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The Propulsive-Only Flight Control Problem

by

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Abstract

Attitude control of aircraft using only the throttles is investigated The long time constants of both the engines and of the aircraft dynamics, together with the coupling between longitudinal and lateral aircraft modes, make piloted flight with failed control surfaces hazardous, especially when attempting to land. This research documents the results of in-flight operation using simulated failed flight controls and ground simulations of piloted propulsive-only control to touchdown. Augmentation control laws to assist the pilot are described using both optimal control and classical feedback methods. Piloted simulation using augmentation shows that simple and effective augmented control can be achieved in a wide variety of failed configurations.

Nomenclature

q	perturbed pitch rate (rad/sec)
α	perturbed angle of attack (rad)
u	perturbed velocity (ft/sec)
θ	perturbed pitch angle (rad)
h	altitude change-down (ft)
γ	perturbed flight path angle (rad)
Γ	glide slope deviation angle (rad)
$K_q, K_\theta, K_\gamma, K_\Gamma$	long. feedback gains
p	perturbed roll rate (rad/sec)
r	perturbed yaw rate (rad/sec)
β	perturbed sideslip (rad)
ϕ	perturbed bank angle (rad)
o	lateral offset angle from runway
$K_\phi, K_\beta, K_p, K_o$	lateral feedback gains
δ_{TR}	perturbed throttle (%)
δ_{TH}	perturbed thrust
δ_{DT}	perturbed differential thrust

Introduction

The failure of hydraulic power to primary flight control systems is an extremely rare occurrence in-flight. Such failures have occurred, however, and their consequences have been especially tragic in commercial operations. In a few of these failures the aircraft remained controllable in-flight by the skillful application of thrust, but the extreme difficulty of this task, combined with the stress of the emergency, did not allow a successful landing.

The fundamental problem is that an aircraft cannot be easily and predictably maneuvered by the pilot with the throttles alone. Although the control power is often sufficient to fly the aircraft, the long time constants and couplings between dynamic modes make pilot control uncertain and precarious for demanding tasks such as landing. Exposure to these situations in training simulations may alleviate the gross misapplication of throttles, but will not eliminate the potential for a serious accident to occur.

A complimentary solution to more training would be the addition of a simple, low cost pilot-assist mode to be activated by the pilot in the event of complete failure of the high bandwidth pitch and roll controls. The goal of such a system would be to provide acceptable flying qualities by driving the throttles through pilot command inputs from the control column. Although the requirements are many for such a system, three factors are worthy of note.

First, the engine power settings and mounting geometry must provide controllability in a mathematical sense for the aircraft equations of motion under a variety of aircraft configurations and failure modes. Second, and possibly the most important factor, the low-bandwidth control system will be coupled with a pilot who will be stressed and anxious under actual emergency conditions. There are no handling qualities requirements to guide the designer here, and even those in military specifications[1] are inapplicable. Third, because of the long time constants of the engines relative to those of the control surface actuators, low-bandwidth control will be most effective for the long-period dynamic modes of the aircraft. This poses a special difficulty for stabilizing the lateral Dutch Roll mode, which may not be a slow mode relative to the engine response.

This paper will concentrate on the development of a practical propulsion-only flight control system (POFCS). The first major issue of controllability due to engine power and geometry will be broadly surveyed in the next section titled "In-Flight Simulations". [2,3] Next, the empirical results of ground simulations using a Boeing 720 aircraft model with failed flight controls will be presented. The third section will present development issues for the POFCS and highlight the difficulties of achieving a robust, practical design.

In-Flight Simulations

Preliminary investigations of throttle-only aircraft control in-flight have been conducted by NASA Dryden Flight Research Facility. The list of aircraft flown includes 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 could be categorized by controlled axis and by task. Typically, longitudinal axis control was Level 2 for approach and Level 3 for landing on a runway. Lateral axis control was Level 2 for both approach and landing. The pilot learning curve in all cases was rapid.

F-15 throttles-only. The basic F-15, shown in Figure 1, has a high wing with approximately 45 degrees of sweep and two vertical tails. Although the engines are near the aircraft centerline, flight tests showed roll rates from differential throttles up to 5 deg/sec over a significant part of the flight envelope. Pitch control using throttles alone was available but inadequate below 200 knots.

With yaw augmentation systems off, three test pilots found that differential thrust alone provided good bank angle control as well as roll rate response. With nose up trim, and stick and rudder centered, they were able to exercise crude altitude and heading control.

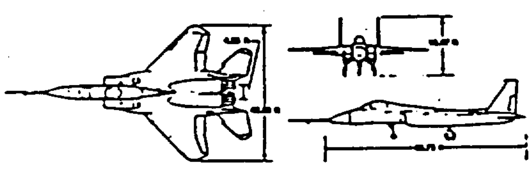


Figure 1. F-15

Lear 24 throttles-only. The twin engine executive jet shown in Figure 2 has a T-tail and fast responding engines. In-flight thrust control of roll rate was effective, reaching 20 deg/sec near 250 knots. Pitch response due to thrust was very poor, due to the high engine location which caused a nose down moment from a thrust increase. The aircraft thus had to be flown using its inherent speed stability, leaving an undamped phugoid and a pitch rate response of approximately 0.2 deg/sec.

Test pilots tried to use bank angle to damp the phugoid with inconsistent results. Only when electric pitch trim was made available could a tractable approach be flown. As with all in-flight tests, no landings were attempted using throttles alone.

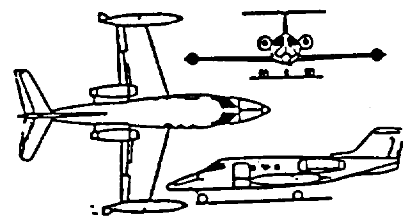


Figure 2. Lear 24

Cessna 152. The single-engine light trainer shown in Figure 3 has a high wing and conventional tail. Rudder was required for directional control, but the throttle provided adequate control of the steady-state speed stability of the aircraft.

Phugoid excitation required damping by pilot application of throttle which was unnatural but easily learned. Pilots stated that they could have landed the aircraft using throttle and rudder alone.

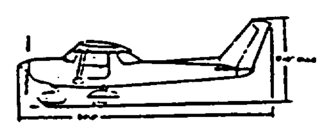


Figure 3. Cessna 152

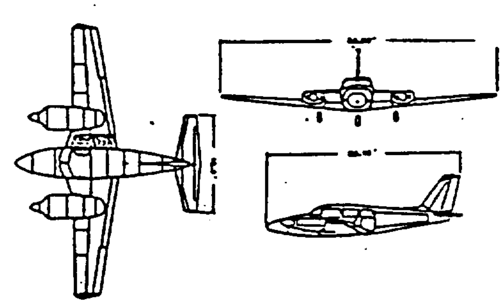


Figure 4. Piper PA-30

Piper PA-30. This twin-engine aircraft shown in Figure 4 has a low wing and conventional tail. The roll control power was considerable but very non-linear, requiring extensive pilot adaptation. Roll rates were observed near 10 deg/sec but bank angle control was very difficult.

Pitch control from throttles-alone came from the inherent speed stability of the aircraft. Pilot damping of the phugoid was difficult and would have made landing under throttles only control dangerous. Providing electric pitch trim alleviated the problem to a great degree, and it was possible for two pilots to simulaneously control flight in this manner.

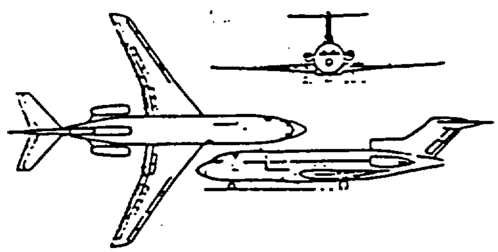


Figure 5. Boeing 727

Ground Simulations

Full six degree-of-freedom simulations of large aircraft were performed at NASA Dryden to investigate throttles-only control. The Boeing 727 and the Boeing 720 represent three- and four-engine variants of passenger jet aircraft as shown in Figures 5 and 6. Although considerable differential thrust exists for roll control, both aircraft have slow responding engines making damping of the dutch roll and phugoid modes difficult. Differential thrust was not used to control pitch attitude. A view of the simulator scene for approach and landing is shown in Figure 7.

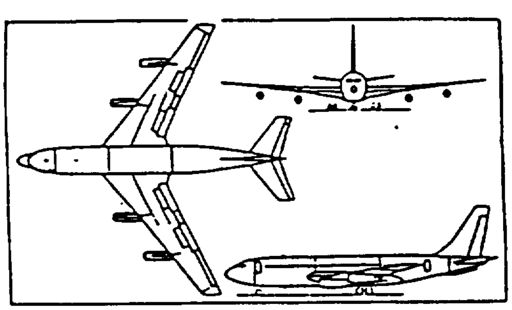


Figure 6. Boeing 720

Boeing 727. This three engine transport has a swept engine and a T-tail. From a level flight trimmed condition, throttles moved in concert produced about 0.5 deg/sec in pitch, and throttles moved differentially produced 3 deg/sec roll response. Electric trim was required to damp the phugoid sufficiently for a landing on a "field." Without the trim extensive practice was required (over 2 hours).

When two pilots divided the control task by axis, they could successfully land the aircraft but not on a runway. Considerable care was required not to excite the dutch roll and phugoid modes. Pilots found this unnatural and especially difficult when approaching touchdown. Level 3 ratings require some sort of stability augmentation for safe flight.

Boeing 720. This four engine jet transport has a low wing with 35 degrees of sweep. Gross attitude control in both the longitudinal and lateral axes was possible without the use of electric trim. If pilots split the tasks and used electric trim, a runway landing could be made.

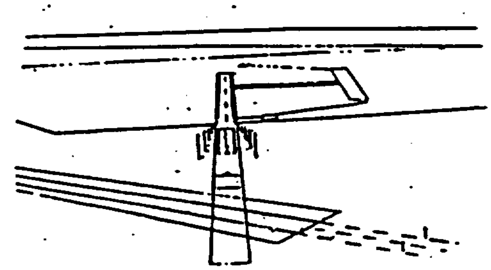


Figure 7. Simulation Visual

An augmentation system to control flight path angle, γ, was developed to convert conventional pilot control inputs into throttle motions. Using this system a single pilot could successfully land the aircraft with practice on a simulated runway. There still was a tendency for pilot-induced oscillations (PIO) near the ground, especially in the lateral axis, and control inputs for stability were requied to be very small to avoid exciting the oscillatory modes.

Control Law Development

An ideal propulsion-only flight control system (POFCS) would provide acceptable handling qualities in the event of any type of flight control malfunction. Essentially, however, the implemented control law must perform three functions. First, it must use the control power of the engines, in concert with the stability derivatives of the aircraft, to provide longitudinal and lateral flight path control under a variety of flight control failures throughout the flight envelope. This is difficult to achieve when the aircraft is far from a trimmed condition, or when the aircraft must descend rapidly under conditions of low thrust.

Second, the control law must allow pilot inputs and pilot-directed configuration changes without exciting large oscillations of the dutch roll or phugoid. Pilots who are trying to perform a high gain task with a low bandwidth control, such as landing an aircraft, must relearn how to generate lead compensation. There are no handling qualities specifications to cover this situation. The pilot must accept watching the throttles move with stick input and must resist the natural tendency to pull power off during the flare. Such a control law must be integrated with actual pilot inputs at each step during its development.

Finally, the engine time constants must be fast enough to control any oscillatory mode which could preclude a successful landing. Other relatively fast modes, such as the short period, must be stable. This condition simply states that the configuration with failed controls, at points in the flight envelope from landing to cruise conditions, must be stabilizable (the uncontrollable poles must be stable).[4]

Boeing 720 Control Law 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. The augmentation control law for each axis was developed from a baseline aircraft configuration (gear-up, flaps-up, 10,000 ft pressure altitude, 160 knots, 190,000 lbs). For this baseline Level 2 pilot ratings were recorded for each axis given the task of landing on a runway. The baseline gains were

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

where other potential gains, such as K_r, were tried but not kept in the baseline since the pilots noted no significant improvement in aircraft response.

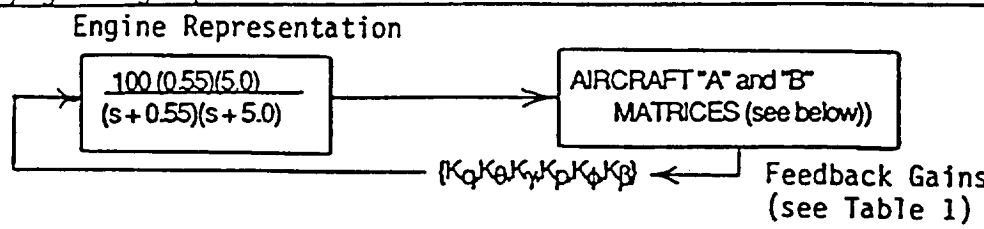
Ten configurations were then flown with the above set of baseline gains and the results are summarized in Table 1. The worst ratings, those for configurations 5, 8, and 9, were for those configurations farthest from the baseline weight of 190,000 lbs. The poor rating (8) for configuration 3 can be considered an anomaly based on pilot comments of full stick throw and starting in too close. Otherwise, pilot comments for poorly rated configurations indicate the problem to be severe lateral oscillations that cannot be damped predictably by pilot inputs.

Table 1. Cooper-Harper Ratings for Boeing 720 Simulation to Touchdown
Baseline: 190000 lbs, 10000 ft, gear-up, flaps-up, 160 knots, light turbulence
$\{K_q, K_\theta, K_\gamma, K_p, K_\phi, K_\beta\} = \{-4,0,-1,0.5,0.5,1.0\}$

#	CONFIGURATION Altitude (ft x 10^3)	Weight (lb x 10^3)	Speed (knots)	Gear/ Flaps	Pilot Rating	Comments
1.	4	140	160	Up/Up	5-6	Landed long; needed small input
2.	4	190	160	Up/Up	4-5	OK!
3.	10	190	160	Up/Up	8	In too tight; kept hitting full stick thrôw; no control power could not get back from 30° bank; excited phugoid.
4.	10	140	160	Up/Up	6	Kept VVI above 500 fpm to keep control power; OK!
5.	4	140	160	Up/50°	9,7	Crashed! Initial excitation caused undampable dutch roll. Second try better but could not get in loop safely.
6.	4	190	160	Up/50°	7	Could not get in control loop safely laterally; pulsed inputs.
7.	4	190	130	Up/50°	5	Small inputs required; excellent control; could damp roll.
8.	4	140	130	Up/50°	8	Controlled crash off of runway!; open loop only; very difficult to damp dutch roll; pulsed inputs did not help.
9.	4	140	130	Down/50°	7	Controlled touchdown off runway; same comments as #8.
10.	4	190	130	Down/50°	5	Excellent! Same comments as #7.

Classical Analysis. A linearized model of configuration 1 of Table 1 is shown in Figure 8. A two dimensional root locus for the lateral modes of response, varying K_p and K_ϕ, is illustrated in Figure 9. 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.



"A" =

DIMENSIONAL DERIVATIVES - A MATRIX

	U	ALP	V	THA	H	P	R	BTA	PHI
U	-.06371	-1.10007	.00015	.00000	.00000	.00000	.00000	.00063	.00000
ALP	1.00000	-.82605	-.00078	.00000	.00000	.00000	.00000	.00000	.00000
V	.00000	13.72051	-.01342	-32.16187	.00000	.00000	.00000	.13790	.00000
THA	1.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
H	.00000	[illegible]	.00000	[illegible]	.00000	.00000	.00000	.00000	.00000
P	.00000	.00000	.00000	.00000	.00000	-.92787	.52784	-2.30484	.00000
R	.00000	.00000	.00000	.00000	.00000	-.00813	-.21198	.72549	.00234
BTA	.00000	.00000	.00000	.00000	.00000	.11158	-.97831	-.11503	.11182
PHI	.00000	.00000	.00000	.00000	.00000	1.00000	.11041	.00000	.00000

"B" =

DIMENSIONAL DERIVATIVES - B MATRIX

[illegible]	[illegible]	[illegible]	[illegible]
.00000001	.00000145	.00000148	.00000061
-.00000012	-.00000012	-.00000012	-.00000012
.00022787	.00022787	.00022787	.00022787
.00000000	.00000000	.00000000	.00000000
.00000000	.00000000	.00000000	.00000000
.00000050	.00000041	-.00000041	-.00000000
.00000091	.00000525	-.00000525	-.00000091
.00000000	.00000000	.00000000	.00000000
.00000000	.00000000	.00000000	.00000000

Figure 8. Linearized Model of Configuration 1

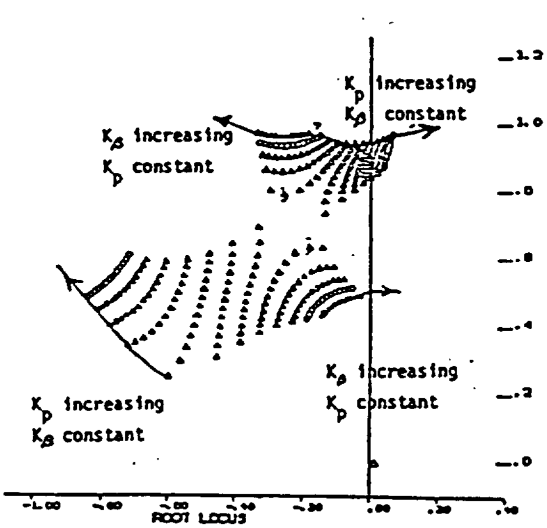


Figure 9. Lateral Root Locus

Optimal Control Analysis. An optimal control law was developed by Azzano for the linearized system shown in Figure 10. In his development a pilot command is directly translated into a single state-variable command. All four throttles were independently controlled, taking advantage of the vertical offset of the engines to allow pitching moments independent of airspeed change.

The design condition for the optimal controller was 4000 ft altitude, 160000 lbs, 175 knots, gear-up, and flaps-up. The engine lag was modeled as a second order system. Azzano's final design, incorporating many limiters, is shown in Figure 11.

$$
A = \left[\begin{array}{ccccc|ccccc}
-.89 & -.98 & .00011 & 0 & 0 & & & & & \\
1 & -.79 & -.00065 & 0 & 0 & & & & & \\
0 & 13 & -.012 & -32 & .00006 & & & \text{—} & & \\
1 & 0 & 0 & 0 & 0 & & & & & \\
0 & -312 & 0 & 312 & 0 & & & & & \\
\hline
 & & & & & -.99 & .55 & -3.0 & 0 & 0 \\
 & & & & & -.053 & -.21 & .76 & .0021 & 0 \\
 & & \text{—} & & & .11 & -.98 & -.11 & .10 & 0 \\
 & & & & & 1 & .11 & 0 & 0 & 0 \\
 & & & & & 0 & 1.01 & 0 & 0 & 0
\end{array}\right]
$$

Mode	Weight
Short Period	1
Phugoid	10
Dutch Roll	200
Spiral	.5
Roll	1

Design LQR Weights

$$
B = \begin{bmatrix}
.000051 & .00012 & .00012 & .000051 \\
-.000009 & -.000009 & -.000009 & -.000009 \\
.020 & .020 & .020 & .020 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
.000068 & .000040 & -.000040 & -.000068 \\
.00080 & .00047 & -.00047 & -.00080 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
$$

$$
\begin{array}{cc}
 & \begin{array}{cccccccc} q & \alpha & V & \theta & p & r & \beta & \phi \end{array} \\
K = & \begin{bmatrix}
594 & -467 & 2.6 & 780 & 93.9 & 584 & 91.6 & 125 \\
1750 & -1290 & 2.1 & 2345 & 55.3 & 344 & 54.0 & 73.4 \\
1750 & -1290 & 2.1 & 2345 & -55.3 & -344 & -54.0 & -73.4 \\
594 & -467 & 2.6 & 780 & -93.9 & -584 & -91.6 & -125
\end{bmatrix}
\end{array}
$$

Figure 10. Matrices for LQG Model

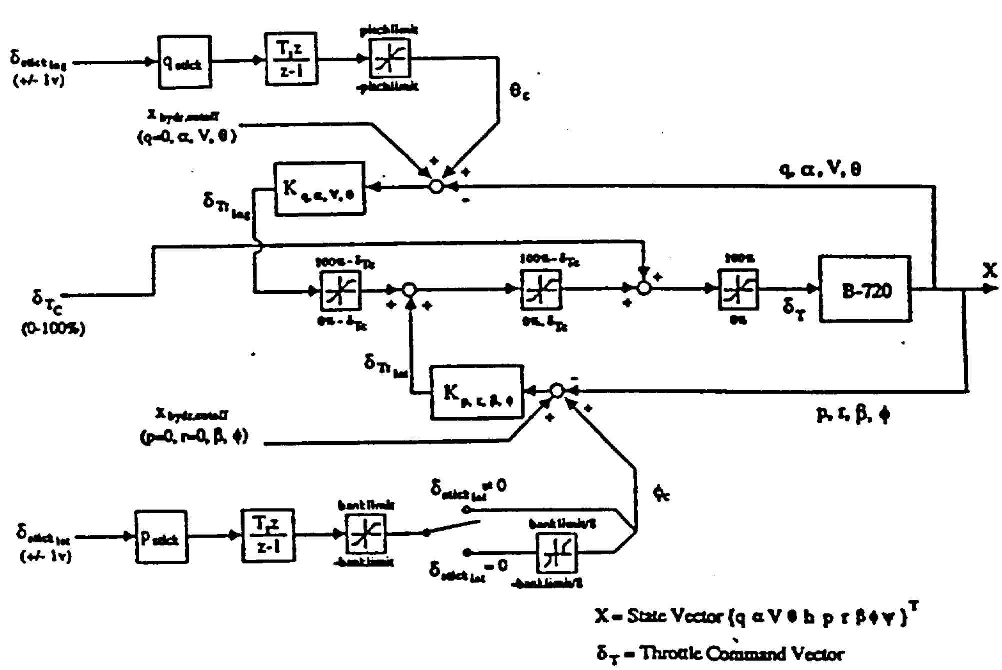


Figure 11. Linearized LQG Model for configuration 1 at 175 knots

Although open- and closed-loop responses of the ground simulator and the linear system matched reasonably well for small inputs, pilots found the optimally-designed augmentation system difficult to use in a few key areas. Pilots described returning to level flight coming out of a turn as unpredictable and velocity change as 'mysterious'. The flare maneuver was not responsive enough. They typically complained of a "wandering bank angle" and had a tendency to excite pilot induced oscillations even when the controller gains were reduced by changing the weights on the cost function.

The augmentation system designed using optimal control theory performed poorly when other failed configurations were tested. This was expected for this type of controller.

Conclusions

The results of in-flight operation using simulated failed flight controls for a variety of different aircraft show that the throttles can be effective low bandwidth controllers. When throttle controllability is a problem, electric pitch trim and/or rudder input may be required for safe flight. Pilot learning is rapid, but performance during high gain tasks such as touchdown is not predictable and requires augmentation. The pilot has difficulty generating lead compensation for a low bandwidth, lightly damped control system.

Ground simulation of a Boeing 720 four-engine jet transport showed that a simple augmentation system could assist the pilot. Problems were apparent, however, when the failed configuration being flown deviated from the design failed configuration, with pilot rating being most sensitive to aircraft weight and center of gravity.

Classical analysis highlighted the problem to be two lightly damped lateral modes which became unstable if either the roll rate or the beta feedback gains were increased from a nominal setting. Flight off of the design condition exacerbated the problem. The pilot found it difficult to control the off-design flight configuration in the lateral mode.

An augmentation scheme designed using optimal control was successful under pilot control but required many limiters and adjustments of design weights. The performance away from design condition was not acceptable.

Work is in progress to use quantitative feedback theory to build a simple compensator for the failed flight control configurations which will be more robust with respect to off-design conditions.

Acknowledgment

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