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DESIGNING LOW BANDWIDTH PROPULSIVE-ONLY FLIGHT CONTROLLERS

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Abstract

Results from an investigation of using engine commands to control flight attitude are described. In-flight operation with simulated failed flight controls is reviewed and ground simulations of piloted propulsive-only control to touchdown are analyzed. A design of an optimal control law to assist the pilot is presented. Recommendations are made for more robust design and implementation. Results to date indicate that simple and effective augmented control can be achieved in a wide variety of failed configurations.

Nomenclature

α	perturbed angle of attack (deg)
β	perturbed sideslip (deg)
γ	perturbed flight path angle (deg)
ϕ	perturbed bank angle (deg)
Γ_{cmd}	glide slope commanded (deg)
ε	glide path deviation angle (deg)
λ	lateral path deviation (deg)
e_T	perturbed throttle (%)
d	deviation above glide path (ft)
h	altitude change - -down (ft)
p	roll rate (deg / sec)
q	pitch rate (deg / sec)
r	yaw rate (deg / sec)
K_x	feedback gain for x
G_{in}^{out}	transfer function (s)

Introduction

Propulsive controls which assist conventional control surfaces in the attitude control of aircraft have been recognized as important enhancements of combat aircraft maneuverability[1]. In commercial operations such maneuverability is seldom required, but in the event of hydraulic failure of controls or damage to control surfaces, the engines of a large commercial aircraft are usually capable of attitude control. Recent flight control failures on commercial aircraft, although extremely rare, have shown that piloted aircraft can remain controllable in-flight by the skillful application of thrust.[2,3] The extreme difficulty of this task, however, combined with pilot stress, cannot be expected to result in a successful landing.

An investigation of propulsive-only flight control by NASA Dryden[4,5] has shown it to be feasible for a wide variety of aircraft types and failure configurations. The list of aircraft flown include the Lear 24, Cessna 152, Piper PA-30, and the F-15 (single-engine aircraft required that the rudder be used in addition to the throttle). None of the in-flight tests were flown to touchdown. Pilot ratings were categorized by controlled axis and by task. Typically, longitudinal axis control was rated Level 2 for the approach and Level 3 for runway landing. Lateral axis control was rated Level 2 for both approach and landing. The pilot learning curve in all cases was rapid.

Although controlled flight was always possible, pilots could not safely and predictably maneuver with the throttles alone. There may be sufficient control power available (presuming the throttles are advanced from idle), but the typically long time constants and couplings between dynamic modes make piloted flight precarious for demanding tasks such as landing. Training may alleviate the gross misapplication of throttles but will not guarantee safe landings.

A pilot-assist mode which automatically moves the throttles in order to control attitude is a potential solution. Such a mode would be activated by the pilot in the event of complete or partial failure of the high bandwidth pitch and roll controls. This presumes that the engine power settings and aircraft geometry provide controllability under a variety of aircraft

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configurations, failure modes, and power settings.

Because of the long time constants of the engines relative to those of the contol surface actuators, low-bandwidth control will be most effective for the long-period dynamic modes of the aircraft. This implies the basic airframe with failed controls should exhibit minimal stability handling qualities in flight[6].

This paper will concentrate on the major considerations in designing a propulsion-only flight control system (POFCS). The empirical results of ground simulations using a Boeing 720 will be reviewed,[7] and finally an optimal linear design of the POFCS will be presented.[8] The paper concludes with some recommendations for future work.

Ground Simulation

Fixed-base simulations of a Boeing 720 aircraft were performed at NASA Dryden to investigate throttles-only control. The Boeing 720 represents a four-engine passenger jet aircraft as shown in Figure 1. Asymetric thrust is available for roll control, but the aircraft has slow responding engines. Pitch-control was obtained by simultaneously advancing or retarding the throttles. A view of the simulator scene for approach and landing is shown in Figure 2.

The Boeing 720 has a low wing with 35 degrees of sweep. Gross attitude control in both the longitudinal and lateral axes during the simulation was possible without the use of electric trim.

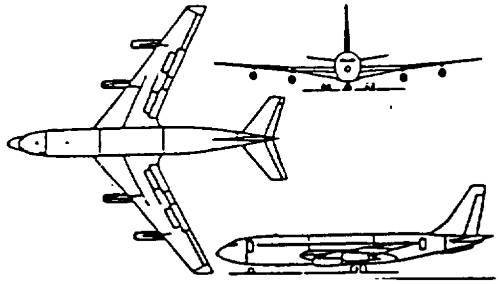

Figure 1. Boeing 720

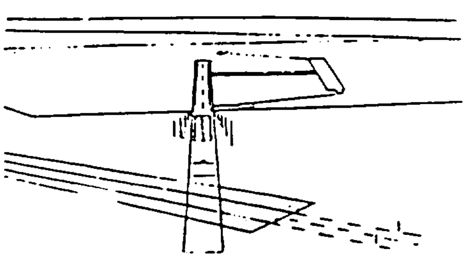

Figure 2. Simulation Visual

Low Bandwidth Control Law

A propulsion-only flight control system (POFCS) must use the control power of the engines, assuming a stable basic airframe, to provide longitudinal and lateral flight path control under a variety of flight control failures throughout the flight envelope.

Pilots must relearn how to generate lead compensation. There are no handling qualities specifications to cover this situation. The pilot may find it difficult to accept watching the throttles move with stick input The control law must allow pilot inputs and pilot-directed configuration changes without exciting large oscillations of the dutch roll or phugoid.

The engine time constants must be fast enough to control any oscillatory mode which could preclude a successful landing. Relatively fast modes, such as the short period, must be stable. In other words, the configuration with failed controls, throughout the flight envelope, must be stabilizable (the uncontrollable poles must be stable).[9]

Boeing 720 Control Law The baseline configuration was gear-up, flaps-up, 10,000 ft pressure altitude, 160 knots, 190,000 lbs. The baseline control law for the four engine jet transport, for both the longitudinal and the lateral axis, was developed by trial and error in the flight simulator at NASA Dryden.[7] The baseline gains corresponding to Figures 3 and 4 were

$$\{K_q, K_\theta, K_\gamma, K_p, K_\phi, K_\beta\} = \{-4, 0, -1, 0.5, 1.0, 0.5\}$$

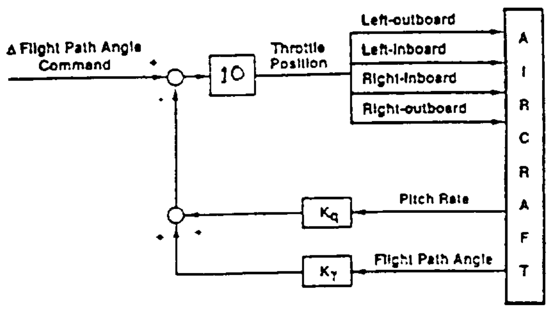

Figure 3. Flight Path Angle Control

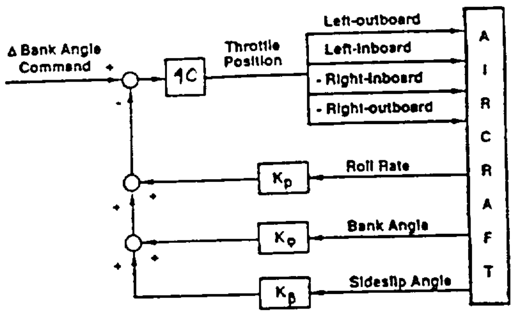

Figure 4. Bank Angle Control

As described in reference 7, ten configurations were then flown with the above set of baseline gains. The worst ratings were for those configurations farthest from the baseline weight of 190,000 lbs. Pilot comments for poorly rated configurations indicated the problem to be severe lateral oscillations that could not be damped predictably by pilot inputs.

Classical Analysis. Linearized models of the longitudinal mode coupled to the glide path by K_ε are shown in Figures 5-7 and may be analyzed in a conventional manner as described by Blakelock.[10] The range to touchdown must be fixed for a linear analysis. Such an analysis shows that the baseline gains chosen are satisfactory longitudinally to ranges within 1000 ft of touchdown.

The lateral mode of coupled flight, however, shows an interesting feature. A two dimensional root locus for the lateral modes of response, varying K_p and K_ϕ, is illustrated in Figure 8. Note the difficulty in selecting these gains using conventional analysis. The lateral response mode has a lateral phugoid in addition to a dutch roll mode. Families of plots of these two pairs of complex roots show that varying either gain pushes one set of roots into the right-half plane. This effect of varying configurations exacerbates this tendency.

Normally, given conventional flight controls, the pilot could compensate for this type of mild and slow instability. Throttles only control, however, even with an augmented system, make such compensation extremely difficult for the pilot. Piloted simulations show that pilots are sensitive to any gain set significantly away from the nominal settings.

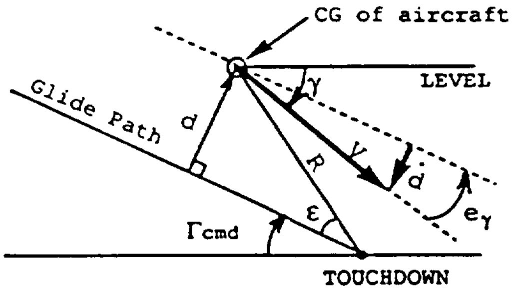

Figure 5. Glide Slope Geometry

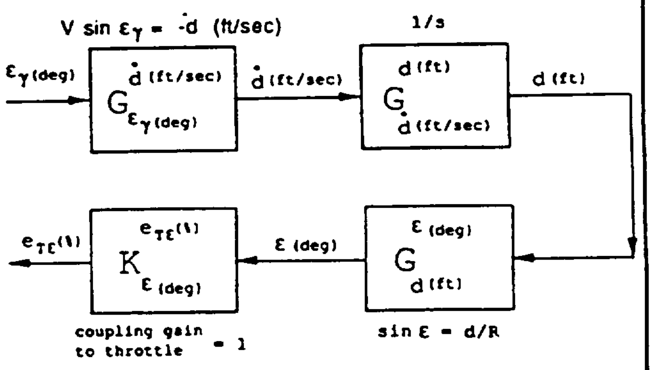

Figure 6. Glide Slope Block Diagram

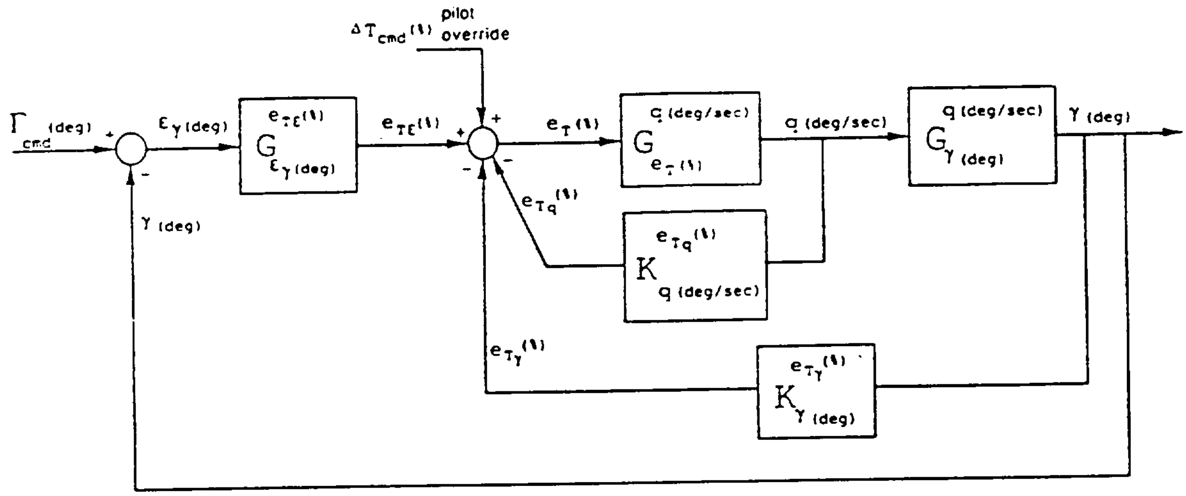

Figure 7. Longitudinal Aircraft Coupled to Glide Path

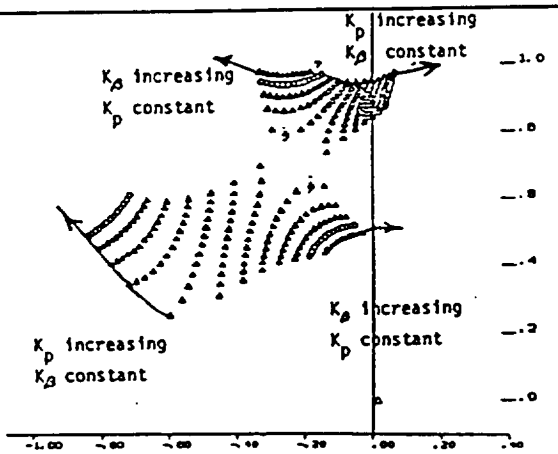

Figure 8. Lateral Mode Root Loci

Optimal Control Law

A Linear Quadratic Regulator (LQR) was developed with modal weights chosen to provide robust behavior.[8] Although this choice results in a complex feedback structure with some loss of insight relative to successive loop closure, the opportunity to use all four engines independently was considered important in a flight control system with such degraded performance. In particular, this provided the capability to control pitch and velocity independently since the thrust lines of the outboard and inboard engines have unequal displacements along the z-body axis. To see this mathematically it is necessary to compare the eigenvalues of the controllability matrix (which is not done here).

Modal Regulator Equations. The regulator consisted of the following feedback control law:

$$\dot{x}_m = M^{-1}AMx_m + M^{-1}Bu \qquad (1a)$$

$$u = K_m x_m = K_m M^{-1} x \qquad (1b)$$

minimizing

$$J = 1/2\int (x^T M^T Q M x + u^T R u)dt \qquad (1c)$$

$$Q_m = M^T Q M \qquad (1d)$$

where the subscript *m* indicates modal coordinates with modal weights Q_m assigned directly to aircraft dynamic modes such as the phugoid. The state variables for the regulator design are

$$x^T = [q, \alpha, u, \theta, h, p, q, r, \beta, \phi \quad]^T \qquad (1e)$$

where all units are radians, feet, and seconds, and where the control is given by

$$u = [\text{four throttles}] \qquad (1f)$$

The LQR design condition was 4,000 ft MSL, 175 KCAS, 160,000 lbs, with gear and flaps up. The plant, throttle control, and feedback matrices for this condition (cg 20.85% MAC) are given in Figure 9.

$$A=\left[\begin{array}{ccccc:cccc}
q & \alpha & u & \theta & h & p & r & \beta & \phi \\
\hline
-.89 & -.98 & .00011 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & -.79 & -.00065 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 13 & -.012 & -32 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -312 & 0 & 312 & 0 & 0 & 0 & 0 & 0 \\
\hdashline
0 & 0 & 0 & 0 & 0 & -.99 & .55 & -3. & 0 \\
0 & 0 & 0 & 0 & 0 & -.053 & -.21 & .76 & .0021 \\
0 & 0 & 0 & 0 & 0 & .11 & -.98 & -.11 & .1 \\
0 & 0 & 0 & 0 & 0 & 1 & .11 & 0 & 0
\end{array}\right]$$

$$B=10^{-5}\left[\begin{array}{cc:cc}
\text{Outboard Left (\%)} & \text{Inboard Left (\%)} & \text{Inboard Right (\%)} & \text{Outboard Right (\%)} \\
\hdashline
5.1 & 12 & 12 & 5.1 \\
-.9 & -.9 & -.9 & -.9 \\
2000 & 2000 & 2000 & 2000 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
6.8 & 4 & -4 & -6.8 \\
80 & 47 & -47 & -80 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array}\right]\begin{array}{c}
\\ q \\ \alpha \\ u \\ \theta \\ h \\ p \\ r \\ \beta \\ \psi
\end{array}$$

$$K=K_m M^{-1}=\text{ Feedback Gains (\%) }=\left[\begin{array}{ccccccccc|c}
q & \alpha & u & \theta & h & p & r & \beta & \phi & \\
\hline
594 & -467 & 2.6 & 780 & 0 & 93.9 & 584 & 91.6 & 125 & \text{Outboard Left} \\
1750 & -1290 & 2.1 & 2345 & 0 & 55.3 & 344 & 54.0 & 73.4 & \text{Inboard Left} \\
\hdashline
1750 & -1290 & 2.1 & 2345 & 0 & -55.3 & -344 & -54.0 & -73.4 & \text{Inboard Right} \\
594 & -467 & 2.6 & 780 & 0 & -93.9 & -584 & -91.6 & -125 & \text{Outboard Right}
\end{array}\right]$$

Figure 9. LQR Plant, Control, and Feedback Matrices for Design Configuration

The insight gained by using modal cost weights can effectively be seen by comparing the open and closed-loop responses of sideslip to an initial sideslip of 10 degrees, as shown in Figure 10. One of the penalties of this approach, however, was the normalization of units so that weights in the cost function did not differ by many orders of magnitude.

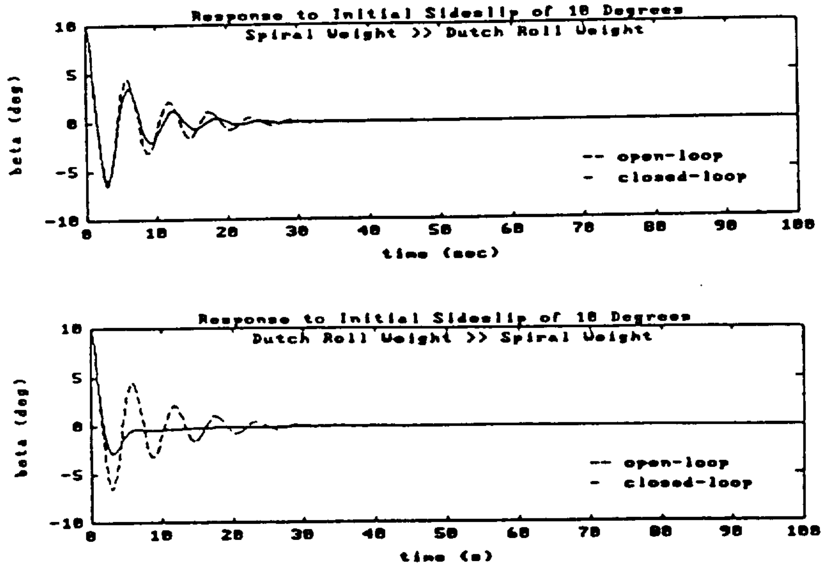

Figure 10. Cost Function Weights Trade-offs (Spiral/Dutch Roll)

Increasing weights on the dynamic modes provided tighter control, but performance suffered when the configurations were altered. This issue of robustness did not exist for the short period or roll modes since they were difficult to realistically excite by the engines, especially when engine lag was taken into account.

The final gain matrix in Figure 9 eliminated state feedbacks for altitude,h, and for the engine model states described in the section below with no adverse effects.

<u>Engine Model.</u> The values in the **B** matrix were obtained from steady-state perturbations in response to thrust. In order to use % throttle position,e_T, and not pounds of thrust in the control **u** of Equation (1f), the **A** matrix was augmented with a second order engine model of the form

$$\begin{bmatrix} \dot{T} \\ \ddot{T} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \begin{bmatrix} T \\ \dot{T} \end{bmatrix} + \begin{bmatrix} 0 \\ K_{T_\infty} \end{bmatrix} e_T \tag{2}$$

where ω_n^2=2.5, ζ=.802, and K_{T_∞}=250. These parameters were chosen to match engine transients at a nominal steady-state throttle setting of 20%. The transfer function form of the engine transient was

$$G_{e_T}^{T} = \frac{100 \cdot 0.55 \cdot 5.0}{(s+0.55)(s+5.0)} \tag{3}$$

The conservative engine model of Equation(2) overestimated the gain K_{T_∞} so the controller would not de-stabilize the system by acting on a low authority plant. Equation (3), on the other hand, is accurate for most steady-state conditions on approach.

<u>System Dynamics.</u> The aircraft and engine models were normalized as described above by the factors shown below in Table 1.

Table 1. Normalization Factors

Dimension	Units	Factor
Angle	Radians	.001
Force	Pounds	5906
Distance	Feet	1
Throttle	Percent	0.1

The weights for the dynamic modes given the normalization factors are shown in Table 2.

Table 2. LQR Weights

Mode	Weight	Period (sec)	ζ
Short Period	1	10	0.7
Phugoid	10	57	0.01
Dutch Roll	200	6.1	0.10
Spiral	0.5	68	...
Roll	1	1.2	...

The discrete version[11] of this system at 50 Hz has the open and closed-loop system roots as shown in Figure 11.

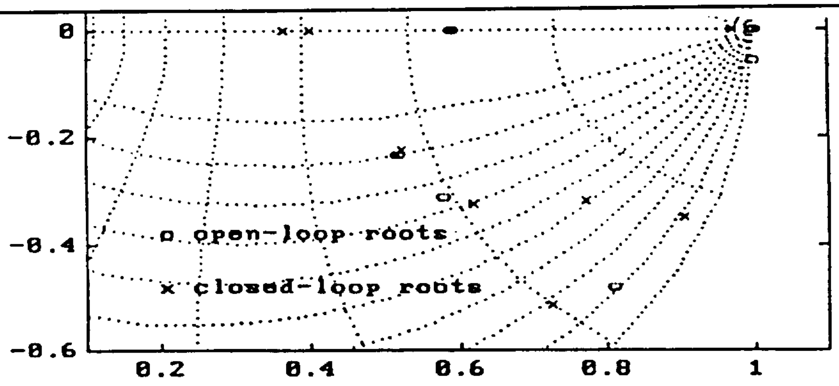

Figure 11. Discrete System Roots at 50 Hz

Pilot Command Interface. A command interface was designed into the LQR loop based on a pseudo rate command for both pitch and roll. This allowed a "batch" test of the linear system prior to implementing the control law on the hi-fidelity nonlinear simulation.

Control authority that would not hinder or "wash out" pilot commands was provided by translating the command into a pseudo rate command. This rate command was digitally integrated over time to determine pitch and bank attitude command. Limiters were also inserted to prevent saturation. Parameter values are shown in Table 3 for the final LQR controller, including pilot interface, of Figure 12.

Table 3. Pilot Interface

Parameter	Value
q_{stick}	0.25
pitch limit	16,000 / gross wt
T_s	0.02
p_{stick}	-0.25
bank limit	$6 \cdot 10^6 / I_{zz}$

Note that the lateral commands take precedence over longitudinal ones, emphasizing the rationale that survivability depends primariy on wings-level flight and touchdown. Also, setting limits as a function of throttle lever position will likely be an impractical implementation. The independent control of velocity and pitch attitude was not accomplished in this investigation.

In general, "batch" linear simulations prior to piloted simulation predicted higher gains for adequate control than were required. Unstable pilot-in-the-loop operation in the nonlinear simulation required that the weights be reduced to those shown in Figure 9. Those gains provided adequate closed-loop performance on the piloted simulator.

Linear system performance did not model the coupled longitudinal and lateral modes, engine nonlinearities, and unequal engine spool-up and spool-down times. The nonlinear simulation also exhibited more Dutch Roll damping. Piloted simulation results follow in the next section.

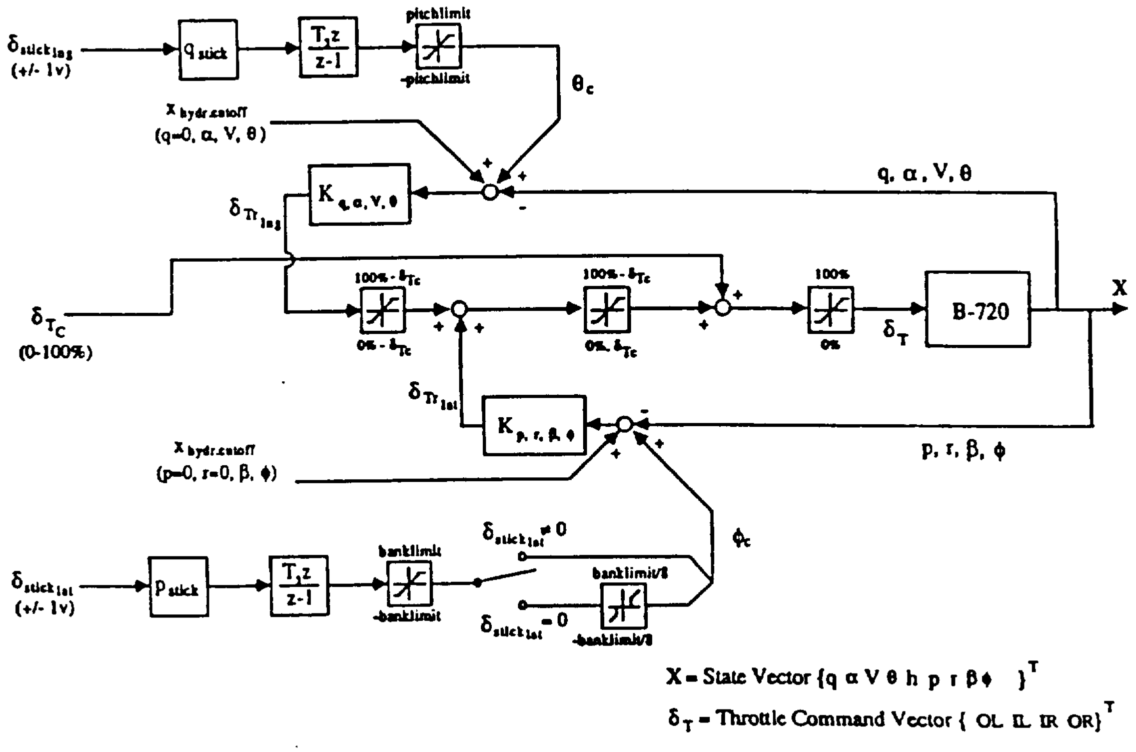

Figure 12. LQR Propulsion-Only Control with Pilot Interface

Piloted Evaluation. The LQR propulsive-only controller of Figure 12 was implemented on a high-fidelity nonlinear simulator at NASA Dryden and evaluated by test pilots. Stick deflection produced thrust commands that were observed on the engine instruments but which did not physically move the throttles.

Pilots were asked to evaluate changes in altitude, velocity, heading, ground track, and flare performance. The LQR implementation did not allow throttles to be physically moved to control velocity since the LQR controller would interpret this as a pitch command. Such motion would also alter the bounds in the limiters shown in Figure 12.

Up-and-away maneuvering did not require excessive pilot workload. The longitudinal implementation, however, made it difficult to fly level, especially when rolling out of turns. Because of the many development changes which occurred during piloted flight, pilot ratings were not documented. In general the aircraft could be considered Level 2. These ratings are similar to those described in this paper's section on the Boeing 720 control law.

The qualitative results of the piloted evaluations are summarized in Table 4. As expected for this type of controller, performance degraded when the LQR control law was implemented on different failure configurations.

Table 4. Qualitative Pilot Evaluation

Task	Pilot Comment
Altitude Change	Holds a rate of climb, but return to level is difficult.
Velocity Change	Somewhat "mysterious"
Heading Change	Holds steady-state turn well, but roll-rate command more intuitive than bank angle command. Difficult to maintain altitude.
Hold Sink Rate	Acceptable after learning curve. Flight path angle command is preferable
Hold Ground Track	Acceptable, but lightly damped roll is somewhat bothersome.
Flare	Too much lag. Will require some practice to determine when to initiate the flare.

Conclusions

Simulations of a Boeing 720 aircraft with failed flight controls show that a propulsion-only flight control system (POFCS) is feasible. Classical analysis using successive loop closure results in simple, effective controllers. Two lightly damped lateral modes,however, can become unstable given minor gain variations or changes in configuration. This suggests that compensation should augment the gains to provide a more robust and stable system.

A LQR augmentation scheme designed using optimal control was flown successfully under pilot control but was not a significant improvement over the gains set by classical analysis. The design implementation employed pseudo rate commands, required limiters, and did not allow the pilot to use the throttles for velocity control independent of pitch.

Despite these limitations it was demonstrated by piloted evaluations that the POFCS concept is feasible and may be implemented as a back-up pilot assist mode when normal flight control has failed. If an optimal controller is employed, an improved pilot interface will be required as well as provisions for velocity control independent of pitch attitude. In particular, the use of differential inboard-outboard thrust should be investigated as a way to uncouple the velocity and pitch modes.

Pilots indicated that improved handling qualities are desired. The wandering bank angle and difficulty in achieving level flight should be rectified. Pitch sensitivity may be reduced by transition to a flight path angle command system.

Research is in progress to investigate the use of compensators for failed flight control configurations. Better performance and more robust behavior for off-design failure conditions are desired. Flight operations which are coupled to the glide path will be analyzed, and the resulting controller is intended to be tested in both ground and inflight simulations.

Acknowledgment

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