant weight penalty. These estimates generally are in the order of 10 to 15 thousand dollars per cooling unit with a weight penalty of about 15 lb per engine. It does appear that using the environmental control system air or cold fuel from the aircraft fuel tank is a better solution. In the case of supersonic aircraft, fuel can heat up in the fuel tanks to the point where it does not provide an adequate cooling function. Here perhaps the penalty of carrying an additional dedicated refrigeration unit for the electronic control might be considered, although that would have to be weighed against the use of air from the aircraft environmental control system.

Control System Power Trade Study

Another study conducted under the control system configuration study series concerned itself with the type of electric power required by the electronic control to best satisfy the cost and "ility" criteria previously discussed. It was determined that so long as shipboard power is permitted to have the type of power interrupts and voltage excursions presently defined by pertinent specifications, this type of power is inadequate for electronic propulsion control. The primary problem is the power interrupts. Generally, the control system must update its output every 20 millisec to provide stable engine operation. A power interrupt of 40 millisec plus the time required to re-initialize the computer and get back on line would far exceed this 20-millisec update requirement. The result could have a significant detrimental effect on safe engine operation. As a consequence, dedicated engine-powered alternators as the power source for electonics appear to be the only alternative. Alternator technology is advancing to the point where these engine-powered alternators can be a two- or three-pound unit integrated within the fuel pump. Further, the projected advances in electronics, sensors, and output devices will allow the entire control system to operate on as little as 100 w with fewer types of power needed. Therefore, much smaller and simpler alternators can be used

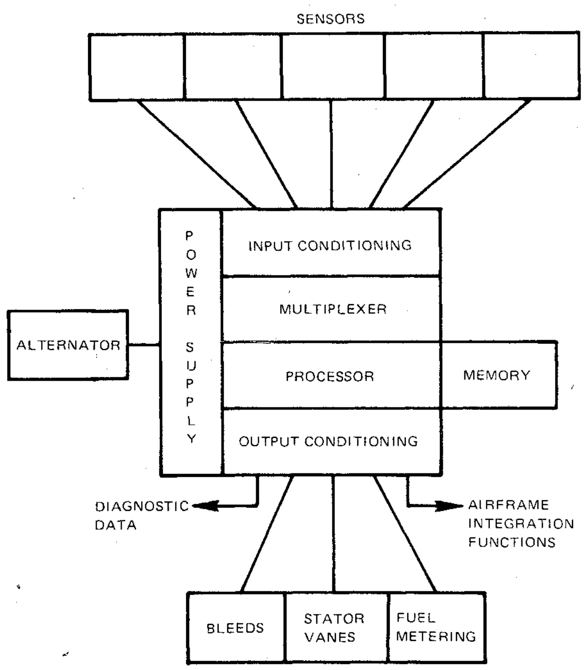

Fig. 6 Typical electronic control system.

Table 3 Engine environment sensor requirements

Sensor	Range (maximum/minimum)	Accuracy (% of point)	Response time (sec)	Reliability mean time between failures (hr)	Digitally compatible available	Technology status
Speed	10/1	0.1	0.02	>250,000	Yes	Available
Pressure	100/1	0.1	0.02	>250,000	Yes	Needs size reduction and reliability improvement.
Temperature	10/1	0.5	0.1	>250,000	No	Needs invention
Fuel flow	100/1	0.5	0.02	>250,000	No	Needs invention
Position	–	1.0	0.02	>250,000	No	Needs invention

Table 4 Electronic component requirements

Component	Function	Reliability mean time between failures (hr)	State-of-the-art electronic component technology	Environment temperature requirements (°F)	Needed technology advancements
Input/output	Conditions signal	100,000 (Input/output, Signal conversion and Multiplexer)	Discrete	<250	Reduce component quantity through hybridization.
Signal conversion	Converts analog to digital and digital to analog		Integrated circuit	<250	Follow electronics industry.
Multiplexer	Feeds data to computer		Integrated circuit	<250	Follow electronics industry.
Processor	Performs arithmetic functions and controls computer	100,000	Integrated circuit	<250	Follow electronics industry.
Memory	Stores data	250,000	Integrated circuit	<250	Follow electronics industry.
Output devices	Convert output data to mechanical signals	>250,000	Electromagnetic	<500	Reliability improvements
Power supplies	Regulate power	250,000	Discrete	<500	Low power loss to regulate high-temperature components.
Alternators	Generate electrical power	>250,000	Permanent magnets	<500	OK
Cabling	Transmits data	>250,000	–	<1000	Improved connectors Use of optics

than are required today without the multiplicity of windings in current alternator designs.

Electronic Component Technology

A typical electronic control system, such as that shown in Fig. 6, consists of sensors, input electronics, processor, memory, output electronics, interface devices, fuel valves and actuators, alternator, power supply, and associated cabling. Each of these elements is at a different stage of technological development requiring different amounts of advancement to achieve the goal required for a completely electronic prime reliable control system.

Sensors

Sensors are probably one of the weakest areas in the electronic control system with respect to range, accuracy, response, reliability, and compatibility with the digital computer.

Table 3 summarizes the variety of sensors needed for propulsion system control. As can be seen, work on sensor technology is needed in most areas to meet the requirements stated on the chart. It is anticipated that optical devices will play a major role in overcoming these technological shortcomings.

Electronic Components

Table 4 lists the various electronic computer elements as well as the components required for the computer to communicate with the outside world. Generally, the computer-oriented components will follow the electronics industry lead and the predictions used in this study are based on electronics industry projections. The peripheral components need considerably more work for size reduction and reduced power consumption to improve reliability.

Payoff

The payoffs which can be obtained through the application of electronic controls to aircraft propulsion systems are substantial. We have seen from the data presented in the configuration trade studies that, in relation to current engine control systems, significant cost savings and improved aircraft availability can be achieved through the use of electronic controls. For the near term, estimated savings of approximately 10% in life cycle cost and a 30% reduction in in-flight shutdown and delays have been shown. Incorporation of projected 1985 technology into the electronic propulsion control system promises potential improvements which are anticipated to reduce life cycle cost by 50%, increase reliability by a factor of 3, and maintain the improved in-flight shutdown rate and dispatch delays at 30% less than they are today. Total savings realized from the use of the electronic controls will, of course, depend upon fleet size and the extent to which such controls are utilized. However, it is predicted that reductions in life cycle cost which will be achieved through the application of the electronic control will be in the tens of millions of dollars for the near term, and hundreds of millions of dollars for the 1985 control systems.

There are other additional benefits to be achieved through the application of electronic control. These benefits will accrue primarily from integration of the electronic engine control with the aircraft system. For transport aircraft, fuel conservation improvement or range improvement of up to 1% has been predicted through coupling of the propulsion control and aircraft control systems for automatic flight patch control. The use of automatic thrust control allows an engine to operate precisely on rating, without overboost or underboost. Predictions show that up to 10% improvement in engine hot-section life can be expected simply by maintaining the proper power setting through automatic control. Projections, particularly for larger aircraft, show that aircraft weight savings of up to 200 lb can be achieved by the elimination of the cable and pulley systems used to operate the throttle in current aircraft. The fully electronic control will eliminate the need for these mechanical systems. In fighter/bomber type aircraft, improvements in the maneuverability, aircraft range, and maintenance are projected. Quantitized improvements in maneuverability have not yet been determined. However, studies of fighter aircraft have shown performance improvements in terms of thrust specific fuel consumption or increased thrust of up to 5% as a result of integrating the engine control and the inlet control, and increasing communications between the aircraft control system and the propulsion control system.

The digital electronic control, with its built-in test features and simplified trim capability, along with its ability to provide diagnostic data to a condition monitoring system, is anticipated to provide significant improvements in maintainability costs for the entire propulsion system.

These substantial payoffs in engine and aircraft performance to be gained through the use of a digital electronic control provide the impetus for the control manufacturers to make the improvements in electronic system reliability that are projected. Electronic propulsion controls are currently being applied in several of the latest commercial and military aircraft. Experience gained from these applications plus the technological advances in electronics expected over the next ten years provide high confidence that the prime reliable digital electronic control will be a reality in the mid 1980s.

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