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NASA Dryden Flight Research Center

"Propulsion Controlled Aircraft Design and Development"

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Propulsion Controlled Aircraft Design and Development

Edward A. Wells
James M. Urnes, Sr.

McDonnell Douglas Aerospace

This paper describes the design, development, and ground testing of the Propulsion Controlled Aircraft (PCA) flight control system. A backup flight control system which uses only engine thrust, the PCA system utilizes collective and differential thrust changes to steer an aircraft that experiences partial or complete failure of the hydraulically actuated control surfaces. The objective of the program was to investigate, in flight, the throttles-only control capability of the F-15, using manual control, and also an augmented PCA mode in which computer-controlled thrust was used for flight control. The objective included PCA operation in up-and-away flight and, if performance was adequate, a secondary objective to make actual PCA landings.

The PCA design began with a feasibility study which evaluated many control law designs. The study was done using off-line control analysis, simulation and on-line manned flight simulator tests. Control laws, cockpit displays and cockpit controls were evaluated by NASA test pilots. A flight test baseline configuration was selected based on projected flight performance, applicability to transport and fighter aircraft, and funding cost. During the PCA software and hardware development, the initial design was updated as data became available from throttle-only flight experiments conducted by NASA on the F-15. This information showed basic airframe characteristics that were not observed in the F-15 flight simulator and resulted in several design changes. After the primary objectives of the PCA flight testing were accomplished, additional PCA modes of operation were developed and implemented. The evolution of the PCA system from the initial feasibility study, control law design, simulation, hardware-in-the-loop tests, pilot-in-the-loop tests, and ground tests is presented in this paper

DESIGN OF THE PCA SYSTEM

F-15 Simulation Model Development

Early in the design process, accurate simulation models of the aircraft aerodynamic, control system and propulsion characteristics were needed for both off-line and real-time development. The existing aerodynamic model needed to be revised to include the latest modeling data and then was judged to be adequate for both environments. The existing control system and propulsion system models also required modifications.

For the PCA flight demonstration, the F-15 control system was required to keep the control surfaces motionless until a pilot input was made. In the off-line simulation this requirement could be easily met, but the real-time simulation needed to be modified to represent the flight test configuration. On the F-15 aircraft, disengaging the pitch, roll and yaw CAS, and setting the pitch and roll ratios to emergency effectively eliminates all feedback commands to the control surface servo-actuators and prevents the control surfaces from moving without pilot inputs. These features needed to be incorporated into the real-time simulation. Additionally, the engine inlet ramps can move during flight and produce a pitching moment. On the F-15 aircraft the engine inlets can be set to an emergency mode to keep them in a fixed position. This feature also was incorporated into the real-time simulation.

Due to the unique nature of our propulsion-only control demonstration, none of the existing propulsion models could be used for development. Because we required accurate, independent left and right Pratt and Whitney +1128 engine models that could be run in a real-time simulation, a totally new simulation propulsion model was developed. The Pratt and Whitney State Of the Art Performance Program (SOAPP) for the 1128 engine was used to generate gross thrust and ram drag engine response time histories for a large set of PLA step inputs over the PCA design envelope. These time histories were then fit using a first order lag filter with a variable time constant. Engine rate limits were incorporated and the result was a non-linear engine model that could be run real-time and was accurate throughout the PCA design envelope.

PCA Cockpit Controller Development

In order to demonstrate and test the propulsion-only control concept in the manned simulator, the type of PCA cockpit controller used by the pilot needed to be addressed. Use of the center control stick was eliminated because control column motion would require an automatic cancellation of the mechanical control system outputs in order to maintain fixed control surfaces during the flight test. There were no other suitable controllers available in the F-15 cockpit, so three possibilities were examined; a side mounted force joystick, a side mounted displacement joystick, and a pair of side mounted thumbwheels. Some key characteristics of the three remaining candidates are listed below.

- Miniature Force Joystick
  - +/- 3.1 lbs full scale
  - spring loaded to center
  - 1 inch stick handle length
- Miniature Displacement Joystick
  - +/- 30 deg full scale
  - spring loaded to center
  - 1.5 inch stick length
- Thumbwheels
  - +/- 175 deg full travel
  - not spring loaded to center
  - detent at center of travel

C-3.

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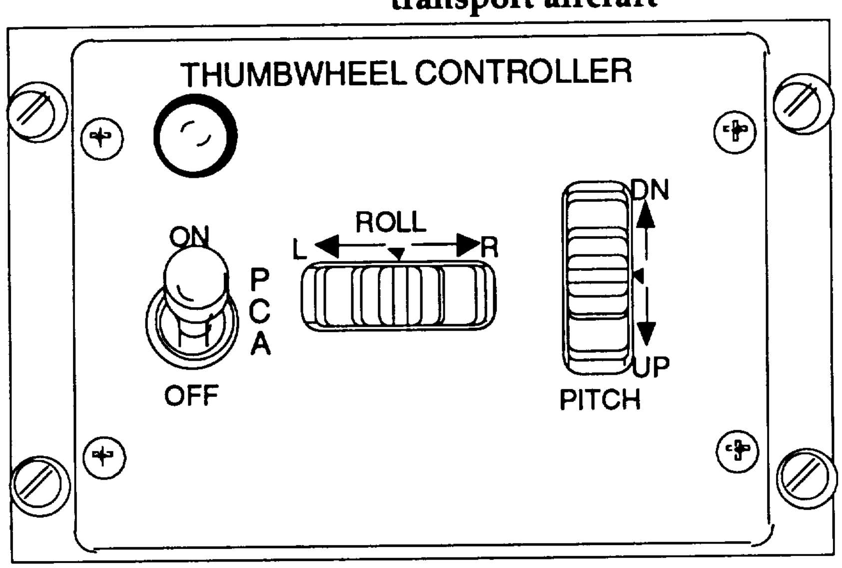
Joystick - Thumbwheel Comparison

The joystick and thumbwheels were evaluated in a series of simulation tests. Two types of joysticks were tested: force sensing and displacement sensing. With both types of joystick, however, NASA test pilots found that precise control was very difficult. Precise inputs were much easier to achieve using the thumbwheels and they emerged from the tests as the clear favorite. The Thumbwheel Controller Panel (TCP) is shown in the figure below and consisted of two thumbwheels mounted just aft of the throttles in the left cockpit console. One thumbwheel controlled flight path angle and the other controlled bank angle. Each thumbwheel had a detent at zero so the pilot could easily reference his commands from the wings level, zero flight path condition.

Joysticks	**Thumbwheels**
Spring-loaded to center **Small size of handle** **Small range/poor resolution** **Incremental command hard to attain**	**Thumbwheels remain where set** **Thumbwheels used in prev pgm** **Large range/good resolution** **Incremental commands easy**
Virtually no pitch/roll isolation	**Separate pitch and roll thumbwheels**
Ability to hold command during flight questioned	**Not required to hold thumbwheel so aircraft motion does not affect command, Similar controls used in transport aircraft**



Thumbwheel Control Panel

PCA Control Law Development Trade Studies

Several trade studies were performed during the development of the PCA control laws. One study focused on the importance of augmenting the phugoid frequency versus the phugoid damping. Because flight data had shown that it was very difficult to damp phugoid oscillations using manual throttle inputs, augmenting the phugoid damping was one of the early design goals. The value of augmenting the phugoid frequency, however, was an unknown and the feasibility study examined the trade off between phugoid damping and frequency. Manned flight simulation tests were performed and it was found that the greatest pilot rating improvement was achieved by maximizing the phugoid damping. Other trade studies addressed which aircraft state would be commanded: flight path angle vs. flight path angle rate for the longitudinal command, and bank angle vs. roll rate for the lateral command. Flight simulation tests with NASA pilots were used and the results showed that flight path and bank angle commands were more desirable. These results are summarized below.

Variations Tested	Parameter Yielding Improvement	Cooper-Harper Rating Improvement
Flight Path Angle vs Flight Path angle Rate Stick Command	Flightpath Angle	3
Low vs High Phugoid damping	High phugoid damping	3
Low vs high Phugoid Frequency	Neither	-
Bank Angle vs Roll Rate Stick command	Bank Angle	1

Results of Four Trade Studies

PCA Control Law Development - Longitudinal Feedback Trade Study

The feasibility study also examined the selection of longitudinal feedback parameters. Flight path angle and flight path angle rate were chosen for three reasons: (1) the HUD display uses the same reference (termed Flight Path Marker or Velocity Vector); (2) these signals could provide augmentation for both phugoid damping and frequency; (3) most current fighters and transports have these parameters available in the flight control computer.

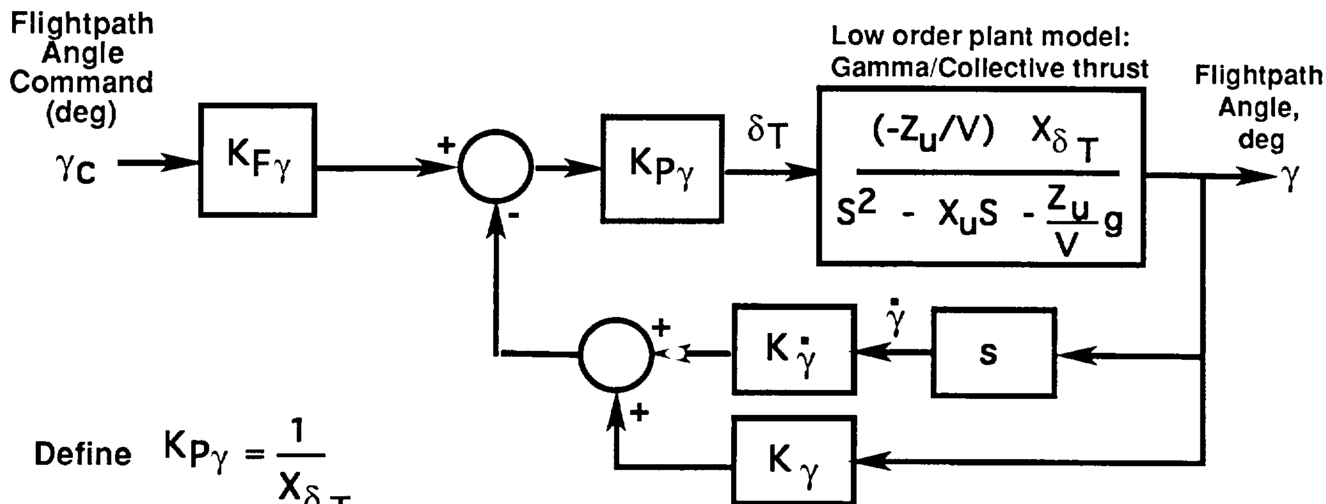
Phugoid Dynamics

Feedback (to thrust)	Low Speed		High Speed	
	Damping	Frequency	Damping	Frequency
Flightpath Angle	—	Good	—	Fair - large gain req'd
Flightpath Angle Rate	Good	—	Fair - large gain req'd	—
Pitch Rate	Good - Wings Level		Fair - large gain req'd	
Airspeed	Good - Need Reference		Good - Need Reference	

Results of Longitudinal Feedback Selection Trade Study

Longitudinal Model Design

Once the requirements were defined, design of the control law gains could begin. The linear, low order model of the airframe is shown below in the upper figure. As shown in the lower figure, the longitudinal gains were selected to provide phugoid damping of 0.7 and frequency of 0.18 radians/second at the design point of 188 knots at 3000 feet Mean Sea Level (MSL). After incorporating the control law into the linear off-line simulation, the final values of damping and frequency were 0.57 and 0.14 respectively.



Define $K_{P\gamma} = \frac{1}{X_{\delta T}}$

Actual Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = K_{F\gamma}\frac{G}{1+GH} = \frac{K_{F\gamma}(-Z_u/V)}{s^2 + (-X_u - \frac{Z_u}{V}K_{\dot\gamma})s + (-\frac{Z_u}{V}g - \frac{Z_u}{V}K_\gamma)}$$

Linear, Low Order Longitudinal Model

Actual Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = \frac{K_{F\gamma}(-Z_u/V)}{s^2 + (-X_u - \frac{Z_u}{V}K_{\dot\gamma})s + (-\frac{Z_u}{V}g - \frac{Z_u}{V}K_\gamma)}$$

Desired Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = \frac{W^2}{s^2 + 2ZW + W^2}$$

Equate Actual and Desired Denominator

$$s^1 = (X_u + \frac{Z_u}{V}K_{\dot\gamma}) = -2ZW \longrightarrow K_{\dot\gamma} = -(2ZW + X_u)\frac{V}{Z_u}$$

$$s^0 = (\frac{Z_u}{V}g + \frac{Z_u}{V}K_\gamma) = -W^2 \longrightarrow K_\gamma = -(W^2 + \frac{Z_u}{V}g\,\frac{V}{Z_u} = -(W^2\frac{V}{Z_u} + g)$$

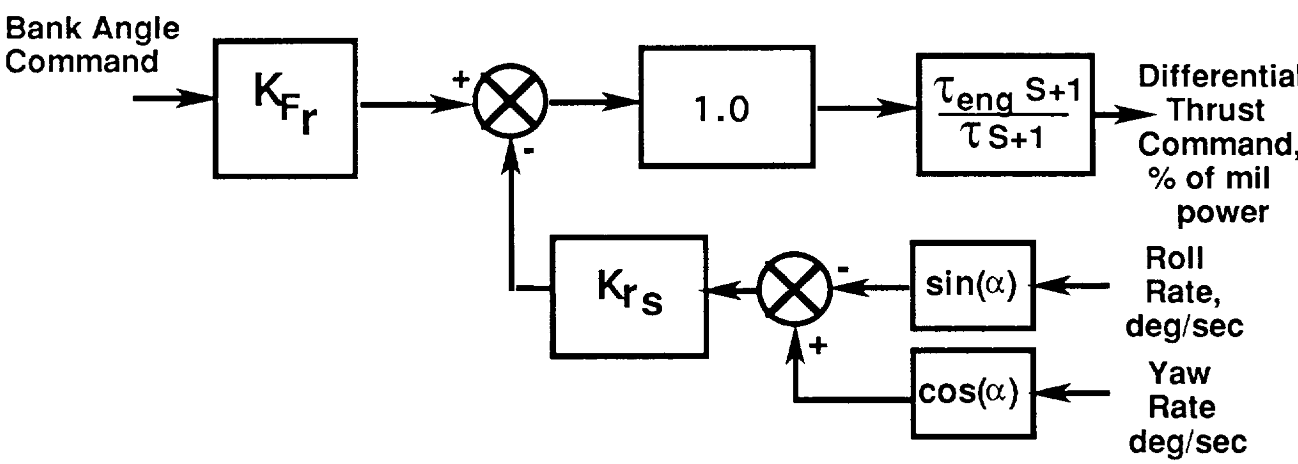
Equate Actual and Desired Numerator

$$\frac{Z_u}{V}K_{F\gamma} = -W^2 \longrightarrow K_{F\gamma} = -W^2\frac{V}{Z_u}$$

Longitudinal Gain Determination

PCA Control Law Development - Lateral Axis

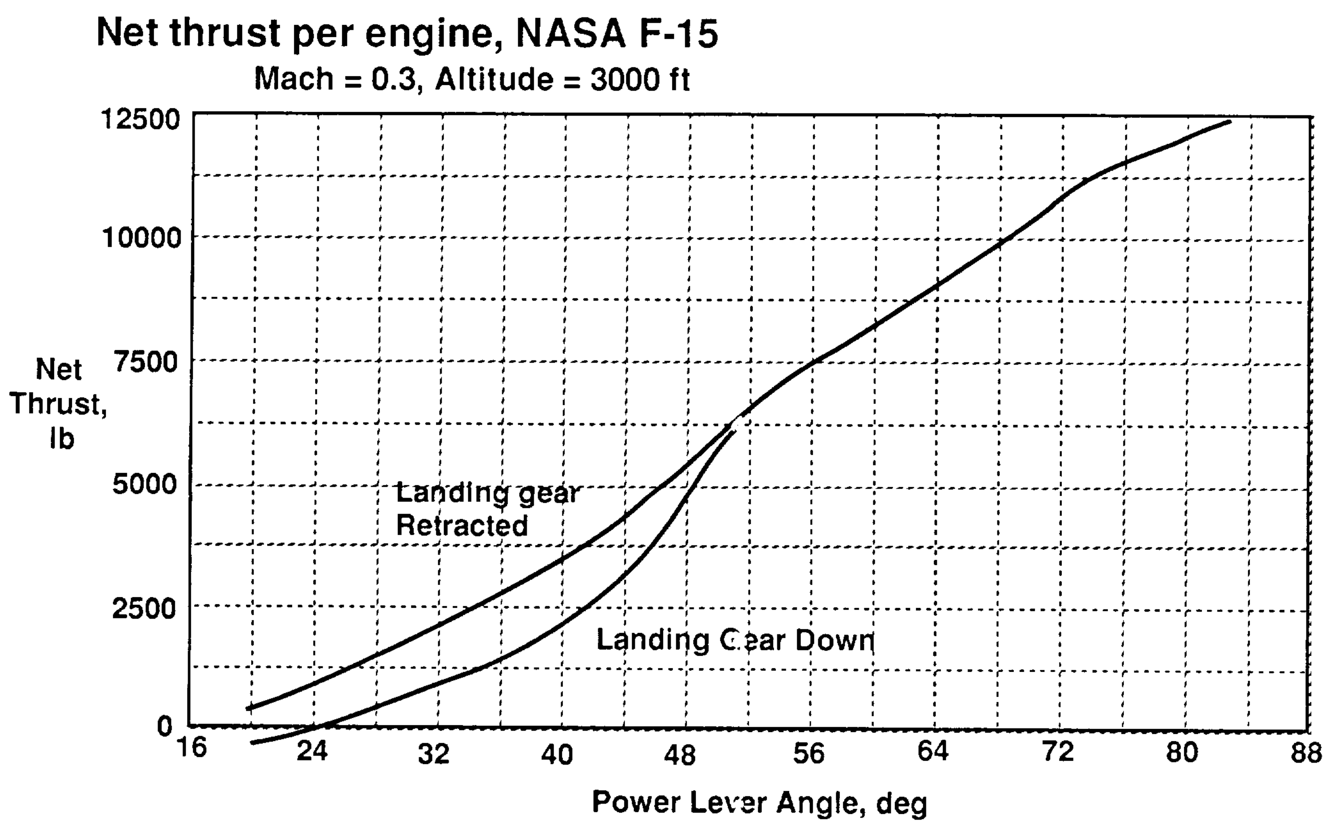
For the lateral control law, stability axis yaw rate was the feedback incorporated to dampen the dutch roll mode and provide a turn rate reference. The gain was selected to maintain a flat frequency response for as high a frequency as possible. Additionally, a lead-lag filter was developed using an engine time constant of 1.3 seconds. Schedules were developed to automatically adjust the control law gains for weight and airspeed variations. This control performed well in the F-15 linear simulation.



Lateral Control Law Block Diagram

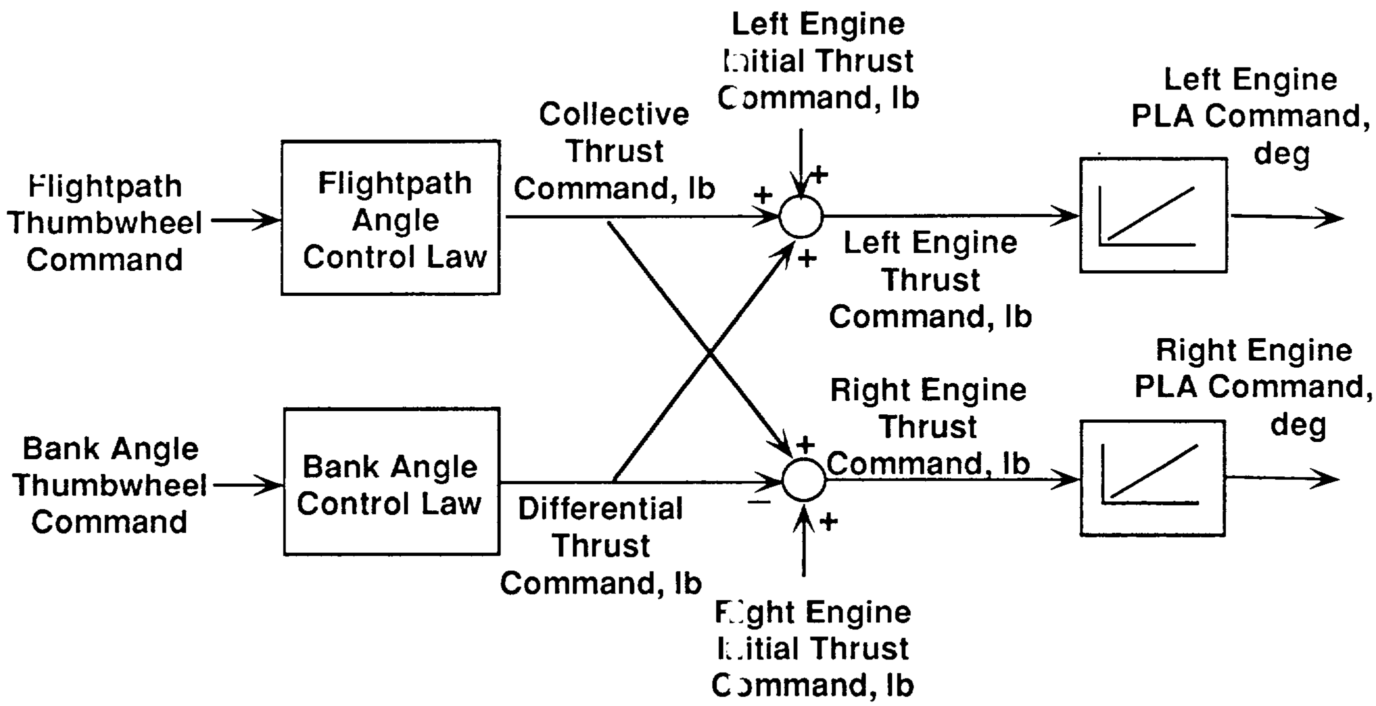
Engine thrust versus power lever angle

In order to evaluate the control in the more complete non-linear simulation, a thrust to PLA conversion function was needed. This was due to the fact that the control law was designed to generate thrust commands, but the engine digital controllers were designed to accept PLA commands. This function was developed using design point data (188 knots at 3000 feet) from the engine model. With the landing gear retracted, the thrust per engine varies from about 500 lb at idle to about 12,000 lb at intermediate power (the maximum limit for PCA operation). With the landing gear down, there is a feature called idle area reset (IAR) that, to reduce thrust, opens the nozzle as PLA is reduced below 50 deg. The effect of this IAR is to make the thrust non-linear and to have a relatively steep slope in the PLA range from 40 deg to 50 deg. This is the PLA range for most PCA operation.



Thrust-PLA Function Integration into PCA Control Law

The thrust versus PLA function from the previous page was integrated into the PCA control laws as shown below. The resulting control law performance in the non-linear simulation was compared to linear results. In almost all cases, an excellent match was obtained between the non-linear simulation and the linear results and was ready to be tested with NASA pilots in the manned simulator.



PCA Control Law - Sensitivity Analysis

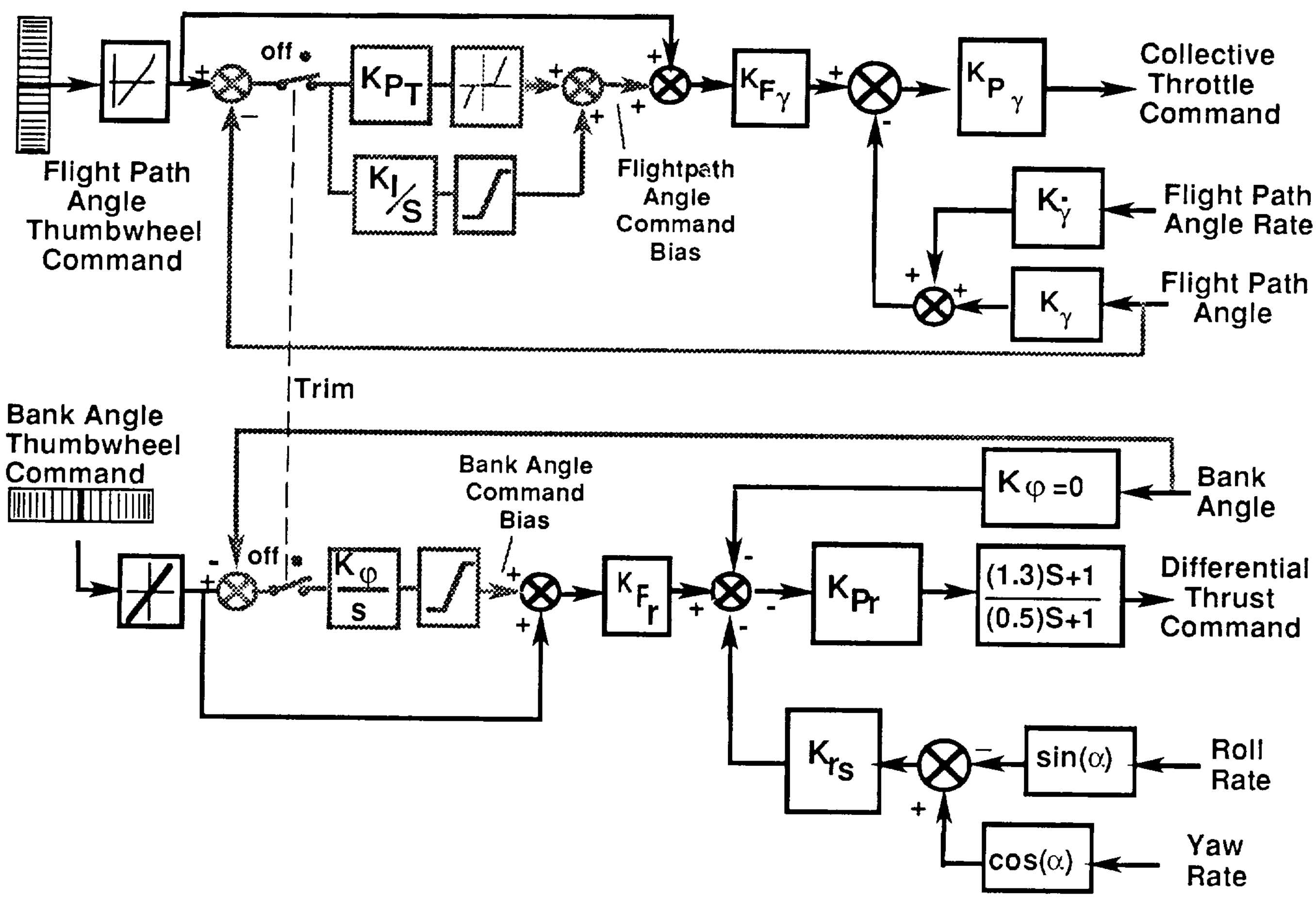
Using the manned simulator, a study was conducted to determine how sensitive PCA performance was to a number of parameter variations. The effects of fifteen parameters were examined during tests with two NASA pilots. The result was that performance was not significantly degraded for any of the parameter variations except one: vertical velocity error. Because the error that was introduced was very large (pilots had not seen errors that large in flight), the system was judged to be sufficiently robust to the parameter variations.

PCA Control Law -Trim requirement

The simulator tests also revealed a need for a PCA trim control law. In the event that the system is engaged while the aircraft is not in trim, the PCA trim control law will eliminate any biases between the commanded flight path and bank angles and the actual aircraft states. These biases could be removed by adding forward path integrators to the baseline PCA control law, but the feasibility study showed that this type of addition could result in larger overshoot, longer settling time, and reduced performance overall. In the absence of some means to eliminate these biases, the aircraft would have to be trimmed and have the command thumbwheels at the zero detent position when the system was coupled in order for level flight path and bank angles to result from zero thumbwheel inputs.

PCA Control Law with Trim

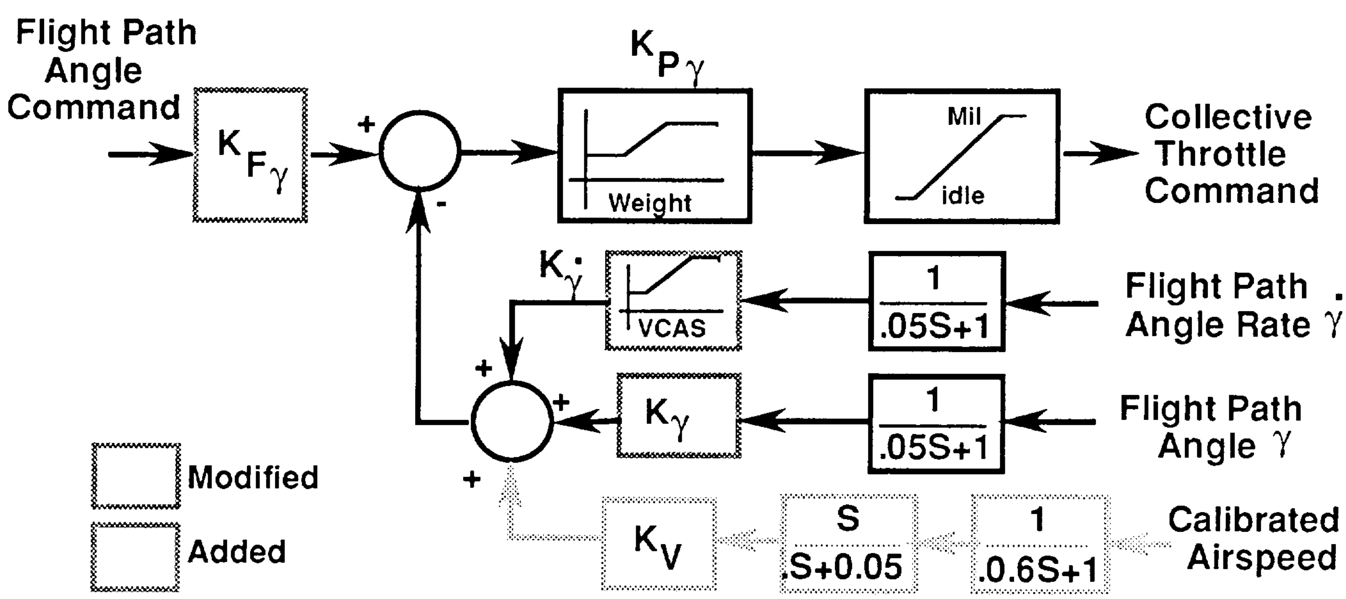
A two step trim mode was developed for the PCA control law. The trim mode would execute when the PCA system was initially coupled and then turn itself off when the aircraft was sufficiently trimmed. For this mode, a proportional plus integral path was added to the baseline longitudinal control law and an integral path was added to the lateral control law. These trim paths were activated when the system was coupled and deactivated when the flight path error, flight path error rate, bank angle error and bank angle error rate were within specified limits. Additionally, the trim paths could be reactivated by the pilot at any time if he felt that biases were present in the system, or he could deactivate them if he felt that the system biases were acceptable.



Inlet Airflow Effect

During the PCA control law development, NASA was performing F-15 manual throttle control flight experiments. By measuring the flight path response for PLA changes, these experiments revealed a transient phase reversal in the pitch axis. When the pilot would apply a negative or nose down throttle step input, the aircraft would initially pitch up before pitching down. This phase reversal was more pronounced at weights below approximately 32500 pounds and airspeeds greater than approximately 160 knots. It was not modeled in current F-15 simulations, but further investigations indicated that the reversal was due to the engine inlet airflow. Such an effect had been identified in a McDonnell Aircraft report prepared for the Air Force titled "Assessment of Installed Inlet Forces and Inlet/Airframe Interactions; Final Report - July 1976". Working closely with NASA, a pitching moment increment as a function of PLA, was developed from the flight and wind tunnel data, shown in the flight test paper. As shown in that paper, this pitching moment increment resulted in a satisfactory comparison between the six-degrees-of-freedom simulation and the flight data.

The existence of this phase reversal caused a re-assessment of the longitudinal control law. A velocity feedback path was added to improve PCA performance at the higher airspeed conditions where the inlet airflow effect was important. Characteristics such as the reversal due to inlet airflow have relatively minor effect when the normal flight control system is operating, but have a more pronounced impact during propulsion-only control.

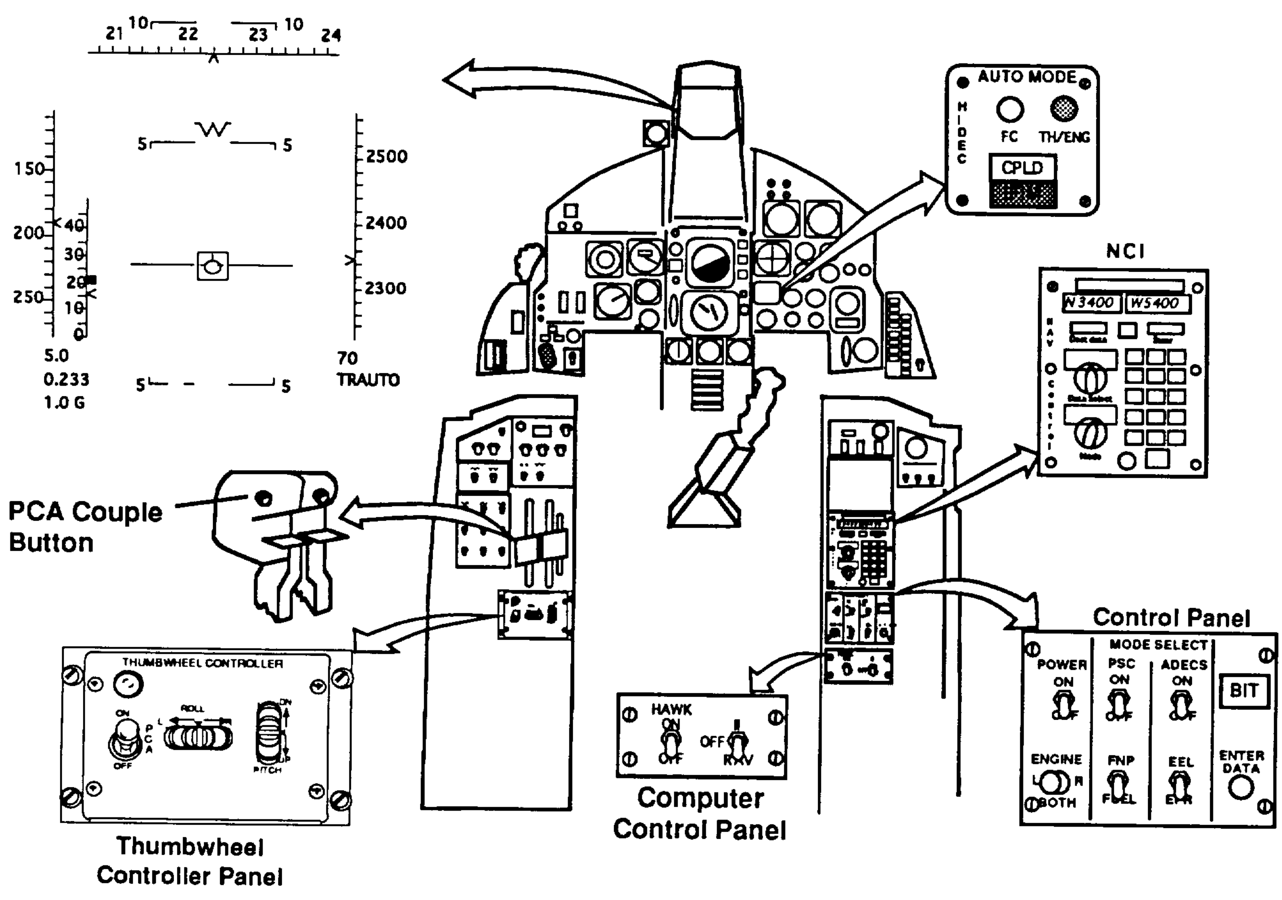


Control Law Modification for Inlet Airflow Effect

PCA Cockpit Control and Display Development

The pilot was able to interact with the PCA demonstration system through several cockpit components. Shown below is the layout of the test F-15 cockpit. The system was armed by setting the appropriate switches on the Computer Control, PSC Control and Thumbwheel Controller Panels. When the system was armed and uncoupled, the Navigation Control Indicator (NCI) panel could be used by the pilot to change various system parameters. Coupling was accomplished by depressing the IFF button on the left throttle quadrant. The pilot could uncouple the system in a number of ways: depressing the couple button a second time; changing a switch position on the Computer Control, PSC Control or Thumbwheel Controller Panels; moving the control stick, rudder pedals or throttles.

The PCA demonstration provided two displays to the pilot, one on the HIDEC upfront panel and the other on the HUD. The white CPLD light on the HIDEC upfront panel illuminated when the PCA system was coupled and the red IFIM light illuminated if the In-Flight Integrity Management software detected a system failure. The green TH/ENG light was illuminated when the PCA switch was on.

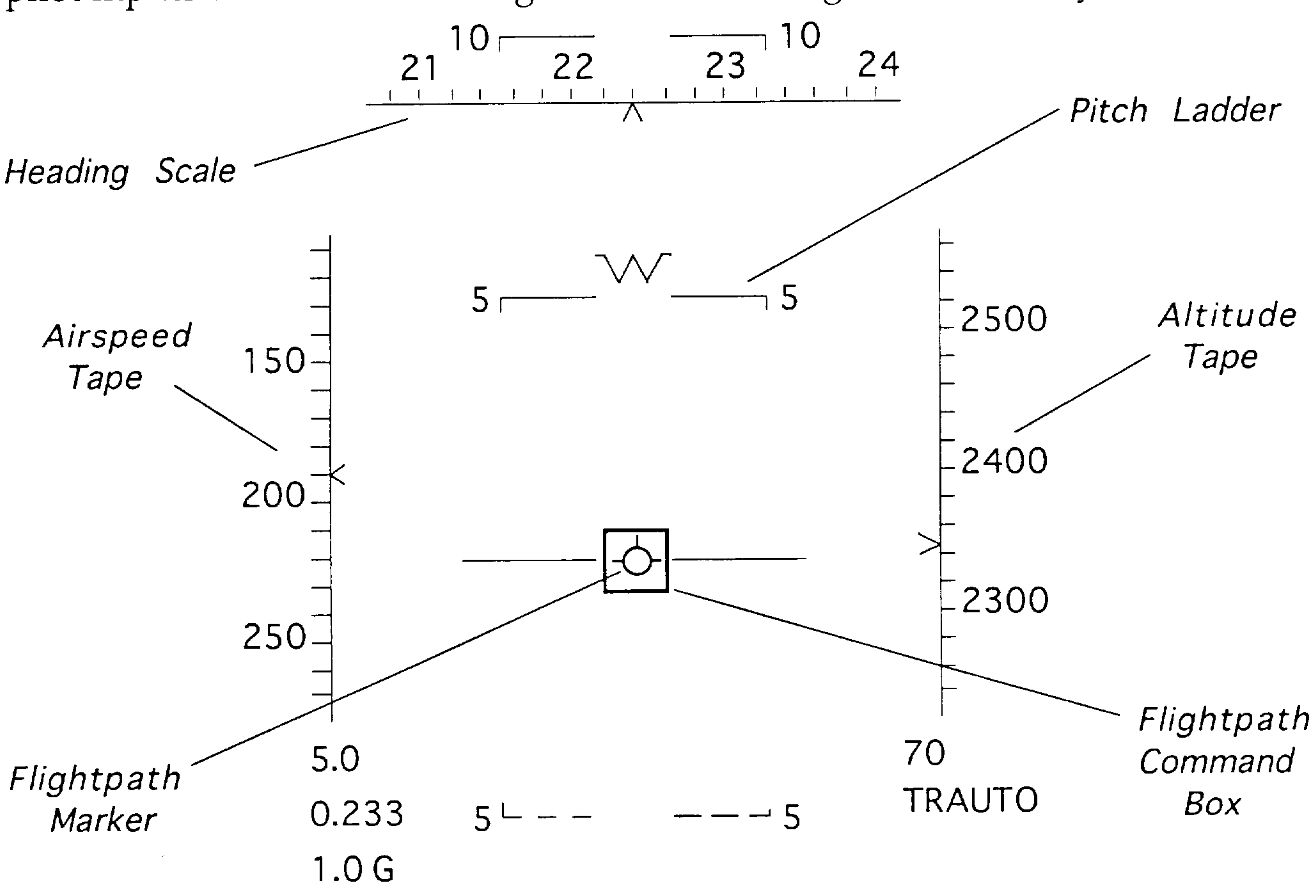


F-15 Crew Station for PCA Testing

PCA HUD Display

The PCA command box was drawn on the HUD while the system was coupled and would flash while the trim control laws were executing. It can be seen centered on the velocity vector in Figure 16. In the lower right corner of the HUD a mnemonic was displayed which indicated the position of the PCA trim switch: TROFF when the PCA trim was off; TRAUTO when the PCA trim was in the automatic mode; TRON when the PCA trim was on. A radar altimeter reading in feet above ground level was displayed above the trim mnemonic.

The PCA command box on the HUD display was developed to give the pilot a positive indication of his longitudinal command. As the pilot moves the pitch thumbwheel, the box moves vertically on the HUD. The pilot can effectively place the box for a particular glide slope and observe the aircraft responding to the command. The velocity vector will move toward the box, and when the commanded flight path angle is equal to the actual flight path angle, the velocity vector will be displayed inside the box. Additionally, when the command box flashes the pilot knows that the PCA trim control laws are executing. This is important because the system will not respond as well to pilot inputs while the trim integrators are working to eliminate system biases

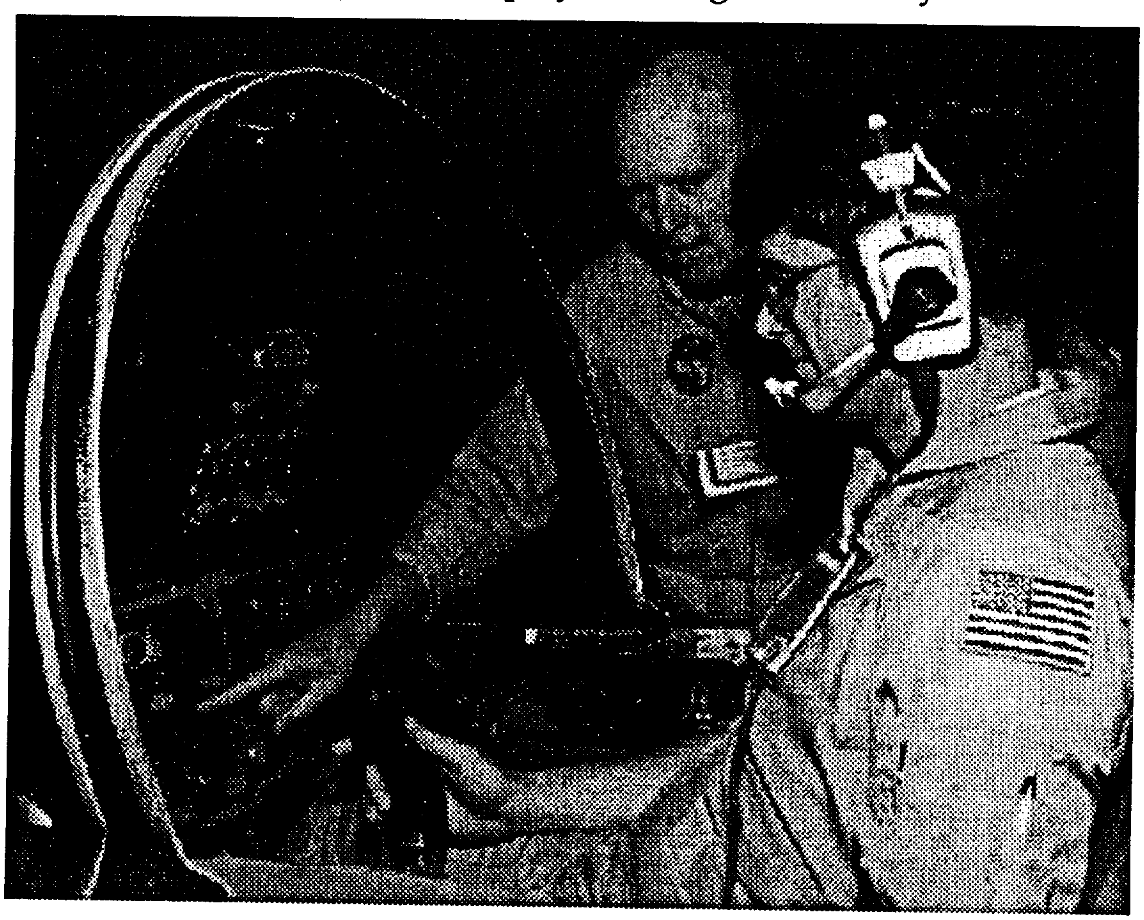


PCA Heads Up Display

Flight Simulator PCA Development

The MDA, manned, real-time flight simulator in St. Louis was used extensively during development of the PCA system. The simulator was an important tool in executing many of the PCA design trade studies. Because propulsion-only control was a new concept and had never been developed before, there were no guidelines or specifications that could be used as design references. Engineering judgment was used to develop initial values for system gains and operating characteristics using off-line simulations. The results of the off-line design had to be verified by manned, real-time simulation. This evaluation was needed for each PCA control law tradeoff, such as the decision to use either pitch rate or flight path angle rate feedback, and also for the net result of combining all design decisions into a unified system.

These simulator evaluations were critical to the success of the program. Because PCA was a new concept, the qualitative data obtained from piloted simulations became very important in determining the initial PCA control law structure. During landing approaches (the primary PCA task) the pilot interface provided information that could not be adequately assessed in an off-line simulation. NASA pilots participated in several simulator evaluations and provided important design feedback on the control response, displays and flight test safety limits.

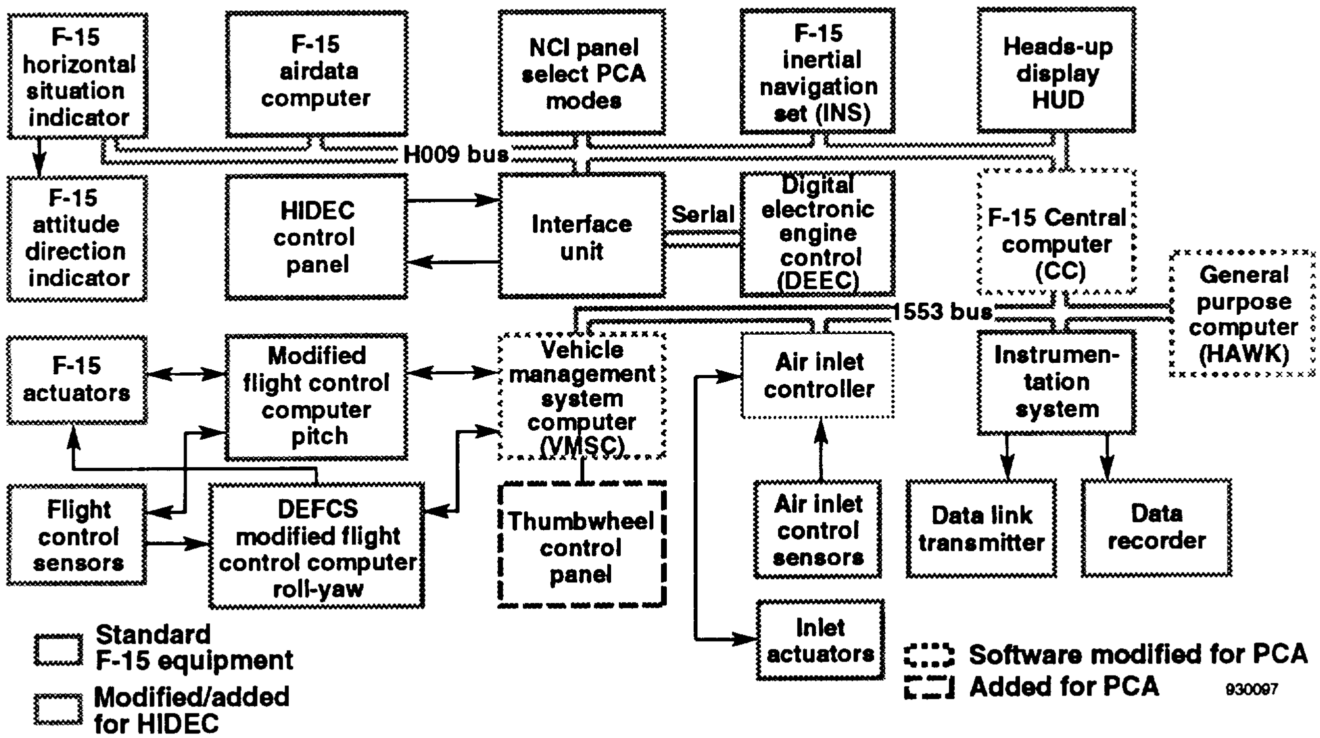


PCA Software tests in the MDA Simulator

PCA Implementation

PCA Hardware Development

The PCA system was installed on the F-15 HIDEC airplane using much of the already then-existing hardware and system interfaces. The only hardware added were the pitch and roll thumbwheels, as shown below.



PCA Hardware Implementation on the F-15

PCA Software Development

The PCA software used on the F-15 testbed was contained in three processors: the flight computer (Vehicle Management System Computer or VMSC), the Central Computer (CC) and the general-purpose research (Hawk) computer. Software development proceeded according to the following guidelines: minimize changes to the VMSC, minimize changes to the CC, make no changes to the Digital Electronic Engine Controllers (DEECs), fully utilize the Hawk computer and maximize flexibility of the PCA software overall. With these requirements in mind, the VMSC was used to read the PCA thumbwheel commands and a thumbwheel validity bit and pass that data on to the Hawk. The CC contained the PCA In-Flight Integrity Management (IFIM) logic, controlled the bus traffic among the three computers and passed the PCA throttle commands to the DEECs. The Hawk contained the PCA control laws and associated flight test software.

Flight Software

The IFIM logic in the CC was used to monitor important aircraft subsystems and uncouple the PCA system in the event of a subsystem failure. Validity discretes were received by the CC from the INS, ADC and the thumbwheel controller panel. A failure in any of these bits would cause an IFIM failure to be declared and a PCA uncouple. The CC also monitored wrap words from the VMSC, Hawk and DEECs. A wrap word is a communication handshaking signal used to indicate the status of the system processors and communication links. A wrap word failure would result in an IFIM failure declaration and a PCA uncouple. Finally, the CC monitored five status bits from each DEEC. The bits corresponded to the DEEC detecting: a UART failure, a wrap word failure, an auto-throttle failure, an engine stall, and a switch from primary to secondary engine control. A failure in any of the five status bits would result in an IFIM failure declaration and a PCA uncouple.

Functionally, the PCA software contained in the Hawk can be broken down into four groups: ground operation, monitor NCI inputs, perform safety checks and execute control laws. The ground operation logic was used to evaluate the PCA system during ground testing and to allow changes to be made to the software on-site at NASA. Each of the other modules will be discussed below.

The Navigation Control Indicator panel was used extensively throughout the PCA program to modify system parameters and change PCA operating modes. Tables of values were stored for virtually every system parameter, and by entering a pre-defined code into the longitude, latitude and altitude windows of the NCI, the pilot had the capability to modify the parameters as desired. Shown below are many of the parameters that could be modified. Thus, for the PCA flight test demonstration the normal navigation function of the NCI panel was changed to provide the necessary means to modify the system during flight experiments. The Hawk software continuously monitored the NCI and set internal parameters according to the pilot inputs.

Signal Monitor Limits	Input Biases	Input Scale Factors
Noise Filters	Envelope Limits	Flight Path Rate Calculation
Weight Input	Signal Channel(s)	Fuel Flow Source
Control Law Gains	PLA Step Biases	Gain Schedule Input Source
Wash-out Filters	Control Law Modes	Trim Control Law Modes
		Thumbwheel Scale Factors

NCI-Selectable parameters

Flight Software (Continued)

In addition to the IFIM logic in the Central Computer(CC), the Hawk software also performed safety monitoring. These monitors could be divided into three categories: dual signal, PCA flight maneuver envelope and subsystem fault. The control laws used five aircraft signals that were dual redundant on the F-15: angle-of-attack, roll rate, yaw rate, pitch thumbwheel command and roll thumbwheel command. Both channels of these signals were monitored and any difference greater than its miscompare threshold would result in a PCA uncouple. The PCA envelope was defined in terms of the Weight-On-Wheels (WOW) switch and six aircraft states: airspeed, roll rate, yaw rate, pitch rate, bank angle and flight path angle. These parameters were monitored and if the WOW switch was set or if any state exceeded its envelope threshold a PCA uncouple would result. Additionally, the control stick, rudder pedals and throttles were monitored and if movement of any beyond its threshold was detected PCA would uncouple. Subsystem fault monitoring was performed in the Hawk similar to the IFIM performed in the CC. The Hawk monitored wrap-around words from the CC and DEECs, and monitored the same five status bits from each DEEC that the CC monitored. A failure detected by the Hawk would result in a PCA uncouple.

The control law execution encompassed input signal conditioning and pilot display as well as engine command calculation. The flight path angle and flight path angle rate feedbacks were not explicitly available on the F-15 testbed and needed to be calculated from inertial navigation set(INS) data. The weight of the aircraft was an input into some of the gain schedules and needed to be calculated from the sensed fuel flow. Before the five dual redundant signals needed by the control laws could be used, the average of each was calculated. Additionally, each aircraft signal used by the PCA system was processed through a first order lag filter to attenuate noise. The Hawk was also responsible for calculating the position of the command box on the HUD.

Verification of the PCA software was performed in two steps: open loop laboratory bench testing and closed loop manned simulator testing. In both cases the software was installed and evaluated in the actual flight hardware. The laboratory testing checked out every operation mode, communication interface, safety feature and display. Each input was excited and outputs were checked against design predictions. The manned simulator testing verified the in-flight operation modes, safety features and displays using a high fidelity, real-time aircraft model. The manned simulator also provided the final pilot assessment of PCA performance before actual flight testing.

Installation and Verification

Installing the PCA system in the test aircraft consisted of loading three computers with their required software and adding the Thumbwheel Controller Panel (TCP) hardware component. The TCP was installed just aft of the throttles in the left cockpit console. Power was supplied through the flap circuit breaker and the wiring was routed to the VMSC along an existing wire bundle. The software for the VMSC and the Hawk was transported to the NASA Dryden Flight Research Center (NASA-Dryden) on magnetic media and loaded into the boxes on-site without removing them from the airplane. The software for the Central Computer was transported to NASA-Dryden on magnetic media, loaded into the CC at the McDonnell Douglas facility nearby and then the unit was re-installed into the airplane.

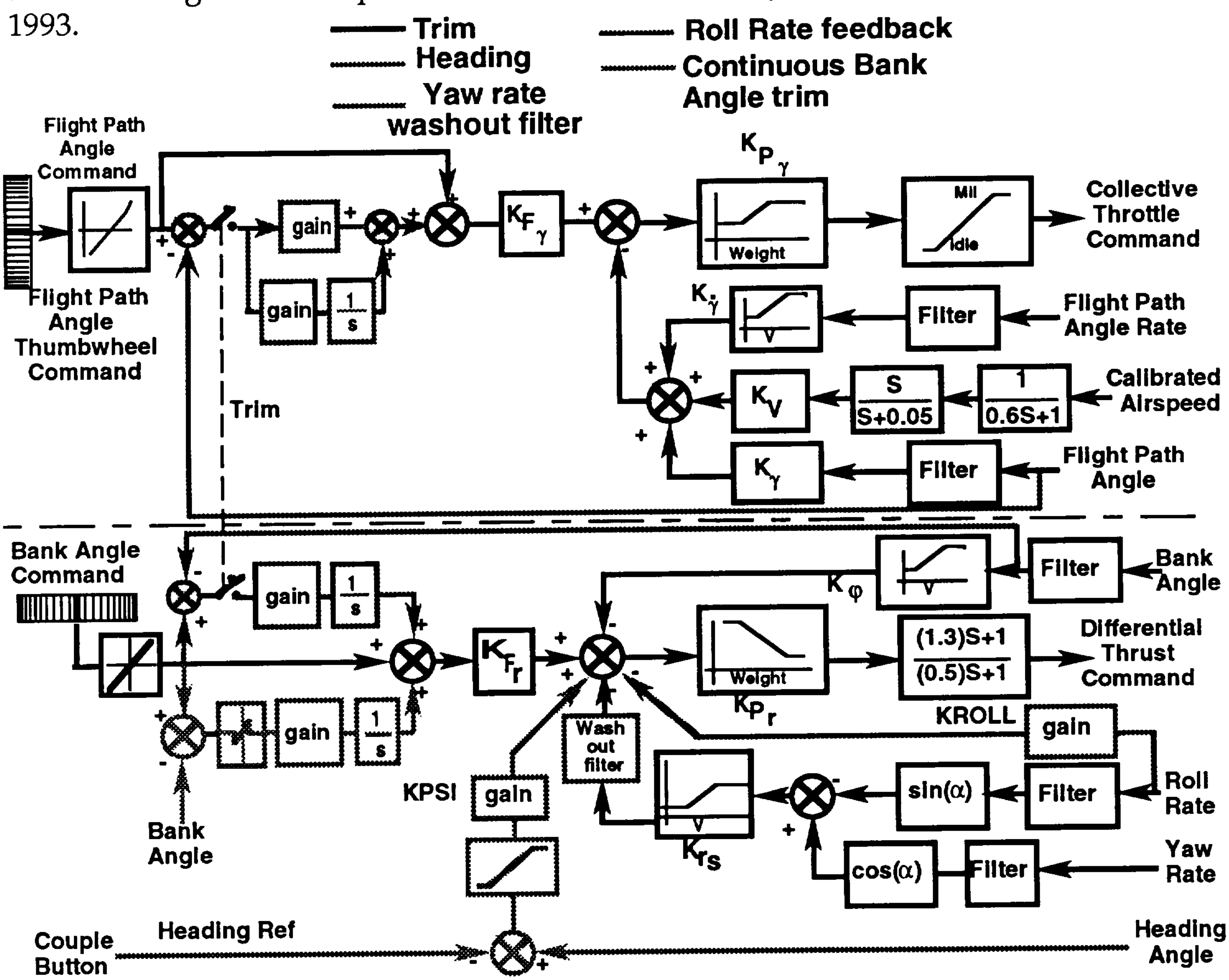
Ground testing at NASA-Dryden consisted of a series of five tests: Instrumentation, Functional, Radiation, Electromagnetic Interference (EMI) and Combined Systems Test. The Instrumentation Test verified that the aircraft telemetry system and the PCA system were working together correctly. The Functional Test verified aircraft communication interfaces and displays as well as PCA operation and safety features. The Radiation Test verified that the real-time display of the telemetry data in the control room was functioning as designed. The EMI test verified that the PCA hardware was neither a source nor a victim of EMI. The Combined Systems Test verified that the PCA, instrumentation, control room and aircraft systems were all functioning together correctly.

Implementation of the PCA system in the NASA test F-15 was efficiently accomplished due to the fact that on-board computers and an interface to accept engine commands were already in place on the test aircraft. A desirable feature of the PCA research flight system was the provision to change system control parameters without re-generating a new software program. This was a valuable tool during integration and ground testing as well as flight development.

Additional Software Development

After the PCA-controlled landings, and the experience gained during the first two series of flight tests and increased attention to the actual transition of PCA technology to a civil platform, two significant software changes were identified. The first was the capability to evaluate an aircraft damage scenario resulting in partial hydraulic and engine failures. The scenario chosen provided for control to the rudder and one engine only. Using the single engine, the PCA system controlled the flight path angle, and the pilot controlled bank angle using the rudder pedals. The only significant software change required to test this mode was the ability to operate PCA with one engine at idle power.

There were several features added to the PCA software, as shown below. The most significant change was the capability to include a heading reference in the lateral control law. Two heading modes were developed: a heading command mode and a bank command with heading reference mode. These PCA test modes were developed, verified in the laboratory, installed in the aircraft, verified with an abbreviated ground test procedure and declared ready for flight testing by mid June 1993.



PCA Logic block diagram additions including Heading mode