

**FUNCTIONAL INTEGRATION OF VERTICAL FLIGHT PATH
AND SPEED CONTROL USING ENERGY PRINCIPLES**

**A. A. Lambregts
Boeing Commercial Airplane Company
Seattle, Washington**

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ABSTRACT

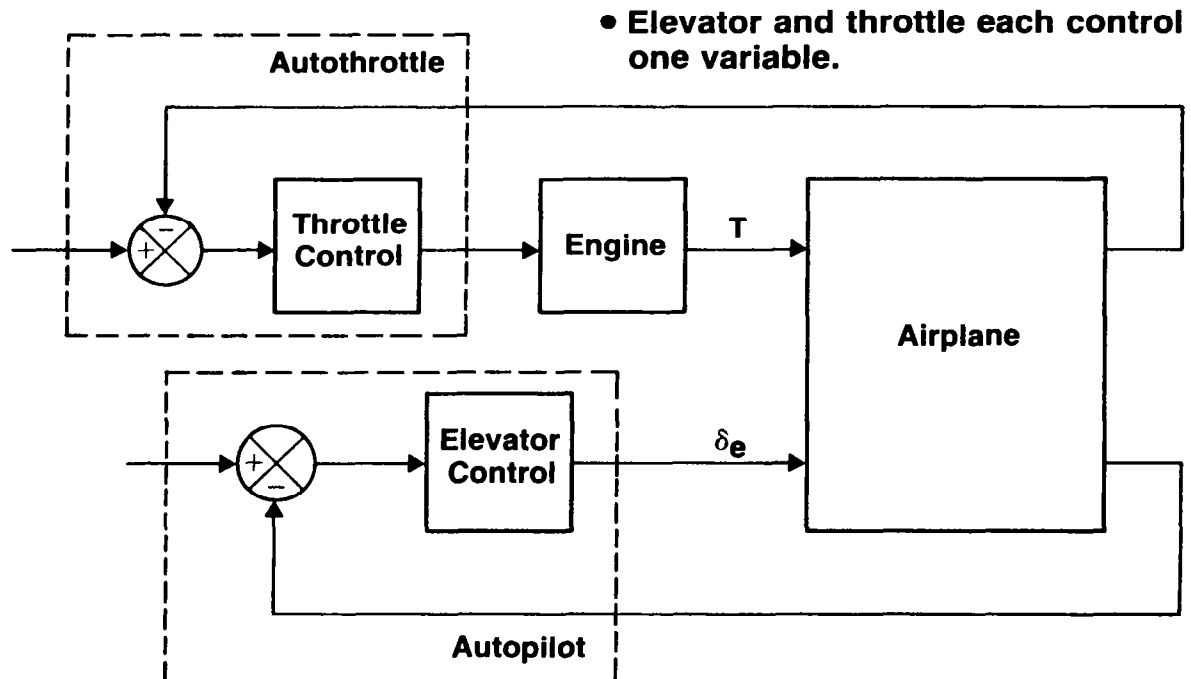
A generalized automatic flight control system has been developed which integrates all longitudinal flight path and speed control functions previously provided by a pitch autopilot and autothrottle. In this design, a net thrust command is computed based on total energy demand arising from both flight path and speed targets. The elevator command is computed based on the energy distribution error between flight path and speed. The engine control is configured to produce the commanded net thrust. The design incorporates control strategies and hierarchy to deal systematically and effectively with all aircraft operational requirements, control nonlinearities, and performance limits. Consistent decoupled maneuver control is achieved for all modes and flight conditions without outer loop gain schedules, control law submodes, or control function duplication.

STATE-OF-ART AUTOPILOT/AUTOTHROTTLE

Virtually every automatic flight control system (AFCS) in use today has been designed using a single-input, single-output control strategy. Although the elevator control loop may be closed on either speed or flight path, the autopilot path control modes have become the most widely used. Automatic speed control using the throttles was then developed as a natural complement to the autopilot path control modes.

Unfortunately, this historic system evolution has not resulted in optimum AFCS capabilities and performance. For certain flight conditions, the autopilot path control at constant thrust produces speed instabilities, while autothrottle speed control at constant elevator results in path instability. Together, they can provide stable flight path and speed control. However, the operation is far from coordinated teamwork. Generally, the autopilot is designed first and satisfactory path control using the powerful elevator is often obtained at the expense of speed control. This leaves the autothrottle in a no-win situation: poor speed control with acceptable throttle activity or acceptable speed control with objectionable throttle activity.

For large autopilot path change commands, the conventional control strategy breaks down because thrust will limit, causing loss of autothrottle speed control, with the ensuing risk of stalling or overspeeding the aircraft.



LIMITATIONS OF THE TRADITIONAL DESIGN APPROACH

The traditional single-input, single-output design approach has a number of other fundamental design limitations. Modes that have not specifically been designed to work together are generally incompatible. This has led to a proliferation of specialized control modes of limited use.

Still, pilots complain that the operation of the present generation automatic control systems is often contrary to the way the pilot uses the controls. The lack of short-term coordination of elevator and throttle commands results in undesirable and inefficient controller activity. This is especially true for the autothrottle system in energy-management-type situations.

Clearly, using the throttles to control speed is not an ideal control strategy. H. A. Soulé summed it all up in the title of his article (ref. 1), "The Throttles Control Speed, Right? Wrong!"

In the present designs, the thrust control loop is subject to extreme variations in loop gain and dynamics due to variations in aircraft weight and engine characteristics for different conditions. Poor system robustness causes wide performance variations.

The fragmented bottom-up design approach makes it difficult to efficiently implement general design requirements, such as limiting of speeds and maneuver rates, because provisions have to be made in many places.

Research Background

Traditional Single-Input – Single-Output Design Approach Has Inherent Deficiencies:

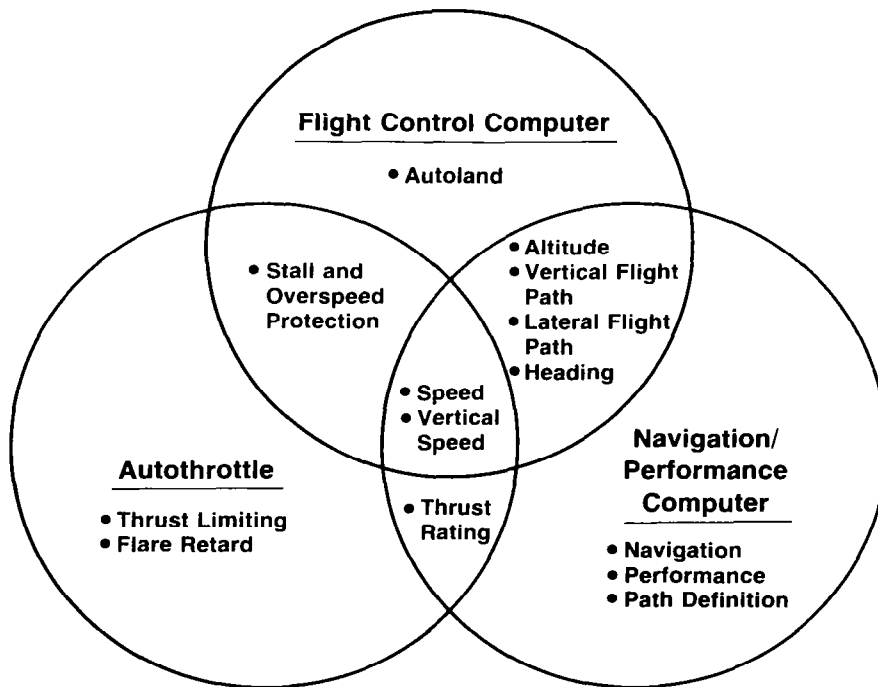
- **Each mode combination is new problem**
- **Performance of one mode depends on other engaged mode**
- **Deficiency of one mode often basis for design of another**
- **Lack of control coordination leads to undesirable coupling**
- **Control coupling limits achievable damping**
- **Difficult to deal effectively with performance/safety limits**
- **Many difficult and iterative development programs have not resulted in fundamental design improvements**

FUNCTIONAL OVERLAP

The numerous efforts to overcome the limitations of the conventional autopilot and autothrottle designs have contributed much to the overall AFCS complexity, but little to the improvement in the fundamental design methodology. This is illustrated in this figure showing the functional overlap in the latest generation AFCS. Basic flight path and speed control capability now exists in all three computer systems! This results in operational ambiguities, unnecessary pilot workload, the need for numerous sensors, computers, interfaces, elaborate configuration control, and high cost of ownership. Obviously, the underlying system architecture is not ideal.

A top-down system synthesis capability, using an efficient control strategy providing maneuver decoupling and the correct control priorities, has been missing in the classical design methodology. Also, design tools using modern control theory remain inadequate for synthesis of multi-mode/multi-flight condition systems that can be implemented readily with today's hardware and software technology.

Typical Control Function Overlap, Conventional AFCS



DESIGN OBJECTIVES FOR THE INTEGRATED SYSTEM

The limitations of the traditional autopilot and autothrottle design have been encountered over and over. During the NASA Terminal Configured Vehicle Program guidance and control experiments using the NASA B-737 aircraft, which was equipped with an advanced autopilot and autothrottle, it was concluded that fundamental system improvements could only be obtained by a multi-input, multi-output design approach. As a result, NASA funded research work at Boeing during the 1979-1981 period to develop a fully integrated vertical flight path and speed control concept.

The primary objective was to devise a methodology for the design of a largely generic elevator and thrust command computation algorithm, providing decoupled flight path and speed maneuver control for any required control modes. A pilot-like control strategy, including energy management considerations, needed to be developed to achieve effective elevator and throttle coordination, along with an appropriate hierarchy of control modes to deal with thrust limiting and provide complete protection against stall and overspeed. A more robust system design was desired to reduce sensitivity to engine characteristics. Further design objectives are noted below.

Integrated Vertical Flight Path and Speed Control Design Objectives

- **Improve operational capabilities and performance**
 - **Decoupled maneuver control**
 - **Complete stall and overspeed protection**
 - **Normal acceleration limiting**
 - **Simpler and more effective mode control**
 - **Consistent operation in all modes**

- **Reduce system complexity, weight, volume**
 - **Eliminate functional overlap**
 - **Integrate control laws, minimize software**
 - **Reduce hardware**

- **Reduce cost**
 - **Development and certification**
 - **Modifications and recertification**
 - **Maintenance**

DESIGN APPROACH

The NASA-sponsored conceptual research work resulted in one very promising generalized design approach based largely on point mass energy control considerations. The basic longitudinal point mass airplane equation of motion, solved for thrust required (T_{REQ}) (shown below), indicates that the aircraft's energy rate is mainly controlled by thrust, while at constant thrust ($\dot{E}_s \approx 0$), the elevator control results in equal and opposite responses of flight path angle and longitudinal acceleration (short-term $D \approx \text{constant}$). The elevator control is, in essence, energy conservative.

It follows then, that from an energy management point of view, the thrust should be used to control the total energy and the elevator to control the desired energy distribution between the flight path angle and acceleration, or altitude and speed.

Based on Energy Considerations

$$\text{Equations: } T_{\text{required}} = \underbrace{\text{weight} \cdot (\text{SIN} \gamma + \dot{V}/g)}_{\text{Total energy rate}} + \underbrace{\text{drag}}_{T_{\text{level flight}}}$$

Potential flight path angle γ_p

$$\text{For } T = \text{constant: } \frac{\partial \gamma}{\partial \delta_e} = - \frac{\partial \dot{V}/g}{\partial \delta_e} \quad (\text{short term})$$

Therefore:

- Thrust used to control total energy
- Elevator used to control energy distribution

Result: Total Energy Control System (TECS)

- General control strategy for all modes
- Normalized, airplane independent control law
- Commonality with proven γ_p display
- Very simple, effective design

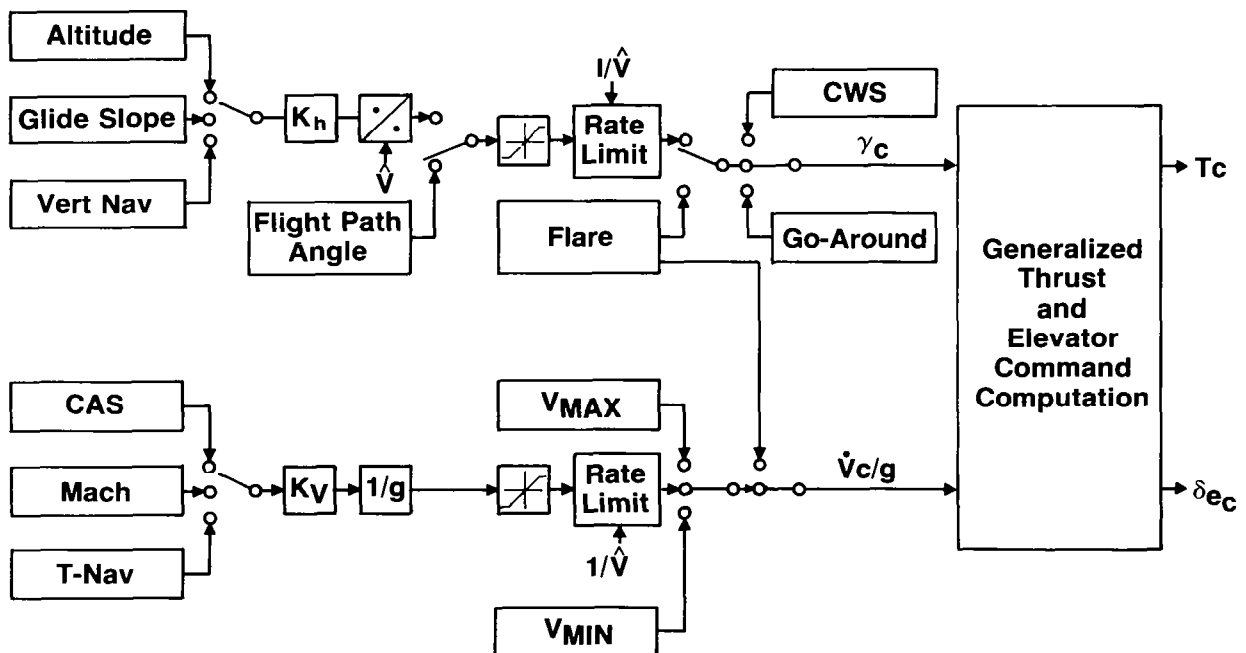
IMPLEMENTATION OF FLIGHT PATH AND SPEED MODES

Using this generalized design approach, all needed flight path and speed control modes of the AFCS can be provided without replication of functions and with the proper hierarchy. The resulting system is called "total energy control system" (TECS). For the outer loop flight path and speed control modes, the altitude and speed errors are simply normalized to form the γ_c and \dot{V}_c/g signals.

The control law calls for an exponential reduction of the altitude and speed errors with a time constant τ inversely proportional to K_h, K_v . Thus, to preserve decoupling for simultaneous altitude and speed maneuvers and to maintain the correct relative energy relationship between altitude and speed errors, $K_h = K_v$ must be chosen.

All flight path modes ultimately produce a flight path angle command γ_c . All speed control modes produce a \dot{V}_c/g . The minimum and maximum speed limiting modes V_{MIN} and V_{MAX} enter downstream of all other speed modes and by autonomous engage logic provide stall and overspeed protection at all times. A more detailed system description is presented in reference 2.

TECS Architecture and Mode Hierarchy



USE OF ENERGY COMMAND RATE LIMITS

The total energy control system meets all functional, operational, and performance requirements of the overall automatic flight control system. General system requirements are met by generic design solutions, implemented at strategic points in the signal processing, so they apply to all intended modes and do not have to be replicated.

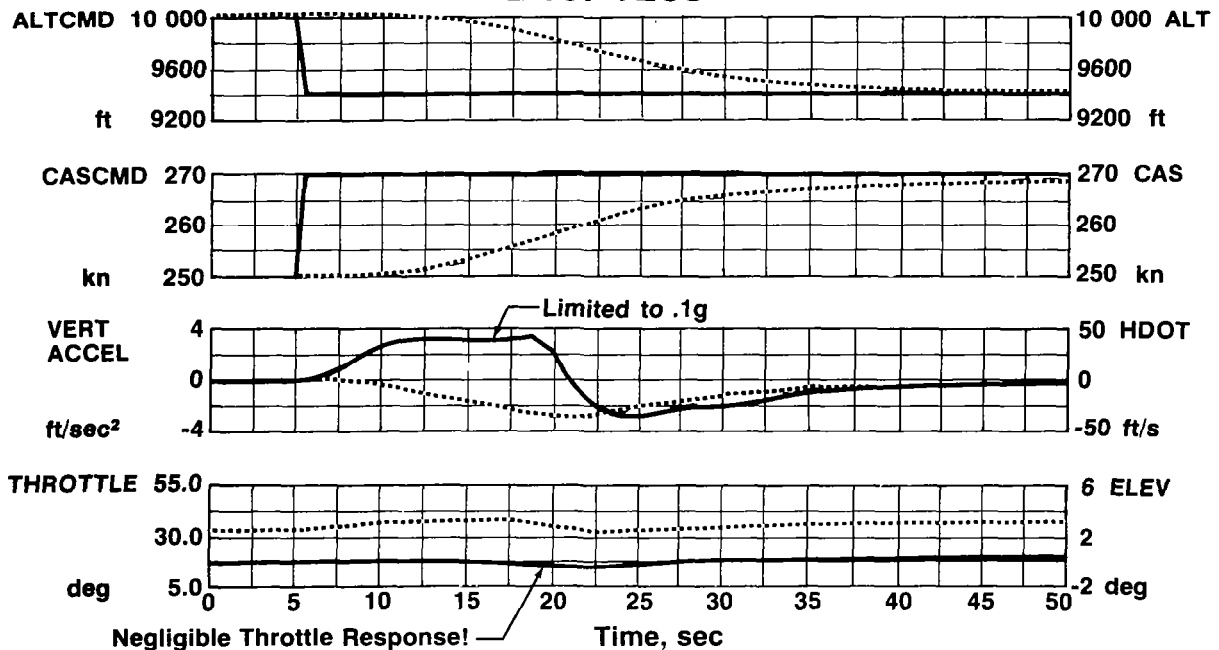
Vertical Acceleration Limiting - Normal acceleration limiting has been implemented at one central point in the control law to cover all modes except GO-AROUND and FLARE, by simply rate limiting the γ_C , since $\dot{h} = \dot{V}\gamma$.

This time history illustrates a case where the vertical acceleration is limited to 3.2 ft/sec² (0.1 g) during the executing of simultaneous commands in the ALTITUDE and CAS modes. Analogous to the rate limit in the γ_C path, an equivalent rate limit is provided in the \dot{V}_C/g signal path.

This rate limit provides vertical acceleration limiting during speed control when thrust is limited, reduces controller activity induced by turbulence, and results in smooth thrust buildup for large speed maneuvers.

Energy Exchange Maneuvers - The equal (energy) rate limits on γ_C and \dot{V}_C/g assure that for dual opposing commands, the system first exchanges energy to the maximum extent possible before commanding thrust to satisfy the required final total energy state. Thus, the system can handle any energy management problem efficiently and avoids unnecessary thrust applications, as the time response shows.

ALT/CAS Modes, Combined Descend/Acceleration B-737 TECS

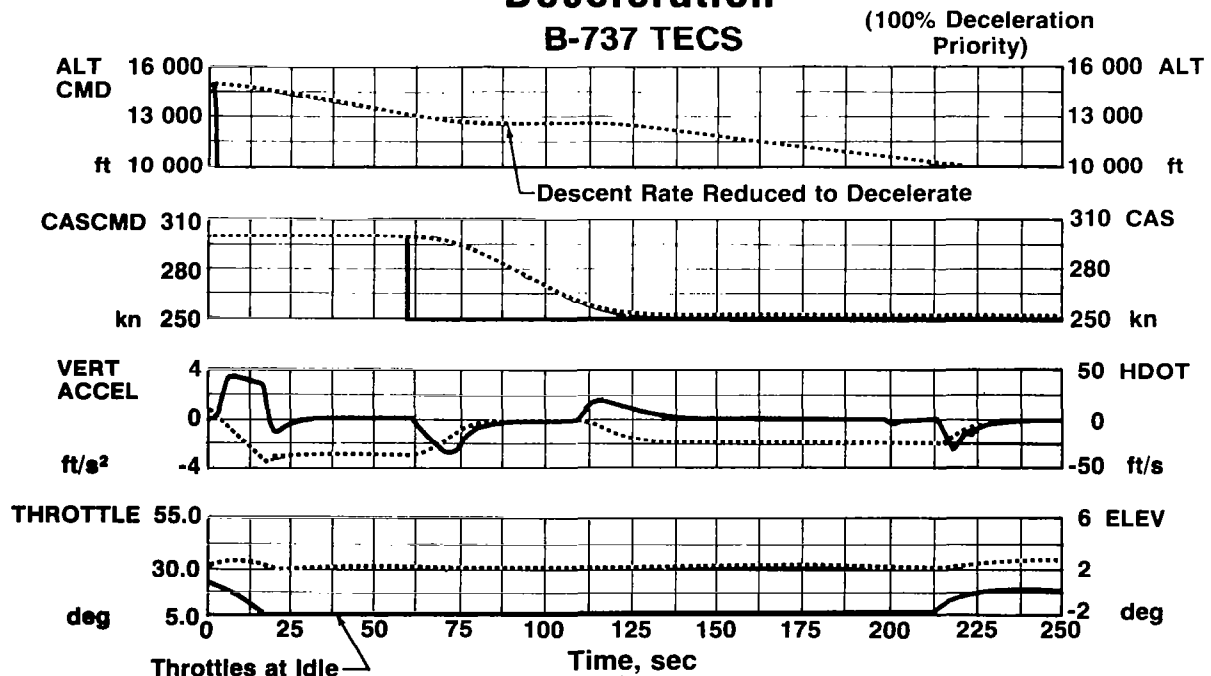


SPEED CONTROL PRIORITY

In the past, there have been numerous incidents where thrust limiting due to large autopilot path commands caused loss of speed control, resulting in airplane stall or overspeed. The TECS design solves this problem elegantly and without adding control laws or complex system reconfiguration.

The flight path angle error crossfeed to the elevator command computation is switched out, and the thrust command integrator is put in HOLD when the flight path command causes the thrust limit to be reached. In this configuration, the speed control is continued through the elevator, and the speed response dynamics remain the same as in the linear case because a change in flight path angle $\Delta\gamma = -V_c/g$ is commanded that provides the same acceleration due to the gravity component along the flight path as the engine provides in the linear case. This figure shows the response to an altitude change command, causing the thrust to go to idle, while speed is being maintained through the elevator. Subsequently, the command to reduce speed is executed by temporarily changing the flight path angle, until the speed is captured. Finally, linear control is resumed when the altitude target is approached, and a thrust rate command is developed to drive the throttles out of the aft limit. During the speed change maneuver at idle thrust, the deceleration command was limited to the available total energy rate, represented by $\gamma+V/g$, thereby preventing the flight path angle from going positive temporarily. Alternatively, the available total energy rate can be shared to provide simultaneous execution of flight path and speed commands at reduced rates.

ALT/CAS Modes, Descent With Subsequent Deceleration



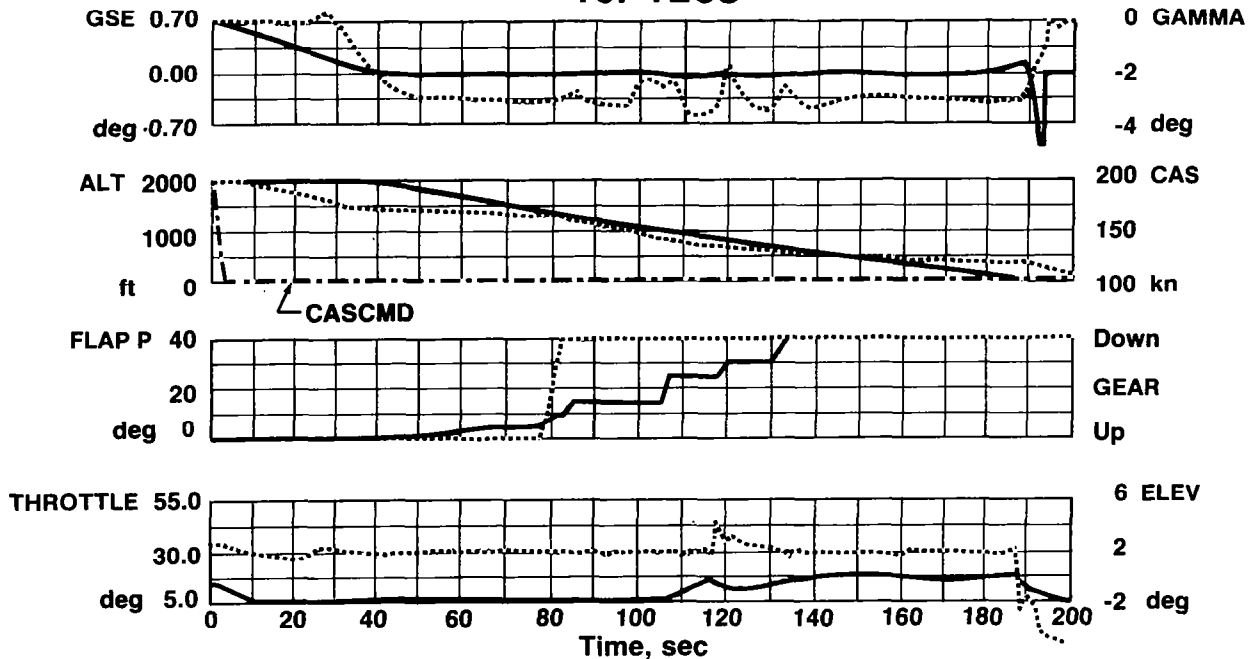
PATH CONTROL PRIORITY

Similar to the provisions to deal with thrust limiting due to large flight path commands, the TECS includes provisions to allow continued path control when the thrust limits due to large speed commands. This figure shows the system's capability to decelerate at idle thrust and capture the glide slope without overshoot while still at high speed. The flight-path-angle-based control provides inherent system adaptation to speed, resulting in consistent path captures and allowing error-free path tracking while changing speed.

In this case, the speed command was reduced to 100 kn before capture of the glide slope. However, the V_{MIN} mode limits the speed reduction to $\sim 1.3 V_{STALL}$ at each flap setting. As the flaps are lowered beyond 15° , the throttles advance to arrest the deceleration rate, and they stabilize the airspeed when the final flap setting is reached.

High-Speed Glide Slope Capture With Flap Extension and V_{MIN} Control

737 TECS

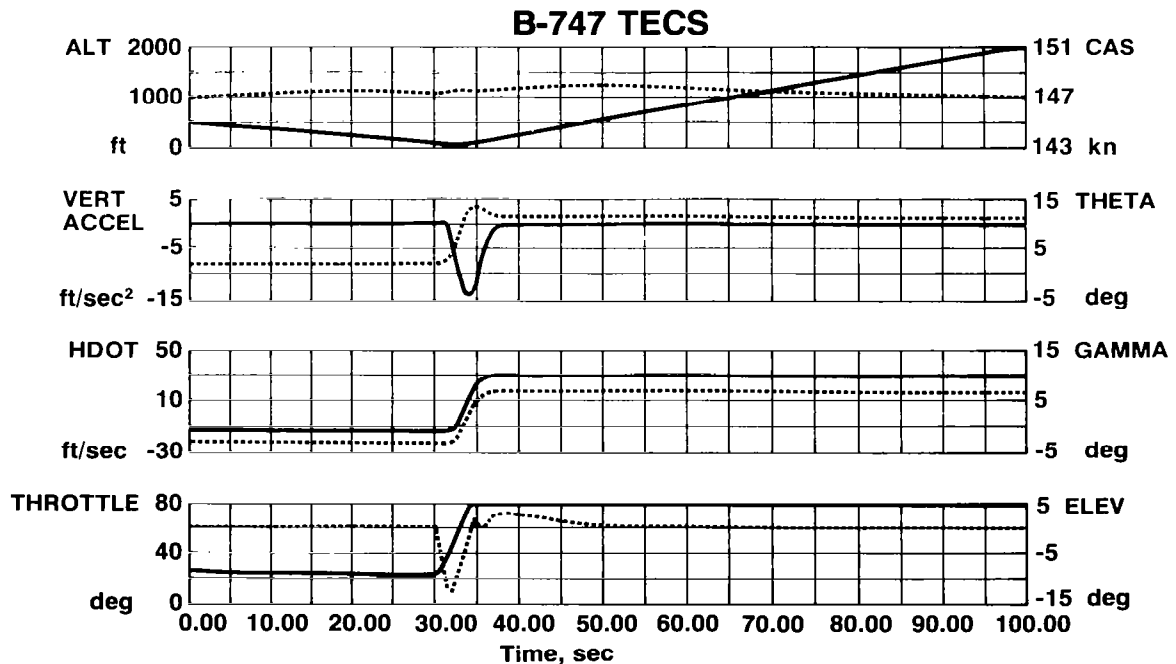


GO-AROUND PERFORMANCE

The GO-AROUND mode is implemented by simply switching to a fixed 10° flight path command (one line of software). Upon engagement of the mode, the commanded flight path angle causes a coordinated rapid throttle advancement and pitch-up. After the throttles reach the limit, the speed control reduces the pitch rate and normal acceleration to zero. The altitude loss after mode engagement is 31 ft for this condition. As shown, approximately a 0.5-g peak incremental load factor is achieved. This can easily be adjusted, as desired. Speed is maintained within ~ 1 kn, and the entire maneuver is very smooth. The attained steady-state climb rate and pitch attitude depend on the aircraft thrust and drag condition. For a heavyweight aircraft, or low available thrust, the 10° flight path angle cannot be achieved. In that case, a limit thrust climb with speed controlled through the elevator will result. For light weight, high available thrust, or low drag conditions, the $\gamma_c = 10^\circ$ is achieved with only partial power. The partial power avoids excessive climb gradients and pitch attitudes.

The system is designed to safely handle engine failures and aircraft configuration changes. In case of flap retraction without a corresponding increase in the commanded speed, the V_{MIN} control takes over to maintain $\sim 1.3 V_{STALL}$.

Go-Around Mode — Engage at 100 ft; Weight, 560 000 lb; Flaps 30° ; Altitude Loss 31 ft

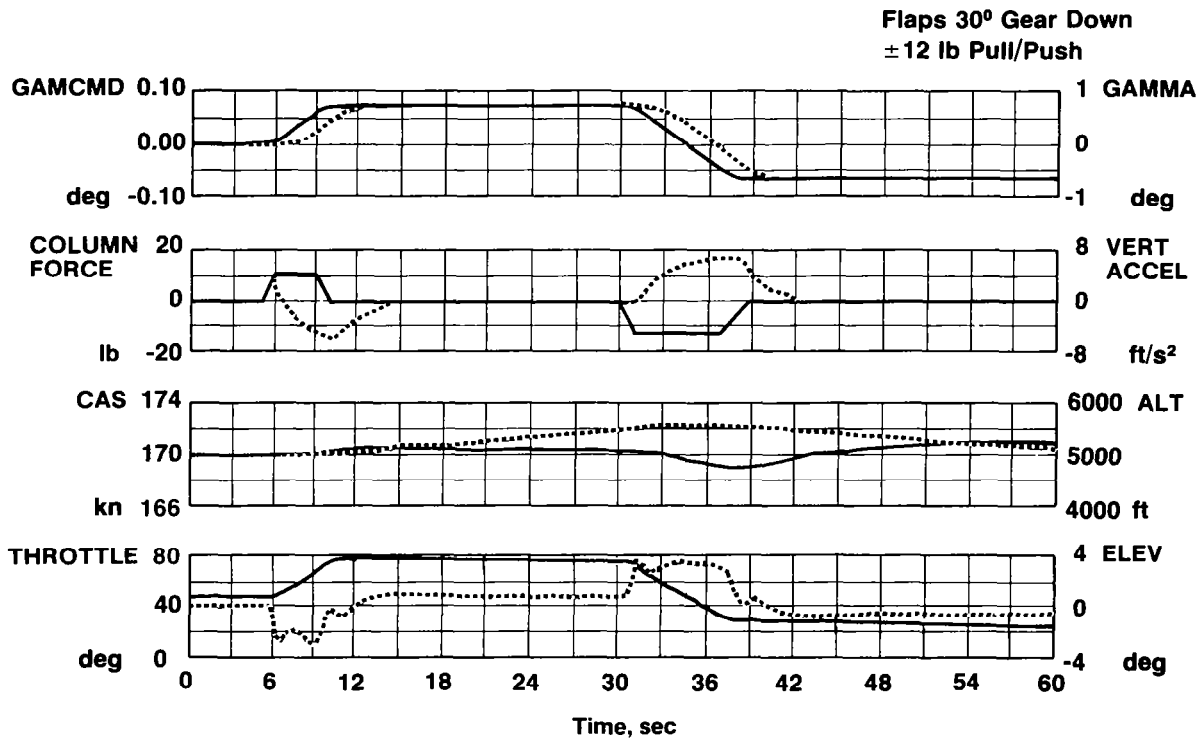


COMPUTER-AUGMENTED MANUAL CONTROL

The total energy control system is well suited for providing flight path angle based computer-augmented control because of the system's decoupled control characteristics. In this mode, also called Velocity Vector Control Wheel Steering (VCWS), a rate of change of flight path angle command (γ_C) proportional to the column force is developed. The column force signal is gain scheduled with $1/V$ to provide constant stickforce per "g", and integrated to develop the flight path angle command γ_C . An inertial flight path angle feedback $\gamma_I = h/V_{GROUND}$ is used to develop the basic error signal γ_E , and provide long-term control relative to an inertial reference. This γ_C signal is also fed forward to the thrust and elevator command to obtain the desired augmented response lag of γ relative to γ_C without causing speed perturbations.

The time history shows responses tailored to yield $\tau_\gamma \approx 2.5$ sec, the fastest response achievable with parallel servos while avoiding elevator over-control and stickforce reversal. It should be noted that this τ_γ is too long for closure of the primary pilot loop using γ display. To overcome this problem, the γ_C is displayed along with γ . The γ_C had been shown on the NASA B737 to be a satisfactory primary pilot display for the flight path angle CWS mode (ref. 3). This mode can be used on various transport aircraft to obtain virtually identical and optimized handling characteristics.

Velocity CWS Responses to 12-lb Column Pull/Push B747 TECS



CONTROL IN WIND SHEAR AND TURBULENCE

To optimize the system's performance in wind shear and turbulence, numerous trade-offs and issues were analyzed, i.e., relative flight path and speed tracking, flight path and speed tracking performance versus control activity, and proper control reconfiguration when reaching performance limits.

A major advantage of the total energy and energy distribution control concept is that it takes maximum advantage of the control effectiveness of thrust and elevator by providing conflict-free decoupled control.

Where possible, the system uses airmass-referenced feedback signals, filtered to remove atmospheric noise in the frequency range where the controls cannot respond effectively.

The simulated time history shows how a severe wind shear of -5 kn/sec causes instant bleedoff of the airspeed and a slower departure from the commanded altitude of 5000 ft. This signifies a sharp loss of aircraft energy. The system responds by bringing the throttles forward quickly. Even when limit thrust is reached, the total energy rate remains negative, causing the V_{MIN} speed control mode to engage and the flight path control to be abandoned. The aircraft captures the minimum speed command ($1.3 V_{stall}$ or α_{REF}) undershoot free and settles into a steady-state descent. In this case, the filtering of the airspeed related feedbacks was adjusted to yield quick response to wind shear.

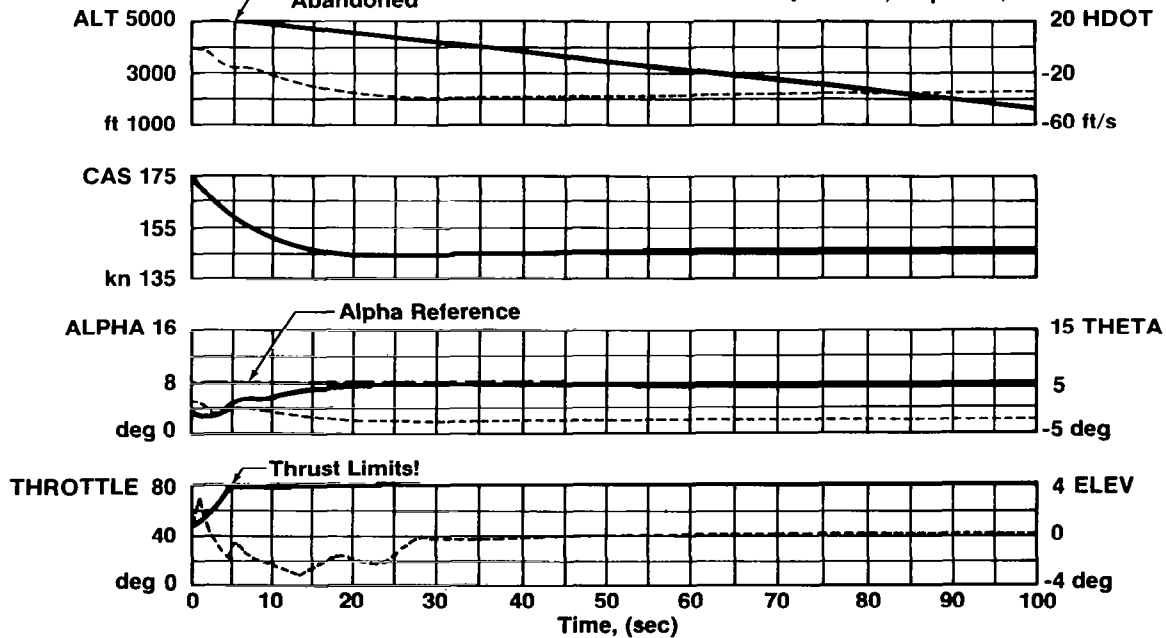
Response to Severe Wind Shear

B747

Wind shear — 5 kn/sec

Altitude/CAS-Control

$\tau_{\dot{V}} = 5 \text{ sec}$, Flaps 30° , Gear Down



CONTROL IN WIND SHEAR AND TURBULENCE (CONT'D)

For the responses below, the same wind shear condition was run with the filtering of the airspeed control feedbacks adjusted to reduce controller activity in turbulence by ~50%. As a result, the throttles respond more slowly to the wind shear and more airspeed is lost. When the thrust limit is reached, the path control is abandoned and speed control is continued through the elevator. Since the total energy rate remains negative, causing the \dot{V}_C of the V_{MIN} mode to be more positive than V_C of the selected speed mode, the V_{MIN} mode engages and the minimum speed is recaptured. In the process, the airplane comes very close to stall, but stays closer to the commanded altitude for a longer period of time, before settling into the steady descent.

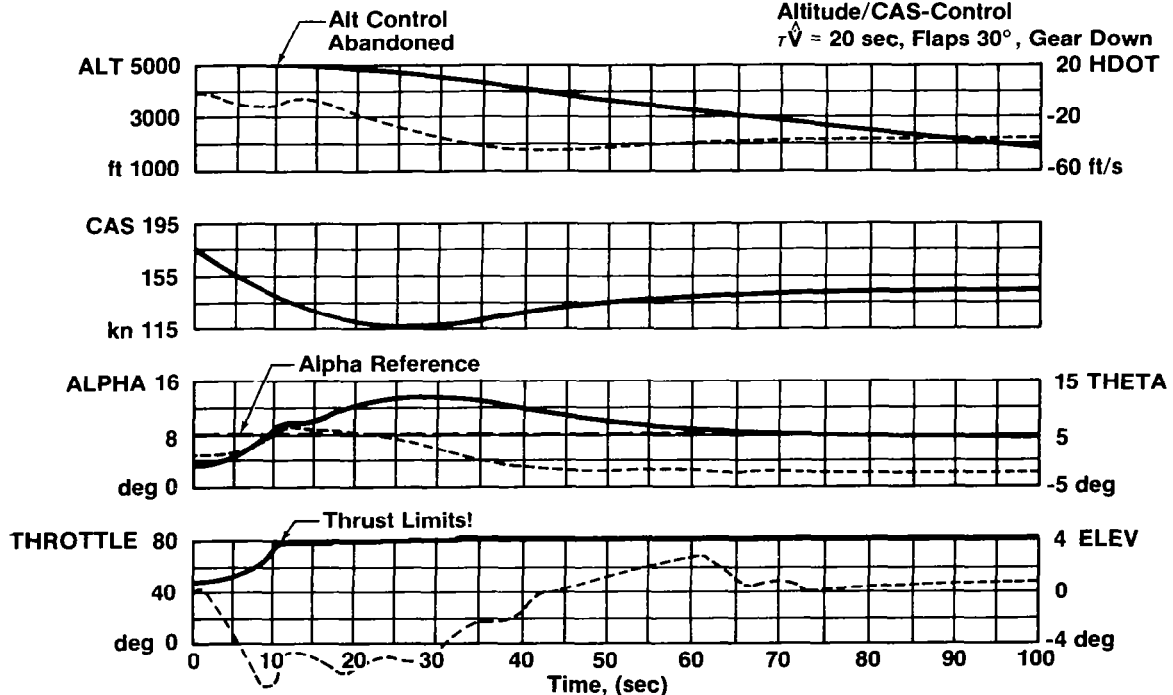
In a similar situation on the glideslope, the system will stay at the V_{MIN} speed until the wind shear subsides to the point where the total energy rate once again becomes positive. At that time, the glideslope will be recaptured first before the pilot-selected speed will be reestablished.

As these time histories indicate, the best insurance in case of severe wind shear is to have excess airspeed energy, together with provisions that prevent the airplane from stalling.

Response to Severe Wind Shear

B747

Wind shear — 5 kn/sec
Altitude/CAS-Control
 $\tau \dot{V} = 20$ sec, Flaps 30°, Gear Down



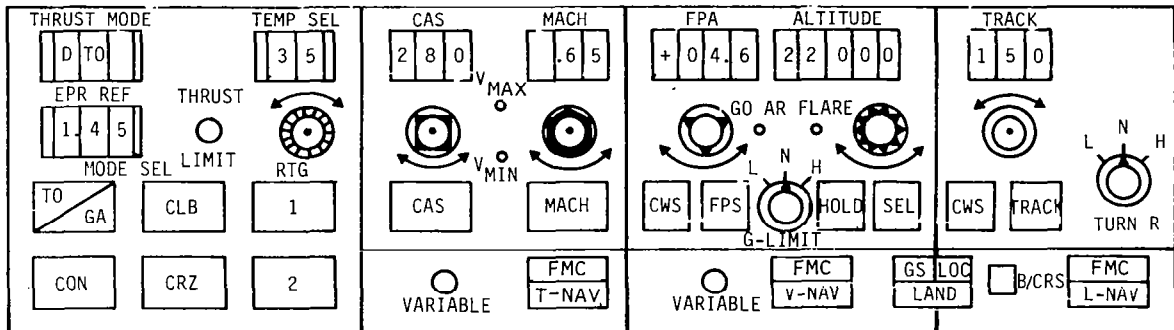
MODE CONTROL PANEL DESIGN

The integration of functions and enhanced operational capabilities of the TECS is reflected in the example mode control panel layout below.

The modes have been chosen to provide all necessary tactical and strategic capabilities. All modes are operable over the entire flight envelope. Any flight path mode is compatible with every speed mode. The panel provides the complete mode and control configuration status. For example, when either flight path or speed control is abandoned due to thrust limiting, the appropriate VARIABLE indication on the bottom of the panel is lit. At the same time, the THRUST LIMIT light on the left of the panel lights. The thrust rating mode selection has been integrated in this panel because the performance capability of the vertical flight path and speed control modes depends directly on the selected thrust rating mode.

The CAS and Mach modes can be preselected for automatic mode transition during climb-out and descent.

The T-NAV, V-NAV, and L-NAV modes allow the navigation/performance computer target speed, target vertical, and lateral paths to be input to the TECS for execution. Reference 2 discusses the operational aspects in more detail.



- INTEGRATED THRUST RATING
- PERFORMANCE LIMIT INDICATION
- INTEGRATED ALT SEL/ALT CLEARANCE

TECS ENGINE CONTROL

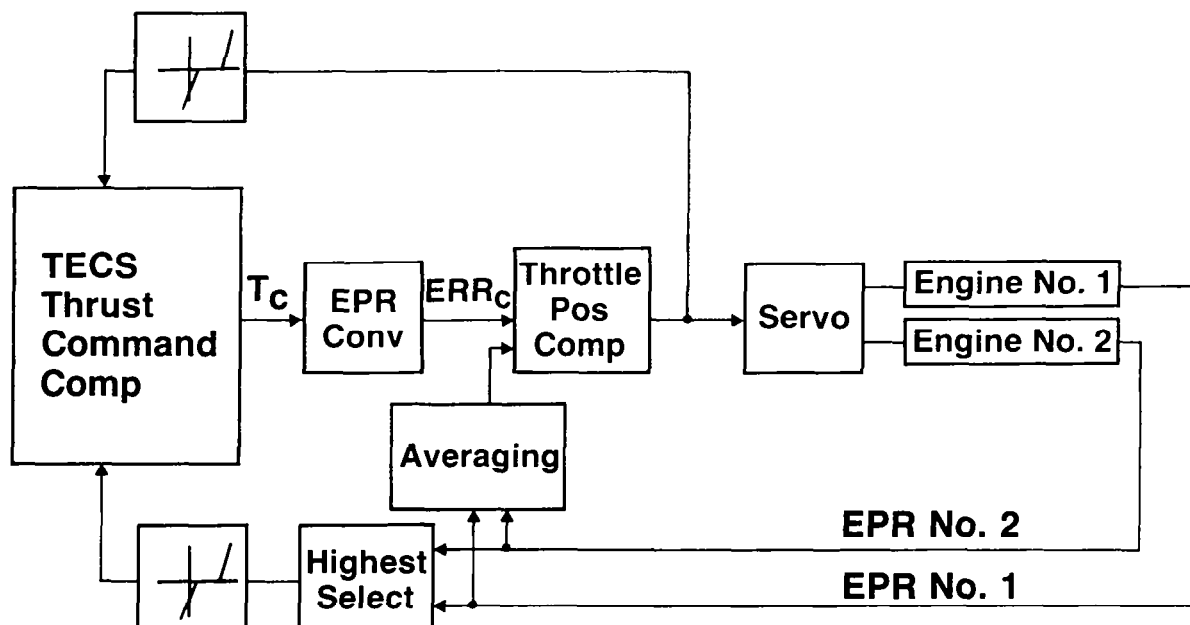
The first major objective of the integrated flight and propulsion control system was the development of a more accurate net thrust computation.

The second major objective of the design was the elimination of arbitrary engine thrust variation due to changes in environmental or flight conditions. Therefore, in the TECS design, all major engine environmental dependencies have been compensated to make the engine produce the desired net thrust on command.

The net thrust command is converted into an EPR command and used for closed-loop engine control. This involves dependencies on the pressure ratio $\delta = p/p_0$ and Mach number. Further, the EPR command is used to predict the steady-state throttle position command. To maintain constant loop gain, the total air temperature dependency has been compensated. The closed-loop EPR control law also serves to reduce the variation in the response dynamics of the engine and the effects of throttle actuation nonlinearities.

Feedback of throttle position and EPR in excess of selected limits to the thrust command computation serves to prevent engine overboost and ineffective throttle control in the low thrust region.

In the future, customization of the automatic flight control system to work with specific engines can largely be eliminated by designing the electronic engine controls to control to a net thrust command and to compensate for all major thrust environmental dependencies (ref. 4).



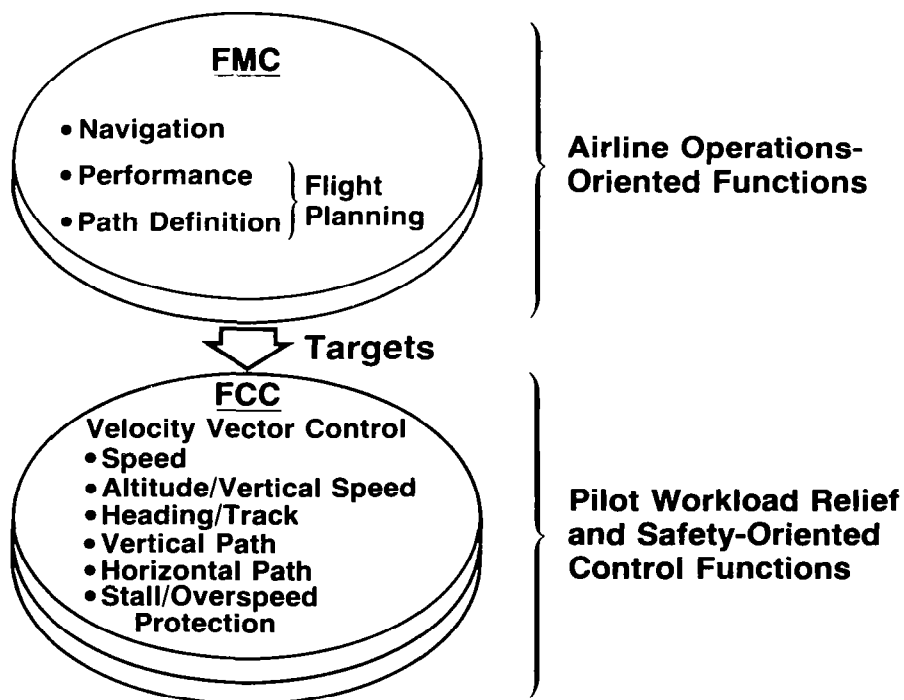
AFCS FUNCTION DISTRIBUTION

The integration of all vertical flight path and speed control functions, together with future integration of lateral directional functions, allows a more efficient system architecture using fewer sensors, computers, interfaces, and a function distribution that is closer oriented toward airline needs.

As shown, all automatic control modes and safety-oriented functions are consolidated in the flight control computers, which will be designed with the necessary redundancy to provide the required integrity of the critical control functions.

The consolidation of all automatic control functions in the flight control computer (FCC) leaves the navigation/performance (flight management) computer with strictly airline-operations-oriented functions: navigation, performance, and path definition. The resulting flight control targets can be transmitted to the FCC for execution. No control loops would be closed in the navigation/performance computer. This design eliminates functional overlap and provides consistency of operation for all modes.

AFCS Function Distribution Using TECS Architecture **(NO FUNCTIONAL OVERLAP)**



TOTAL ENERGY CONTROL SYSTEM PAYOFF

The payoff of the total energy control system development is evident: the design provides proper integration of the flight path and speed control functions, resulting in optimum thrust and elevator control efficiency. The design eliminates the numerous limitations of the previous state-of-the-art autopilots and autothrottles. The system implementation is simple, without functional overlap or operational ambiguities, requiring less software and less hardware.

Safety has been enhanced by complete stall and overspeed protection in case of operational errors and severe wind shear.

The potential for cost reductions is substantial.

The design is largely generic. For example, transfer of the complete TECS design from the B737 to the B747 simulator, including adaptation and checkout of innerloops and V_{MIN}/V_{MAX} schedules, required only 6 engineering man months. No energy control concept related changes were needed. The total energy control system is scheduled to be evaluated in flight on the NASA B-737 aircraft under the Air Transport Operating System Program, in the summer of 1984. The Boeing Company will provide the system definition and under contract assist NASA with checkout of a complete TECS simulation, flight software specification, software test, and flight test.

- **Fully integrated, generally applicable design**
- **Improved performance for all modes**
 - **Decoupled path and speed maneuvering**
 - **Energy efficient thrust control**
 - **Uniform stability bandwidth, transient responses**
- **Enhanced operational capabilities**
 - **Complete safety and maneuver envelope limiting**
 - **Configuration control when thrust limited**
 - **Reduced pilot workload — (simpler mode control, VCWS)**
- **Control law software reduced $\approx 75\%$**
- **Fewer sensors, computers**
- **Large cost reductions**
 - **Development, flight test, procurement, maintenance**

REFERENCES

1. H. A. Soulé, "The Throttles Control Speed, Right? Wrong!" AIAA Journal of Astronaut. & Aeronaut., vol. 7, no. 12, Dec. 1969, pp. 14-15 and 81.
2. A. A. Lambregts, "Operational Aspects of the Integrated Vertical Flight Path and Speed Control System," SAE Paper No. 831420, October 1983.
3. A. A. Lambregts and D. G. Cannon, "Development of a Control Wheel Steering Mode and Suitable Displays That Reduce Pilot Workload and Improve Efficiency and Safety of Operation in the Terminal Area and in Windshear," AIAA Paper No. 79-1887, August 1979.
4. A. A. Lambregts, "Integrated System Design for Flight and Propulsion Control Using Total Energy Principles," AIAA Paper No. 83-2561, October 1983.