VERTICAL FLIGHT PATH AND SPEED CONTROL AUTOPILOT DESIGN USING TOTAL ENERGY PRINCIPLES

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Abstract

A generalized automatic flight control system has been developed, that 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 non-linearities and performance limits. Consistent decoupled maneuver control is achieved for all modes and flight conditions without outerloop gain schedules, control law submodes or control function duplication.

Introduction

The automatic flight control systems (AFCS) in use today have evolved by successive addition of functions. This is especially true in the pitch axis, where the pitch attitude hold mode was the first attempt to automate the elevator control and relieve the pilot of constant control attention. Soon the speed hold and altitude hold modes followed as more useful ways to stabilize the aircraft. Next, the maneuvering modes vertical speed and altitude select were added. The jet age brought with it the introduction of the automatic approach and landing control modes and the automatic throttle system to control the approach speed. The full flight regime autothrottle system was introduced only recently, after the rise in fuel prices prompted the need to cruise at speeds near the minimum drag or maximum range speed. At these speeds, long term autopilot path control through the elevator at constant throttle causes poor speed stability or even instability and therefore high pilot workload. Closure of the speed control loop through the throttle alleviates the problem. Extension of the autothrottle to serve during cruise and other flight regimes was therefore a logical decision.

It should be noted that, over the years, numerous AFCS development and improvement programs were spurred by the desire and need to remove operational limitations and performance deficiencies. More and more new modes and design provisions resulted, often without yielding a better insight in the fundamental system design problem.

The perception of inadequacies in the basic autopilot and autothrottle capability precipitated a complete new array of elevator and throttle control modes in the latest navigation/performance computer systems. Also, new take off, go around and "flight level change" modes were added to the autothrottle. As a result, the latest AFCS designs have become quite complex, with replication of the basic flight path and speed control capability in three computer systems.

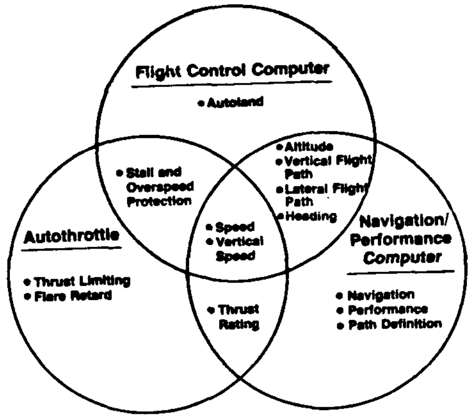

Figure 1. Typical Control Function Overlap, Conventional AFCS

Figure 1 shows an example of the functional overlap of the three computer systems. The underlying system architecture is obviously not ideal. The root of the problem lies in the traditional but non-optimal bottom up design method of adding one control loop/control mode at a time. Figure 2 shows schematically the control system structure for a conventional autopilot and autothrottle. Traditionally, the autopilot controls the flight path through the elevator, the autothrottle controls speed through the throttles.

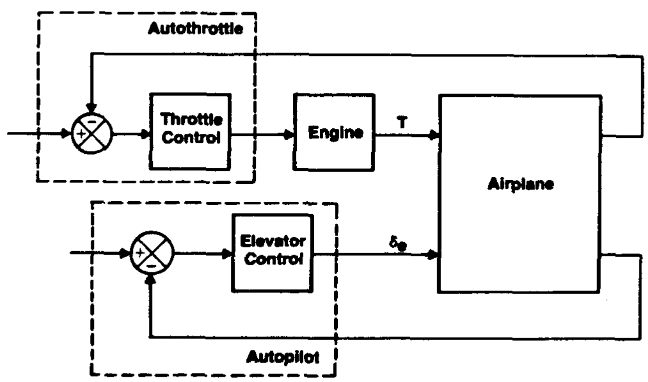

Figure 2. Conventional Autopilot/Autothrottle

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This control strategy has serious limitations:

- Stable altitude control through the elevator, with thrust held constant, can only be achieved conditionally, depending on a sufficiently high thrust level and speed. It prompted the need for a full flight regime autothrottle.

- Stable speed control through the throttles is generally not possible with constant elevator. Because the basic airplane control must be speed stable, speed changes require elevator trim changes. Thus, the autothrottle is unusable unless the autopilot is engaged.

- Climb and descent maneuvers can be initiated through the elevator, but generally not sustained without retrimming thrust. The autothrottle speed control loop can provide the thrust trimming function, but only to the extent there is enough thrust margin to satisfy the flight path command from the autopilot. For large path commands, the thrust will limit, causing loss of speed control. By design the elevator authority always exceeds the pitch trim requirement at maximum or minimum thrust, allowing the autopilot to induce stall or overspeed. Numerous incidents of this nature have occurred. Reference 1 gives an example.

  An autopilot speed reversion mode can safeguard against this risk. However, for nearly all AFCS in use today the pilot must provide this safeguard--at least for some autopilot/autothrottle mode combinations.

  In the latest designs (Boeing 737 Advanced, 767, 757) the flight level change mode alleviates this problem during transition from one altitude to another by temporary speed control reversion to the autopilot and vertical speed control to the autothrottle. However, good vertical speed control through the throttles is difficult to achieve, and so is smooth maneuver initiation and termination, while having to "switch horses."

- Both the elevator and throttle control produce coupled flight path and speed responses. As a result, path control maneuvers by the autopilot induce speed perturbation, and speed control maneuvers by the autothrottle produce path deviations. These control coupling errors and associated controller transients are undesirable. Efforts to minimize these coupling errors and provide good system damping lead to high feedback gains. This in turn produces unacceptably high control activity in turbulence, particularly on the throttles.

- Historic precedence of the autopilot and superior control authority of the elevator have allowed the path control requirements to be satisfied first, often at the expense of the autothrottle speed control. This has resulted in an unsolvable design problem for the autothrottle and a poor reputation for the design and designers alike! For example, tight autopilot path control will aggravate throttle activity in turbulence for conventional autothrottle systems. Autopilot reversion to the attitude hold mode generally cuts down the throttle activity dramatically, while turning the autothrottle off altogether often produces the lowest RMS of speed errors. However, in the process, long term path tracking and speed tracking is also lost.

- The autothrottle performance is particularly sensitive to the static and dynamic engine characteristics. Basically, with both the autopilot and autothrottle engaged, the engine becomes a "thrust actuator," much like the elevator actuator. The autopilot depends heavily on the dependable and invariable operation of the elevator actuator. The high degree of variability of the engine as a thrust actuator has been another source of endless autothrottle design modifications. The engine's thrust output per degree of throttle varies widely as a function of altitude, Mach number and temperature. Bleed valve operation, bleed air extraction, thrust limits, control cable back lash, hysteresis and variability in the response dynamics make the present jet engines extremely problematic elements in the automatic control loop. Compensation for all major engine sensitivities in the autothrottle control laws has been necessary to make the system work. This has required autothrottle redesign and recertification with each new engine and each major engine revision.

- The design method to achieve a satisfactory compromise between the desired path tracking, speed tracking, controller activity, maneuver responsiveness and fuel efficiency for all mode combinations and flight conditions is not well established. The design process relies heavily on experience, intuition, empirical approaches and tradition.

- The fragmented system architecture does not lend itself to efficient implementation of general design provisions such as speed limiting and normal acceleration limiting, because provisions have to be made at numerous places and the required solutions are different each time. This leads to complex design implementations with many ad hoc solutions of limited usefulness, sometimes void of a sound physical basis. The danger of such a design approach lies mostly in the fact that such designs are exceedingly difficult to test adequately during the design stage. This in turn sets the stage for difficult and costly improvement programs later.

- One of the most persistent criticism expressed about the present generation of AFCS, in particular about the autothrottle, is the lack of pilot-like control strategy in the execution of flight path and speed commands. Pilots intuitively coordinate elevator and throttle inputs. They also take advantage of stored energy by using the elevator to convert speed to altitude and vice versa when possible, to avoid unnecessary thrust transients. In turbulence, pilots move the throttles infrequently. If windshear is detected, the pilot generally responds with large discrete throttle inputs.

In the early seventies, extensive efforts at Boeing were directed to produce an improved autothrottle system for the B747. The throttle activity problem was alleviated considerably by a signal cancellation technique, using the ~180° phase difference between turbulence induced airspeed deviations and inertial acceleration.[2] The resulting sluggish response to windshears was corrected by the addition of a nonlinear windshear detection and compensation circuit[3]. The autopilot/autothrottle control coordination problem was addressed on the B747 with the development of a method to prevent accelerations induced by flight path deviations, from causing inefficient throttle activity and exciting a poorly damped autopilot autothrottle coupling motion[4]. This method, called "energy compensation," was a first attempt to use thrust for control of the aircraft's energy state short term, and control of speed long term. It decoupled throttle response from elevator control and improved the system damping. The difficulty was the lack of autopilot/autothrottle crossfeed to recognize intentional flight path changes to inhibit the compensation and avoid large speed errors.

Other attempts at implementing pilot-like control considerations may be found in the Lockheed L-1011 (ARMA) and Boeing 747 (DELCO) Performance Management Systems. Here the idea is to crossfeed speed errors, limited in signal amplitude to the energy equivalence of ~100 ft, to the elevator for "control assistance," thereby reducing energy inefficient throttle activity, but incurring a slight altitude wandering.

Many of the above described operational and performance limitations were also experienced by NASA during the Terminal Configured Vehicle Program (TCVP) flight experiments, using a B-737 aircraft. Boeing was instrumental in the design of an advanced state of the art guidance and control and avionics system onboard this aircraft and assisted the NASA during the 1974-1979 period with research to develop airborne system concepts, operations procedures, and avionics technology to provide safer and more efficient aircraft operations in the terminal area.

Here again, the area of improving the simultaneous operation of autopilot and autothrottle was addressed, with particular attention to the need to anticipate thrust requirements for vertical maneuvers and the trade off problem between speed tracking in windshear and throttle activity in turbulence. This work soon established that the conventional AFCS design had reached a development plateau and that further improvements were not simple to obtain within the existing architecture. It also established that the thrust pitching moments--earlier believed to be an important contributor to undesirable thrust/pitch interaction--had little effect on the throttle activity and the speed/flight path control coupling. This result pointed straight back to the inefficient handling of the point mass control problem by the autopilot and autothrottle!

As a result, the Boeing research contract work was redirected in 1979 by NASA to begin the conceptual development of a fully integrated automatic flight path and speed control system that can handle all design requirements without duplication of functions and incorporate many long standing design objectives. The work was carried out under NASA contracts NAS1-14880 and NAS1-16300 during 1979-1980 and 1980-1981. Detailed system design and reduction to practice was carried out under Boeing IR&D funding during the 1979-1982 period.

Integrated Elevator and Thrust Control Design

The objectives of the research were:

- Integration of all control functions of the pitch autopilot, autothrottle, and navigation/performance computer system into a single generalized control concept, serving all modes and flight conditions.
- Provide decoupled flight path and speed maneuver control by the use of pilot-like control strategies.
- Eliminate functional overlap and structure the control reference hierarchy to preclude exceeding the airplane performance and safety limits (g-limit, γ_{LIMIT}, $1.3V_{STALL}$, V_{MO}/M_{MO}, flap placards).
- Minimize elevator and throttle activity consistent with meeting flight path and speed tracking requirements at each flight condition.
- Simplify the pilot-machine interface and extend the operational capability.
- Reduce hardware and software.
- Provide consistency in design of various modes and commonality with display concepts.

Design Considerations

An earlier Boeing study had investigated flight path angle crossfeed to the autothrottle and speed to the autopilot to provide decoupled speed and flight path responses. A V-canonical system representation was used to identify the transfer functions for the desired controls of speed due to thrust and flight path due to elevator, as well as the transfer functions for the undesired coupling effects of pitching moment due to speed ($M/\Delta V$) and force along the flight path due to flight angle ($F/\Delta\gamma$). These cross coupling effects can be eliminated by generating equal and opposite pitching moments and forces with the elevator and throttle. This technique was found to be impractical because the modelled cancellation transfer functions are ill-conditioned and cause serious degradation of the controller activity in turbulence.

Interestingly, the "energy compensation" technique, feeding back flight path angle to the autothrottle with the opposite sign, prevents thrust response to flight path perturbations and elevator control. Its characteristics were desirable, except that proper thrust response to intentional flight path changes would have to be developed.

Also, the potential flight path angle (γ_p) concept was considered. Display of γ_p had been proven to be valuable to the pilot for setting the required thrust for a desired flight path angle:

$$\gamma_p = \gamma + \dot{V}/g = \frac{T - D}{W} \qquad (1)$$

where γ = flight path angle = $\dot{h}/V$

$\dot{V}$ = acceleration along the flight path (airmass referenced)

g = gravity constant

T = thrust

D = drag

W = aircraft weight

$\dot{h}$ = vertical speed

V = airspeed

Assuming low maneuvering rates, the drag D is mainly affected by long term speed changes. Thus, short term γ_p is mainly a function of the thrust setting T and not affected by elevator control. Therefore, at a given thrust level γ_p indicates the "potential flight path angle" that can be achieved by bringing the acceleration to zero by applying elevator until the displayed actual flight path angle γ becomes equal to the γ_p. The γ_p signal can also be related to the total energy rate (E) of the aircraft:

$$E = Wh + 1/2\ (W/g)\ V^2$$

$$\dot{E} = W(\dot{h} + V\dot{V}/g)$$

Thus $$\dot{E} = VW(\gamma + \dot{V}/g) \qquad (2)$$

or $$\dot{E}_s = V\ \gamma_p \text{ (specific energy rate)} \qquad (3)$$

Further, the elevator and throttle control characteristics were considered. The elevator can be used short term for both speed control and flight path control. Long term, the use of elevator is essential for speed control. The thrust can be used short term, for both speed and flight path control. Long term, the use of thrust is generally essential for path control. Initiation of a speed maneuver without flight path perturbation or vice versa requires coordinated elevator and thrust inputs. Accordingly, the first successful integrated throttle and elevator control system used the elevator control short term for both flight path and speed maneuver initiation and long term for speed trimming. Likewise, thrust was used short term for both flight path and speed maneuver initiation and long term for trimming of the flight path. This design worked but did not provide the desired smooth and decoupled maneuver control, although all feedbacks were scaled in relative energy quantities.

Total Energy Control Concept

Numerous variations of the above design were investigated to achieve all of the objectives. The best overall configuration was found to be one in which the thrust command (δT_c) is developed from the sum of flight path angle error (γ_ε) and the acceleration error ($\dot{V}_\varepsilon/g$), for both short term and long term control:

$$\delta T_c = (K_{TP} + K_{TI}/S)(\gamma_\varepsilon + \dot{V}_\varepsilon/g) \qquad (4)$$

where K_{TP} and K_{TI} are gain constants, S represents the Laplace operator. This was a logical development, considering the analogy of γ_p as a thrust director display. Equation (4) may be expressed in terms of the energy rate control:

$$\delta T_c = (K_{TP} + K_{TI}/S)\ \frac{\dot{E}_{s_\varepsilon}}{V} \qquad (5)$$

or

$$\delta T_c = \frac{K_{TP}\dot{E}_{s_\varepsilon}}{V} + \frac{K_{TI}E_{s_\varepsilon}}{V} \qquad (6)$$

This control calls for the use of thrust to reduce the total energy error to zero with a first order time constant $\tau_E = K_{TP}/K_{TI}$. Since the engines are the basic energy source of the aircraft, it is appropriate to develop the thrust command based on the energy demand. The suitability of this control also follows from the equation of motion along the flight path, solved for thrust required:

$$T_{REQ} = W(\gamma + \dot{V}/g) + D \qquad (7)$$

Assuming the initial thrust is trimmed against drag, then it follows that the short term thrust requirement is proportional to the sum of flight path angle and acceleration and also proportional to weight. The drag variation is generally slow, especially for commercial transports, and can be taken care of by integral control. Therefore, a drag related feedback is not needed. The thrust command (4) and (6) are in normalized form for unit weight. The total thrust command is therefore obtained by scaling the specific thrust up in proportion to the total weight of the airplane.

With thrust control used to satisfy the total energy rate requirement, an energy rate distribution error can still exist, i.e., too high a flight path angle/too low an acceleration or vice versa. The elevator is the ideal controller to rectify this problem, since it provides in essence only a rotational control which does not directly affect the total energy state of the aircraft. Correction of the energy rate distribution can, in principle, be accomplished either by feeding back the flight path angle error γ_ε, or the acceleration error $\dot{V}_\varepsilon/g$ to the elevator. The uncontrolled variable will automatically go to zero. However, choosing either γ_ε or $\dot{V}_\varepsilon/g$ for feedback to the elevator will result in favoring short term control of that variable over the uncontrolled variable under conditions of external disturbances, such as turbulence or windshear. In that case, a path deviation may be transformed into a speed deviation short term or vice versa. If on the other hand both the acceleration error $\dot{V}_\varepsilon/g$ and the flight path angle error γ_ε are fed back to the elevator, then the energy rate errors (energy errors) will be weighted equally and therefore tend to be redistributed equally between $\dot{V}_\varepsilon/g$ and γ_ε short term. The latter approach was choosen as the starting position. Thus, using proportional plus integral control the elevator command becomes:

$$\delta_{e_C} = (K_{EP} + K_{EI}/s)(\dot{V}_\varepsilon/g - \gamma_\varepsilon) + \text{damping} \quad (8)$$

The quantity $(\dot{V}_\varepsilon/g-\gamma_\varepsilon)$ will be referred to as $\dot{L}_\varepsilon$-the energy rate distribution error, where L is known in classical dynamics as the "Lagrangean". Then

$$\delta_{e_C} = (K_{EP} + K_{EI}/S)\,\dot{L}_\varepsilon + \text{damping terms} \quad (9)$$

$$= K_{EP}\dot{L}_\varepsilon + K_{EI}L_\varepsilon + \text{damping terms} \quad (10)$$

This control calls for the use of the elevator to redistribute the energy rate error equally between flight path angle and acceleration, following a first order response with a time constant $\tau_D = K_{EP}/K_{EI}$.

The damping terms in (9) consist of the conventional feedbacks (i.e., pitch rate, pitch attitude) that are necessary to stabilize the short period pitch dynamics. The resulting basic system implementation is shown in figure 3.

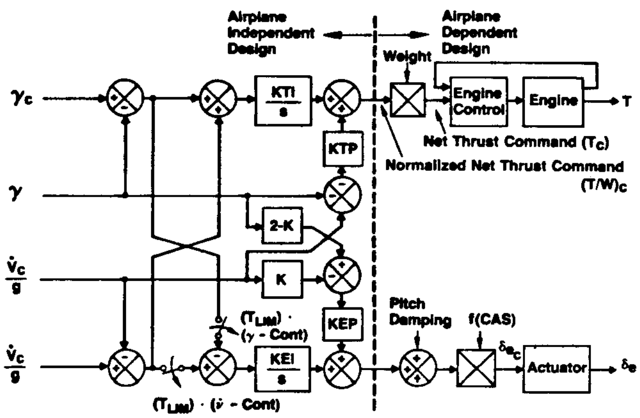

Figure 3. Basic Total Energy Control System

It should be noted that the proportional terms $K_{TP}\dot{E}_{s_\varepsilon}$ and $K_{EP}\dot{L}_\varepsilon$, have been implemented as $K_{TP}\dot{E}_S$ and $K_{EP}\dot{L}$ without reference to the commands. Thus, these quantities are the absolute total energy rate and the difference in energy rate between the flight path angle and acceleration. In the regulator sense of the control (stability, bandwidth), this change makes no difference. However, the advantage of this implementation relates to the transient response of the controller to command inputs γ_C or $\dot{V}_C/g$. Step command inputs are processed only through the integral control signal paths and result in controller rate commands, making the control responses smooth and also eliminating command overshoot during capture. Proportional signal paths of γ_ε and $\dot{V}_\varepsilon/g$ would contribute an unwanted zero in the numerator of γ/γ_C and V/V_C transfer functions, hence response overshoots.

Control Decoupling, System Stability & Bandwidth

The energy based design approach clearly reveals the relative elevator and thrust control requirements to decouple flight path and speed maneuvering. In case of either a flight path or acceleration maneuver, both the total energy rate error $\dot{E}_\varepsilon$ and the energy rate distribution error $\dot{L}_\varepsilon$ must go to zero simultaneously, otherwise energy will be transferred from one variable to the other, before both errors settle to zero. This requires in principle that $\tau_E = \tau_D$ or $K_{TP}/K_{TI} = K_{EP}/K_{EI}$. Considering the flight path angle change maneuver, requiring $\delta T_C = W\Delta\gamma_C$ and steady state $\Delta\theta_C = \Delta\gamma_C$, the other basic gain relationships $K_{TP} = K_{EP} = 1.0$ and $K_{TI} = K_{EI}$ follow. Further, the pitch and thrust responses must be matched. The following approach was used to solve this problem.

First, the engine is made to produce the required net thrust at all flight conditions, by conversion of the net thrust command to a command in terms of the engine control variable (engine pressure ratio EPR, or fan speed N_1) and closing a feedback loop around the engine using this variable. This engine control loop is designed to minimize variation of the engine dynamics at different flight conditions and provide overshoot free thrust response. For conventional engines, actuated through the throttles, the steady state throttle position command is provided by a separate forward feed predictor term.

Next, the pitch innerloop dynamics are matched to the thrust dynamics by judicious choice of the innerloop feedbacks and gains. The variable elevator effectiveness must be compensated by gain scheduling the overall elevator command as a function of dynamic pressure. Finally, the gains K_{TI} and K_{EI} (τ_E and τ_D) are chosen to produce decoupled, overshoot free acceleration and flight path angle responses.

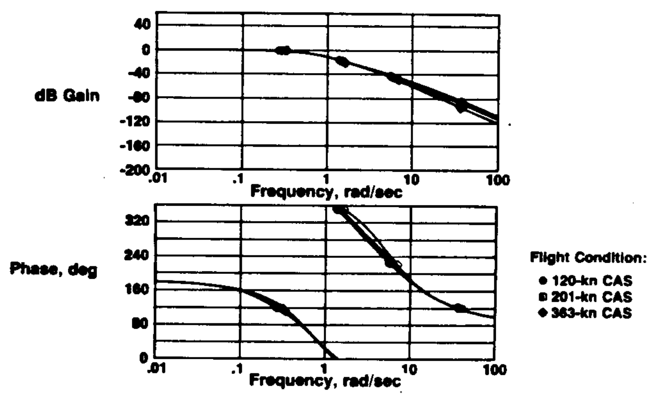

Figure 4. Frequency Response γ/γ_C

The resulting "natural decoupling" of flight path angle and acceleration maneuvers allows very high damping to be achieved ($\zeta \geq .8$) for all dynamic modes. In fact it was possible to achieve approximately critical damping on all modes, without resorting to low bandwidth. Figure 4 shows examples of the γ/γ_c frequency responses at different flight conditions and illustrates the smoothness of the control. There is no evidence of coupling modes and the bandwidth is constant (~1 rad/sec).

Speed and Path in Space Control Modes

This basic total energy control concept requires normalized commands γ_c and $\dot{V}_c/g$. For the speed and path-in-space control modes, these are developed as follows. When a speed error V_ε exists, an acceleration is commanded proportional to and counteracting that speed error:

$$\dot{V}_c = K_V V_\varepsilon, \tag{11}$$

This control calls for an exponential reduction of the speed error with a time constant $\tau_V = 1/K_V$. Likewise, when an altitude error relative to the desired path exists, a vertical speed is commanded proportional to and counteracting that altitude error:

$$\dot{h}_c = K_h h_\varepsilon \tag{12}$$

commanding an exponential reduction of h_ε with a time constant $\tau_h = 1/K_h$. The $\dot{h}_c$ signal is then normalized into a γ_c by division of this signal by speed V:

$$\gamma_c = \dot{h}_c/V \tag{13}$$

To preserve the correct relative energy relationship of speed errors and altitude errors, the gains K_V and K_h are selected equal, yielding also identical dynamics of speed and altitude. The magnitude of K_V and K_h is selected to provide the desired response bandwidth consistent with the innerloop gains, such that the responses are overshoot free.

The outerloop error of any speed or flight path control mode can thus be normalized into the $\dot{V}_c$ and γ_c signals for input to the generalized elevator and thrust command computation. For the speed modes (MACH, CAS), the outerloop errors are first converted to true airspeed errors to assure correct signal scaling.

Using this design approach, the complete "Total Energy Control System" (TECS) was built up, to provide all the control functions previously provided by the autothrottle and pitch autopilot. Figure 5 shows the resulting TECS architecture and mode hierarchy. The VERT NAV and TIME NAV mode provide the capability to control to flight path and speed trajectories (4D) specified by a navigation/peformance computer system. The V_{MAX} and V_{MIN} modes engage automatically to provide speed limit protection.

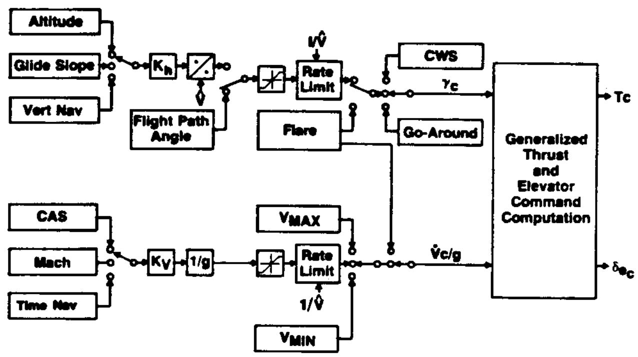

Figure 5. Basic TECS Architecture and Mode Hierarchy

After extensive linear analyses of the basic control modes, the entire TEC system was implemented in a fully nonlinear real time simulator and coupled to a control cab, allowing detailed system development and pilot evaluation of all the modes and at any flight condition. This way, many detailed system features were developed interactively with the evaluating pilots. The described system responses were obtained from this detailed nonlinear simulation.

Normal Acceleration Limiting

The normal acceleration is $a_n = V\dot{\gamma}$. Since the flight path angle γ responds to a command γ_c in a smooth overshoot free way, normal acceleration limiting is simply implemented by rate limiting the γ_c signal to $\dot{\gamma}_c = a_{n_{LIMIT}}/V$ (figure 5). The same rate limit is also applied to the $\dot{V}_c/g$ signal so that $\dot{V}_{c_{LIMIT}}/g = a_{n_{LIMIT}}/V$, to maintain the same processing in both signal paths. This assures that for dual commands, the signals add up to zero for either the thrust commands or the elevator command, thereby assuring smooth control without undesired controller activity.

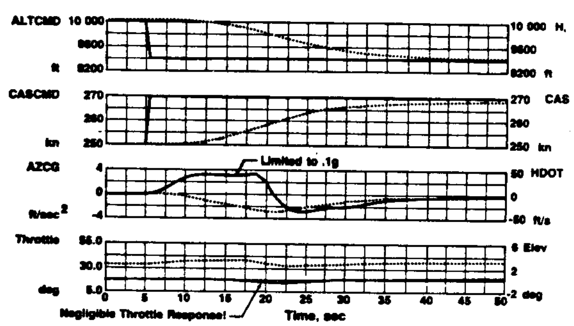

Figure 6. ALT/CAS Modes, Combined Decent/Acceleration

Figure 6 illustrates the normal acceleration limiting (.1g) and the negligible throttle response for simultaneous descent/speed up commands, with ~ zero total energy change. Since the $\dot{V}/g$ response is equal and opposite to the γ response at constant thrust, the rate limit on $\dot{V}_c/g$ also provides normal acceleration limiting for speed maneuvers with thrust at the limit. This rate limit yields very smooth thrust build up for large speed maneuvers and helps to cut down controller activity in turbulence.

Operations With Limit Thrust

When thrust reaches the limit, only the elevator remains available to control one variable. Most often, it is the flight path angle command γ_c that causes the thrust to limit, e.g., in the flight path angle mode when too high a command γ_c is selected (figure 6), or in the altitude mode when a large change in altitude is commanded. In those cases, speed control is continued through the elevator, the flight path error control loop is opened at the crossfeed to the elevator command computation (figure 3) and the thrust command integrator is put into hold. Linear control is resumed when a thrust rate command is developed to drive the thrust command back into the linear range. Thus, speed control will generally be given priority, eliminating the risk of stalling on climb out with a γ_c that cannot be satisfied or overspeed due to too steep a descent. This operation yields climb and descent with limit thrust for large altitude change commands, see figure 7.

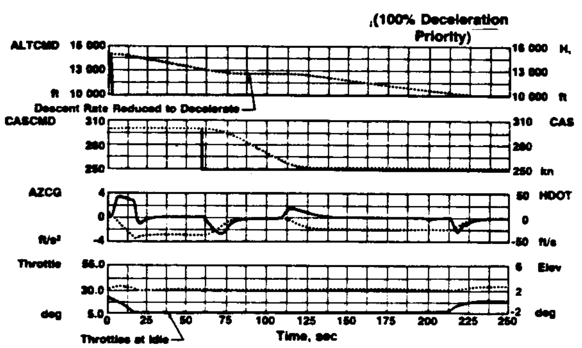

Figure 7. ALT/CAS Modes, Descent with Subsequent Deceleration

The speed priority also provides the operational flexibility to change speed during climb/descent at maximum/minimum thrust without the need for the pilot to manually reconfigure the modes, see figure 7. Here, after thrust limits at idle due to a large descent command in the altitude control mode, a command is given to decelerate from 300 Kt to 250 Kt. This is accomplished through the elevator control by temporarily reducing the descent rate until the speed command is captured. The vertical velocity is prevented from going positive during deceleration at idle thrust by limiting the deceleration command $\dot{V}_c/g$ to the total available energy rate, represented by $(\dot{V}/g+\gamma)$. Alternatively, it is possible to limit the acceleration/deceleration to only a portion of the total available energy rate, and reserve the remainder for climb/descent.

It should be noted that when thrust is limited, the speed control dynamics through the elevator are identical to the linear case because acceleration is in effect obtained by commanding a flight path angle change that yields the same force from gravity as would be obtained from the engine in the linear (decoupled) control case. Note also in figure 8 that speed does not deviate during the descent maneuver initiation and during final capture of the commanded altitude. The altitude and speed capture time constants are selected to provide sufficient anticipation for the thrust to respond, starting from a spooled down idle condition and avoid command overshoots.

Speed Limiting

Speed limiting is implemented as an absolute priority control. Normalized $\dot{V}_c$ signals are computed at all times for the V_{MIN} and V_{MAX} speed limiting modes. The $\dot{V}_c$ of the engaged mode (CAS, MACH, or TIME, NAV) is continuously compared with the $\dot{V}_{c_{VMIN}}$ and $\dot{V}_{c_{VMAX}}$ commands of the minimum speed and maximum speed limit modes. These modes engage autonomously when $\dot{V}_{c_{VMIN}} > \dot{V}_c$ or $\dot{V}_{c_{VMAX}} < \dot{V}_c$ and provide full anticipation, so that undershoots/overshoots are avoided. Unsafe speed commands by the pilot or the nagivation/ performance computer will thus be rejected. As discussed previously, speed limit control is not impaired by thrust limits. Figure 8 shows a high speed glide slope capture with V_c reduced below the final approach speed. The airplane captures V_{MIN} and the glide slope simultaneously, while the throttles remain at idle. Then speed reduces to recapture V_{MIN} at each flap extension.

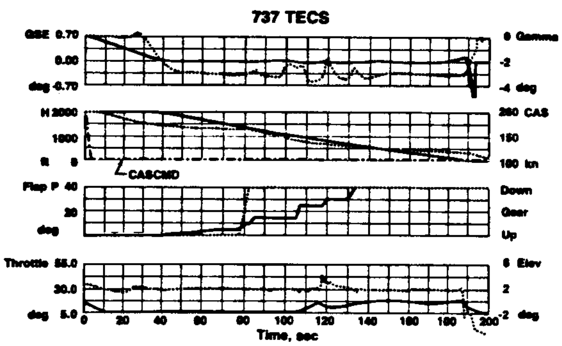

Figure 8. High-Speed Glide Slope Capture with Flap Extension and V_{MIN} Control

Flight Path Control Priority

In the Glide Slope control, the Vertical Navigation and Velocity Vector Control Wheel Steering modes, it is sometimes desirable to maintain path control priority when the thrust limits. In these cases, the acceleration error $\dot{V}_\varepsilon/g$ error input to the elevator command computation, rather than the flight path angle error γ_ε, is removed during periods with thrust in the limit (figure 4). As a result speed will wander. However, when either $V_{C_{VMIN}}$ or $V_{C_{VMAX}}$ becomes the controlling speed command, path control will be abandoned and speed control will once again become priority, so that stall or overspeed is avoided.

Segment to Segment Flight Path Transition

Control to any straight line segment of a path in space is accomplished by developing a normalized incremental flight path angle error between the current and the upcoming path segment (figure 9):

$$\gamma_\varepsilon = \left(K_h h_\varepsilon - \frac{S h_\varepsilon + \tau_{VP} S \hat{\dot{h}}}{(\tau_{VP} S + 1)}\right) \frac{1}{\hat{V}} \tag{14}$$

In (14), $\hat{\dot{h}}$ and $\hat{V}$ are inertially smoothed vertical speed and airspeed. The first term develops an incremental flight path angle command relative to the upcoming path segment. The second term develops the relative flight

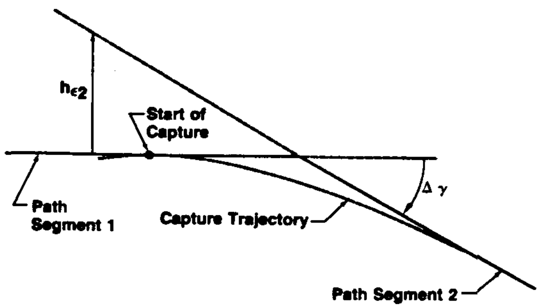

Figure 9. Segment-to-Segment Path Transition

path angle $\Delta\gamma$ between the current and the upcoming path segment. Computation of this γ_ε starts as soon as the control is armed to intercept a new path in space.

For large h_ε, the first term will dominate and call for a steepening of the intercept angle. As long as this condition exists, control toward the next segment is inhibited. As the airplane progresses toward the new path, the γ_ε will change sign. At that point, the current path segment is tangent to the exponential capture trajectory toward the next segment and control relative to the next segment is engaged. The control then smoothly develops fully coordinated thrust and elevator commands based on γ_ε to capture the new path overshoot free, without the need for extraneous capture logic or capture submodes (figure 8). The K_h sets the capture time constant.

Both the Glide Slope and Vertical Navigation modes are implemented this way. Figure 10 illustrates how the Vertical Navigation mode allows precise following of a five segment path in space, without inducing speed errors. Note that no path error develops during a speed change from 250 to 300 Kn.

Note that equation (14) provides for path captures which are fully adaptive to speed. With increasing speed, it takes an increasing

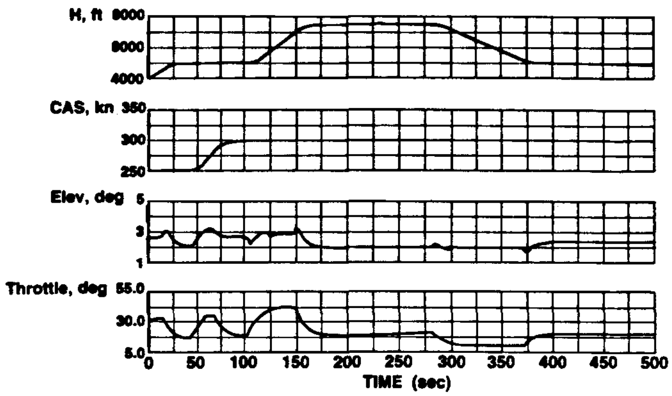

Figure 10. VERT NAV/CAS Modes, Control to Preprogrammed Path

h_ε to make $\gamma_\varepsilon = 0$, hence the capture will start sooner, so that the vertical accelerations will remain the same.

For the glide slope mode, the linear altitude error h_ε is derived by gain scheduling of the angular beam deviation. The γ_ε derivation, together with the integral control structure, provides inherent inertial smoothing of beam noise, depending on the selected τ_{VP}.

Special Modes

Go Around Control

The Go Around mode is simply implemented by switching to a fixed γ_C (one line of digital code). It provides fully adaptive performance for weights and available engine thrust. The flight path angle command is selected to provide the desired initial pull up and final climb gradient. This γ_C is not rate limited in order to minimize altitude loss. It is possible to obtain over .5 g vertical acceleration, if desired. For a heavy aircraft, more than the available thrust may be required to satisfy γ_C. In that case, full thrust climb is obtained with speed controlled by the elevator. For light weight conditions, only partial thrust will satisfy γ_C. The partial power avoids excessive climb gradients and pitch attitudes. The mode is safe in case of engine failures: the thrust on the remaining engines will be increased and if insufficient to satisfy γ_C, a max thrust maneuver with speed controlled by the elevator will result.

Automatic Landing Flare Control

The automatic landing flare control has been implemented using a modified "Variable Tau" h control law[5]. Upon reaching a fixed flare height, the γ_ε signal is replaced by the signal $(h + h_{BIAS}) K_h V_G/\hat{V}$ which in effect develops a $\Delta\gamma_C$ through the integral control paths, commanding the airplane to fly a geometrically fixed flare trajectory to the runway, for all flight conditions. This comes about through the groundspeed dependent gain $K_h V_G$. The $\hat{\dot{h}}$ signal which is also used for developing γ is dynamically changed over from a barometric to runway referenced quantity. In the speed control path a negative $\dot{V}_C$ is introduced during flare, which augments the pitch rotation and drives the throttle to the aft stop. The throttle rate will be modulated by feedback of the actual acceleration. Good performance was achieved on the simulator for a variety of conditions. However, exhaustive testing has not yet been conducted.

Computer Augmented Manual Control

The Total Energy Control system is ideally 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[6], a rate of change of flight path angle command ($\dot{\gamma}_C$) proportional to the column force is developed. The column force signal is gain scheduled with $1/\hat{V}$ to provide constant stickforce per "g", and integrated to develop the flight path angle command γ_C. An inertial flight path angle feedback $\gamma_I = \hat{\dot{h}}/V_G$ is used to develop the basic error signal γ_ε, and provide long term control relative to an inertial reference. This $\dot{\gamma}_C$ signal is also fed forward to the thrust and elevator commands to obtain the desired response lag of γ relative to γ_C without causing speed perturbations.

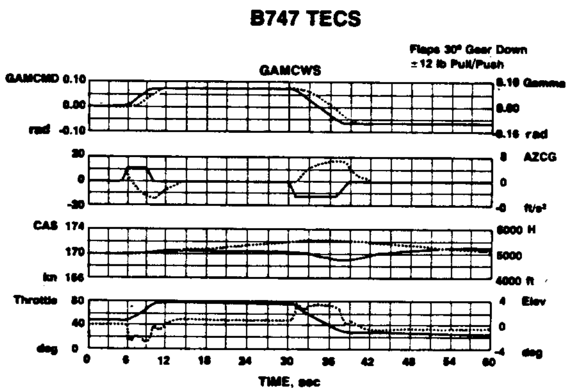

Figure 11. Velocity CWS Responses to 12 lb Column Pull/Push

Figure 11 shows examples of responses tailored to yield $\tau_\gamma \sim 2.5$ sec, the fastest response achievable with parallel servos while avoiding elevator over control and stickforce reversal.

It should be noted that the 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.

Feedback Signal Synthesis

The Total Energy System uses filtered or estimated feedback signals, $\hat{h}$, $\hat{\dot{h}}$, $\hat{V}$ and $\hat{\dot{V}}$. The altitude and altitude rate signals h and $\dot{h}$ are developed by inertially smoothing barometric altitude with vertical acceleration from an inertial reference system, using a continuously running bias compensated third order complementary filter. The inertially smoothed true airspeed signal $\hat{V}$ is developed in a first order complementary filter using groundspeed V_G. This signal is used to normalize the outerloop path deviations into flight path angle errors and also to develop the proportional flight path angle feedback signal $\hat{\gamma} = \hat{\dot{h}}/V$ for all modes. The filtering is done to minimize controller activity in turbulence and airmass referenced flight path angle quantities are used because the energy concept and the thrust requirements (equation 7) relates to airmass referenced quantities.

The flight path acceleration $\hat{\dot{V}}/g$ is derived short term from the thrust to weight ratio T/W and the airmass referenced flight path angle γ, and long term from true airspeed V_T:

$$\hat{\dot{V}}/g = \frac{(T/W - \hat{\gamma})\ \tau_{\dot{V}}S + SV_T}{(\tau_{\dot{V}}S+1)} \qquad (16)$$

Like the $\hat{\gamma}$ signal, $\hat{\dot{V}}/g$ is referenced to airmass long term, because the objective is to control airspeed. The signal component $(T/W - \hat{\gamma})$ represents the flight path acceleration minus the effect of drag changes. It is used instead of inertial acceleration to eliminate undesirable control responses to large gusts, windshear, speedbrake and flap changes. Since drag changes are not sensed directly, the throttles will not respond immediately to speedbrake or flap changes, allowing the airplane to slow down/speed up naturally and giving the pilot time to make appropriate speed command adjustments.

In the preferred TECS configuration the T/W signal is developed by processing the computed T/W command through a transfer function approximating the actual engine transfer function (observer). This approach reduces the effects of engine dynamics variations between low and high thrust settings and reduces signal interface requirements for the actual system implementation.

Control in Turbulence and Windshear

In conventional AFCS designs, the autopilot generally uses the higher elevator control authority to control the path at the expense of autothrottle speed control. Airspeed is the variable most seriously affected by turbulence and conventional autothrottle systems are often ineffective in reducing the RMS speed errors, because of the relatively low authority and slow engine response. For large gusts or windshear and operations near the reference speed, the situation is further aggravated when the autopilot attempts to compensate speed lift loss by commanding a pitching up. Several incidents of induced stalls and loss of control, attributable to this problem have been reported and studied by D.E. Johnston, et al.[7]
Johnston concluded that maneuvers involving energy change can leave the airplane out of trim on elevator and thrust, and therefore vulnerable to surprise turbulence and windshear. To survive such encounters he recommends high gain attitude and low gain airspeed feedback control

through the elevator, combined with a "potential flight path angle" thrust director. J.G. Jones (reference 8) argues at length why thrust should be used to control total energy and elevator to control energy distribution to effectively combat turbulence and windshear.

The TECS system does exactly that and forces the designer to consider the trade off between flight path and speed tracking. Both thrust and elevator control work equally hard in a coordinated way and using the same information to reduce the errors to zero. On the one hand, speed perturbations tend to be converted to path perturbations for the short term by the elevator control, which tends to equalize the energy errors. On the other hand, the more effective thrust control reduces the total energy errors quicker. On balance, for the same path tracking in turbulence as for conventional autopilots, the speed tracking and throttle response is improved.

The balance of flight path and speed errors due to external disturbances can be shifted by redistribution of the relative flight path angle and acceleration proportional feedback gains, to the elevator (K and 2-K in figure 3). This does not effect the system bandwidth or damping basically, because these feedback signals are complementary at constant thrust.

In windshear, the feedback of airmass referenced $\hat{\gamma}$ and $\hat{\dot{V}}/g$ provides direct thrust corrections through the proportional signal path, thereby reducing deviations from the inertial reference path. The speed tracking performance is further affected by the acceleration complementary filter time constant $\tau_{\dot{V}}$ and the overall speed feedback gain level. Small $\tau_{\dot{V}}$ yields tight speed tracking in windshear but higher controller activity in turbulence. The effect of $\tau_{\dot{V}}$ on path tracking is opposite. This performance trade off is shown in figure 12. At higher altitudes tight speed control in windshear is less critical and low controller activity is desired, hence $\tau_{\dot{V}}$ is programmed to increase with altitude. Figure 12 indicates that for $\tau_{\dot{V}} <$ 10 sec the control activity penalty in turbulence for improving speed tracking in windshear becomes high. Alternate design approaches, using explicit windshear detectors, were found to yield virtually identical performance trade offs. Such detectors use the same basic information and add unnecessary complexity[2].

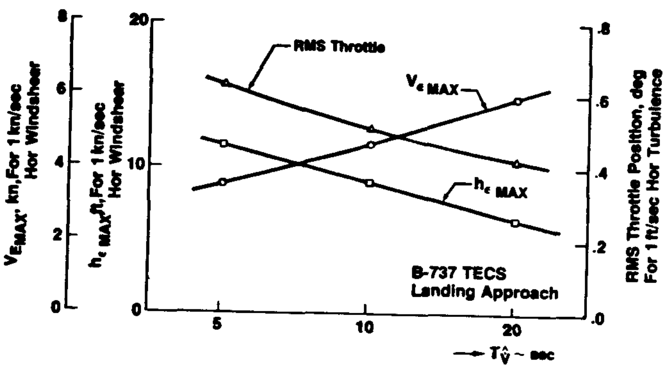

Figure 12. Windshear/Turbulence Performance Trade

A far more effective control strategy is to relax the speed control somewhat (higher $\tau_{\dot{V}}$) and recover the speed safety margin in windshear by increasing the airspeed. This approach was implemented by simply adding a bias proportional to the headwind (the only dangerous case) onto the speed command of the V_{MIN} mode. It results in a high approach airspeed for headwinds which is allowed to bleed down to the final approach speed, as the headwind shears out during descent.

Figure 13 illustrates that using this control strategy, a windshear of 5 Kn/sec, far in excess of the performance of the airplane, could be handled without stalling and with relative relaxed control ($\tau_{\dot{V}}$ = 10 sec). The airplane was set up in the ALTITUDE/CAS mode at 500 ft altitude. The headwind results in an initial approach speed 30 Kn above the reference speed.

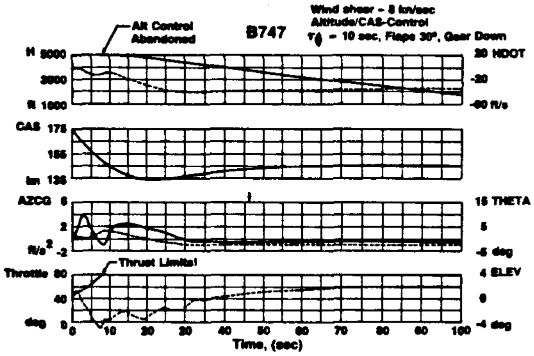

Figure 13. TEC System Response to Severe Windshear

After the speed starts to bleed off due to the windshear, the throttles start forward, the pitch attitude increases slowly, but the angle of attack increases rapidly. After the throttles hit the forward limit, path control is abandoned, but speed control continues through the elevator. The airplane then pitches down to recapture the V_{MIN} speed and the airplane settles into a constant speed descent. In the process, the speed energy bleed off holds the path as high as possible.

Using this control strategy, the system can be tailored to yield an optimum flight path and speed performance trajectory to enhance chances of survival of a given level of severe windshear.

Flight Evaluation

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 assist the NASA under contract with checkout of a complete TECS simulation, flight software specification, software test development and flight test planning. Flight tests will be directed to evaluate the system performance and all operational aspects of the system.

Conclusions

The described Total Energy Control System satisfied the stated design objectives for a functionally integrated thrust and elevator control system and incorporates the following desirable features:

- All automatic flight path and speed control modes are normalized to use the same generalized elevator and thrust command computation.
- All control modes will have consistent dynamic characteristics.
- Decoupled flight path and speed maneuver control is achieved naturally by forward feed of either command to both controllers.
- Throttle response to constant energy aircraft dynamics are eliminated.
- All maneuver and flight envelope limiting provisions are implemented at one central point in the control law, affecting all modes.
- Control priority in cases of thrust limiting is dealt with in a simple and safe manner.
- In windshear, the feedback of both flight path angle and acceleration errors to the thrust and the elevator contributes to more effective and safer control.
- In turbulence, path tracking and speed tracking errors can be weighted to produce the desired performance balance.
- Mode switching is transient free, and the switching logic uses only internal control law states. Command reinitialization, capture submodes and outerloop gain schedules have been avoided.
- This energy based control system is generally applicable. Transfer to another airplane requires only the elevator and thrust innerloop adaptation and implementation of the airplane specific flight envelope limits. For example, transfer and checkout on the simulator of the complete system with all modes from the B-737 to B-747 was accomplished in 6 engineering man months, without changes to the energy based outerloop control system structure or gains.

The design reduces hardware by elimination of the autothrottle computer and the associated interfaces and redundant sensors. The complete single channel control law software requires only ~2500 words of memory--a factor of 4 less than for conventional designs of comparable capability. Numerous improvements in performance and operational capability have been realized. Pilot workload is reduced by simpler more effective mode control and system configuration annunciation, without ambiguities, functional overlap or operational restrictions.

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