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THCS Generalized Airplane Control System Design

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Abstract The Total Heading Control System (THCS) was developed in the late eighties to overcome well known safety/design deficiencies of traditional SISO-based Flight Guidance and Control (FG&C) systems. THCS uses generalized MIMO based airplane control strategies to functionally integrate all desired lateral directional automatic and augmented manual control modes and achieve consistently high performance. The counterpart to the THCS is the Total Energy Control System (TECS), which functionally integrate all desired vertical automatic and augmented manual modes for vertical flight path and airspeed control. Recent TECS developments are described in a companion paper. This paper documents further insights gained over the past years on THCS design details for achieving precision control decoupling, integration of augmented manual control modes and innerloop design using airplane dynamic model inversion. Also a TECS/THCS-based Mode Control Panel concept and a Primary Flight Displays concept that incorporates the TECS/THCS control and guidance strategies are discussed.

1 Introduction

Automatic Flight Guidance and Control (FG&C) systems have evolved into highly capable systems. These systems have contributed immensely to the improvement of aviation safety. Unfortunately, these systems still use traditional SISO control strategies that do not provide full 6 degrees of freedom airplane control. Therefore, airplanes equipped with these systems are still vulnerable to Loss of Control (LOC). Furthermore, these systems have become exceedingly complex, due to an excessive number of modes, mode overlap and mode idiosyncrasies, making it a challenge for the flight crew to avoid mistakes using these systems that can jeopardize operational safety. Most of the FG&C system modes are considered “non-flight critical”. This means that the flight crew is assumed to recognize and safely manage any failure of function of such modes. However, too often this assumption has proven to be unwarranted. As a result there have been too many automation related incidents and accidents, due to stall, roll divergence after an engine failure, icing etc. The current generation of FG&C systems do not take full advantage of modern MIMO control strategies to functional integrate all modes, eliminate well known safety deficiencies (e.g. by incorporating full flight envelope protection) and provide simpler, more efficient and less costly designs. The THCS concepts described in this paper were developed to overcome the noted deficiencies.

TECS and THCS Development

FG&C system design and safety deficiencies were well recognized as long ago as the late seventies. In the early eighties NASA initiated research to address these deficiencies. This work resulted in the Total Energy Control System (TECS), which uses a generalized MIMO-based energy control strategy to functionally integrate all vertical flight path and speed control modes. The approach provides inherent envelope protection and avoids open ended SISO mode operations, thereby largely eliminating LOC safety risks. System complexities are reduced sharply by eliminating mode overlap, simplifying mode processing and providing more intuitive Man Machine Interfaces (MMI). Design generalization makes the system directly reusable, thereby reducing development costs for new applications. The system was successfully implemented and flight tested on the NASA B737 in 1985. The counterpart to TECS is the Total Heading Control System (THCS) which integrates all lateral directional control modes. Its design objectives and strategies are analogous to TECS. It was developed in the late eighties on the Condor High Altitude Long Endurance autonomous UAV program. TECS and THCS were successfully applied on the Condor and flight tested to demonstrate autonomous control capability under all operational and variety of failure conditions.

The original THCS concept is described in **[2].** This paper describes THCS design updates since the early nineties, including

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- Roll/Yaw control innerloop design, using Model Inversion, feedback normalization and feedback concatenation
- development of a simple and effective design methodology for the augmented manual control modes, to meet traditional handling qualities requirements
- development of integrated vertical and control NLF authority allocation and envelope protection
- various approaches to providing integrated airspeed, normal load factor and roll angle envelope protection

This paper also discusses a TECS/THCS-based Mode Control Panel concept and a Primary Flight Displays concept that incorporates the TECS/THCS control and guidance strategies. A companion paper **[3]** describes TECS design updates. Another companion paper **[4]** provides more details on Flight Envelope protection strategies.

Design objectives. The THCS design objectives include:

- use of ***one*** pilot-like MIMO-based control strategy for all automatic and manual control modes
- full authority integrated lateral directional control, including automatic roll and yaw retrim, to prevent LOC due to engine out roll-yaw divergence
- generalized functionally integrated design, consistency of operation between modes
- elimination of Yaw Damper, Turn Coordinator and Thrust Asymmetry Compensator
- Decoupled Mode Command responses, reduced controller activity
- reduced design complexity by using shared modular building blocks, elimination of mode overlap and simpler mode processing
- simpler, more intuitive Mode Control Panel (MCP), clearer Flight Mode Annunciation (FMA),
- large cost reductions by generalized/reusable design, minimal application specific development, reduction in laboratory and flight testing and shorter application development cycle.

2 THCS – Architecture and Conceptual Design

Core Controller Design

Original Core Controller. The original THCS Core Controller is shown in Figure 2.1. The control strategy of the THCS is analogous to the TECS. A number of variations of this architecture are possible to suit the application need or design preference. One variation will be discussed below.

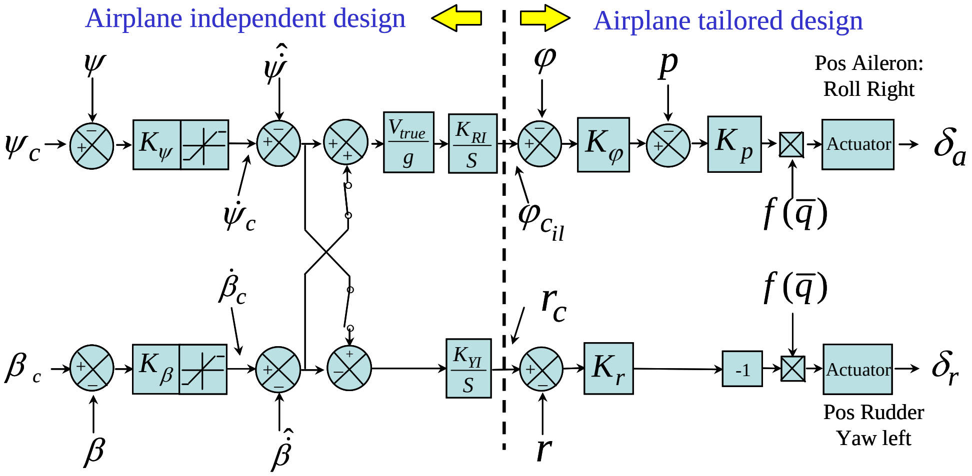

Figure 2.1 THCS Core controller – basic functional architecture

The outerloop horizontal path mode (lateral path, heading or track angle) error is normalized into a standard yaw rate command $(\dot{\psi}_{c_{ol}})$ (or an equivalent roll angle command $(\varphi_{c_{ol}})$), and the directional control mode (sideslip control) error is normalized into the standard sideslip rate command $(\dot{\beta}_c)$ and these signals are used as the command input the THCS Core Controller. In the THCS Core Controller (Figure 2.1), the sum of the error signals $(\dot{\psi}_\varepsilon + \dot{\beta}_\varepsilon)$ is formed and used to develop the roll control effector command, while the difference between these error signals $(\dot{\psi}_\varepsilon - \dot{\beta}_\varepsilon)$ is used to develop the yaw control effector command. To achieve coordinated turns without inducing a sideslip during lateral maneuvering (perfect roll/yaw decoupling), the dynamic response of $(\dot{\psi}_\varepsilon + \dot{\beta}_\varepsilon)$ and $(\dot{\psi}_\varepsilon - \dot{\beta}_\varepsilon)$ for a lateral maneuver command must be designed to be identical. Then also the dynamics of $(\psi_\varepsilon + \beta_\varepsilon)$ and $(\psi_\varepsilon - \beta_\varepsilon)$ will be the same, assuming $K_\psi = K_\beta$. For a weather-cock type yaw oscillation about the airplane's z-axis, with negligible side acceleration, the response is characterized by $\beta = -\psi$. Such a motion should be heavily damped by the rudder control, without a considerable roll control response. In principle this requires this $K_\psi = K_\beta$ and removal of the cross coupling effects. The THCS Core Controller roll control channel develops an innerloop roll angle command $(\varphi_{c_{il}})$ and features conventional roll-error and roll rate feedback control loop. The THCS Core Controller yaw control channel develops an innerloop yaw rate command $\{r_c = (g / V_{true}).\varphi_{c_{il}}\}$ that is coordinated with $(\varphi_{c_{il}})$ and uses body axis yaw rate to form a yaw-rate error control loop. Therefore the numerical value of K_{RI} and K_{YI} should be the same. A gain factor V_{true} / g is included in the forward signal path of the roll control channel, to maintain the proper kinematic relationship between $\dot{\psi}_\varepsilon$, $\dot{\beta}_\varepsilon$, $\varphi_{c_{il}}$ and r_c at all flight conditions. The feedback signals $\hat{\dot{\psi}}$ and $\hat{\dot{\beta}}$ are derived from free running complementary filters. The processing for the individual lateral outerloops control modes is analogous to the processing for TECS outerloop modes. For automatic mode operations the outerloop β_c is normally zero. The β_c can be used to command a sideslip to minimize the drag during engine out operation and to provide a decrab function as part of the automatic landing control mode. The decrab function may be designed to align the airplane heading with the runway heading just prior to touchdown, without causing the airplane to drift sideways.

β-Filter. A raw aerodynamic β signal can be derived from a β-vane or hemispherical differential pressure sensor, calibrated for the local potential flow distortion around the airplane nose structure where it is mounted. It also may need to be calibrated to remove the angular yaw acceleration effect due to the location forward of the airplane center of gravity. Furthermore, such a calibrated aerodynamic β-signal is too noisy under conditions of atmospheric turbulence. Therefore a $\hat{\beta}$-filter is used, as shown in figure 2.2. This filter uses an inertial sideslip rate signal developed from the airplane side force equation:

$$\begin{aligned} \dot{\beta}_I = (\dot{v}_I / V_I) &= \{(\Sigma F_{y_{aer+prop}} / m) + g.\cos\theta.\sin\varphi\} / V_I - r + p.\tan\alpha_I \\ &= (A_y + g.\cos\theta.\sin\varphi) / V_I - r + p.\tan\alpha_I \end{aligned} \tag{2.1}$$

Here V_I is the inertial velocity vector, but for most applications a groundspeed or a filtered true airspeed can be used without a significant impact on performance. The $\hat{\beta}$ signal is used in the THCS Core Controller for airplane Dynamic Model Inversion and sideslip angle feedback. [The TECS Core uses a similarly filtered Angle of Attack signal ($\hat{\alpha}$).]

The $\hat{\alpha}, \hat{\beta}$ filter gains are determined to achieve the preferred compromise between control activity and effectiveness in suppressing induced pitch, roll, yaw, acceleration responses and path deviation in turbulence.

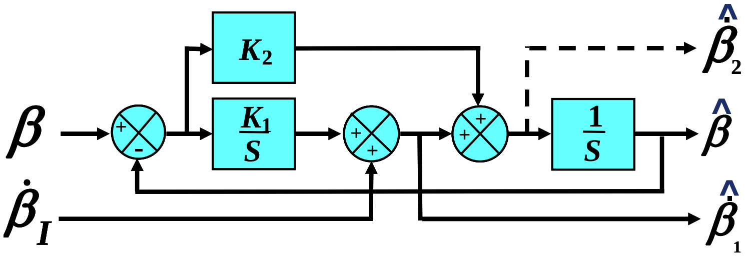

Figure 2.2 $\hat{\beta}$-Filter

Automatic Roll/Yaw trim. The processing of $\dot{\psi}_\varepsilon$ (or φ_ε in the design variation discussed below) and $\dot{\beta}_\varepsilon$ signals through integral control signal paths also provides for trimming of the roll and yaw control effectors, to null out any rolling and/or yawing moment imbalance due to thrust asymmetry (e.g. engine failure), fuel load imbalance or lift asymmetry due to wing icing or damage. So, depending on which lateral control mode is engaged, the roll channel will trim to null its outerloop mode error, e.g. roll angle for the augmented manual mode, or when an automatic mode is engaged it will trim that mode error to zero, thus eliminating the need for manual roll and yaw trim functions. The yaw channel will trim the rudder to establish $\beta = \beta_c$.

Provisions Roll and Yaw Control Effector Command Saturation. The classical way to limit the control effector command to prevent integrator windup, is to continually calculate and apply the instantaneous integrator limit. The instantaneous integrator limit is computed by subtracting from the actual control effector limit the incremental control effector command contribution by all the proportional signal paths downstream of the integrator output. Alternatively, the integrator may be moved to end of the control effector command processing path, where the output to the integrator can simply be limited to the control effector limit. The input to such an integrator represents the control effector command rate, which can also be limited to the actual effector rate capability. If the integrator is placed at the end of the command processing chain, a differentiator must be placed in all the original proportional signal path that contribute to the control effector command. In the later TECS and THCS designs the latter approach is used, because it is simpler. With this design approach care must be taken to avoid propagation step commands (originating from mode commands) through the original proportional signal paths to the control effector, because a step change in signal amplitude cannot be reproduced when passed through a differentiator/integrator combination. In the TECS/THCS design step commands to the control effectors are avoided.

Outerloop Modes Design

The most basic outerloop mode is the Heading Angle control mode, which is included in the THCS Core controller architectures, shown in Figure 2.1 and 3.1. The Track Angle mode is entirely analogous to the heading mode, requiring in principle only the substitution of Track Angle for Heading Angle. The Localizer and LNAV modes require the closure of an additional control loop for controlling the cross track error. In the Condor UAV application and in the TECS/THCS real time system demonstration systems this additional feedback loop is concatenated around the heading control. In effect the cross track error signal is multiplied by the normalization gain K_y and divided by $\hat{V}_{true}$ to form the heading angle command, in a manner analogous the feedback error normalization used in the Glide Slope and Altitude Acquisition modes. The detailed mode processing is fairly standard, so for brevity reasons further details will be skipped in this paper.

3 THCS – Design Updates

THCS Core Controller architecture updates

The THCS architecture of figure 2.1 is not directly compatible with the Augmented Manual Lateral Directional control mode requirement for controlling roll angle by a roll control inceptor and sideslip angle by a yaw control inceptor. The architecture can be made compatible by replacing the $\hat{\dot{\psi}}$ feedback with an equivalent roll angle feedback using the relationship for a level coordinated turn: $\dot{\psi} = (g/V_{true}).\tan\varphi$ or for relatively small angles $\dot{\psi} \approx (g/V_{true}).\varphi$, resulting in the architecture shown in Figure 3.1.

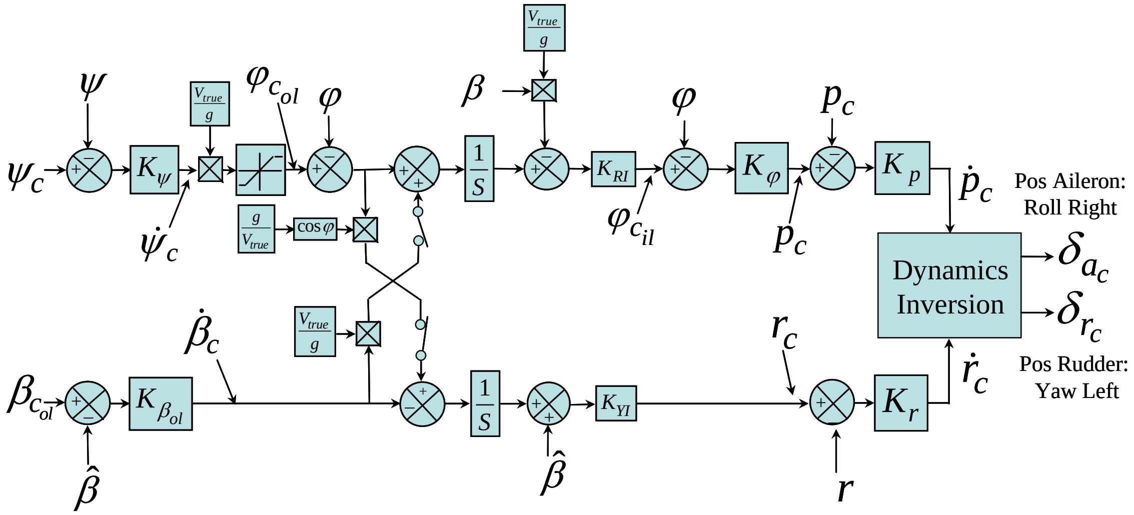

Figure 3.1 THCS Roll Attitude based Core controller

System Stability at High Roll Angles. During the early evaluation of the manual control mode incorporated in the architecture of Figure 3.1 a roll/yaw system stability degradation observed at high roll angles in the, e.g. for φ>45 degrees. A that time gains used were identical to the corresponding gains in the architecture of figure 2.1. Analyses showed that the stability degradation at high bank angles was due to a missing $\cos\theta$ gain factor in outerloop roll angle error cross feed signal path to the yaw control channel. This became clear by considering the relationship between yaw rate and the measured body axis yaw rate r in a steady turn:

$$r = \dot{\psi}\cos\theta\cos\varphi - \dot{\theta}\sin\varphi \qquad (5.1)$$

In this expression the pitch rate term can be neglected and $\cos\theta = 1$ may be assumed. Therefore, without the roll to yaw channel cross feed gain $K_{RY} = \cos\varphi$, the resulting magnitude of r_c was excessive at high bank angles, relative to the measured body axis yaw rate feedback. Addition of this $\cos\theta$ gain factor eliminated the stability degradation.

Engine out Control. During further evaluation of the system of Figure 3.1 it was found that the performance for a worst case engine out condition (Max thrust Go Around) was marginal and that the performance for this condition could be improved significantly by restructuring the yaw channel β-innerloop to be analogous to the ϕ-innerloop of the roll channel. This restructured THCS architecture, shown Figure 3.2, includes new gain $K_{\beta_{il}}$ when compared to the architecture of Figure 3.1. and the gain $K_{\beta_{ol}}$ has been moved to cross feed signal path from the yaw channel to the roll channel, in order to maintain the same gain for the β-error input to the roll channel as in Figure 3.1 Now, by selecting $K_{YI} = K_{RI}$, $K_{\beta_{il}} = K_{\varphi}$ and $K_r = K_p$ the resulting yaw channel response dynamics to $\beta_{c_{ol}}$ -command will be identical to the roll channel response dynamics to a $\varphi_{c_{ol}}$ -command, since the Dynamics Inversion results in fully decoupled roll and yaw axis dynamics. Both the β-error outerloop integral control gain and the β-error proportional innerloop gains are considerably higher than the corresponding gains in Figure 3.1, thereby achieving the desired engine out control performance. It also resulted in much tighter sideslip control during turn entry.

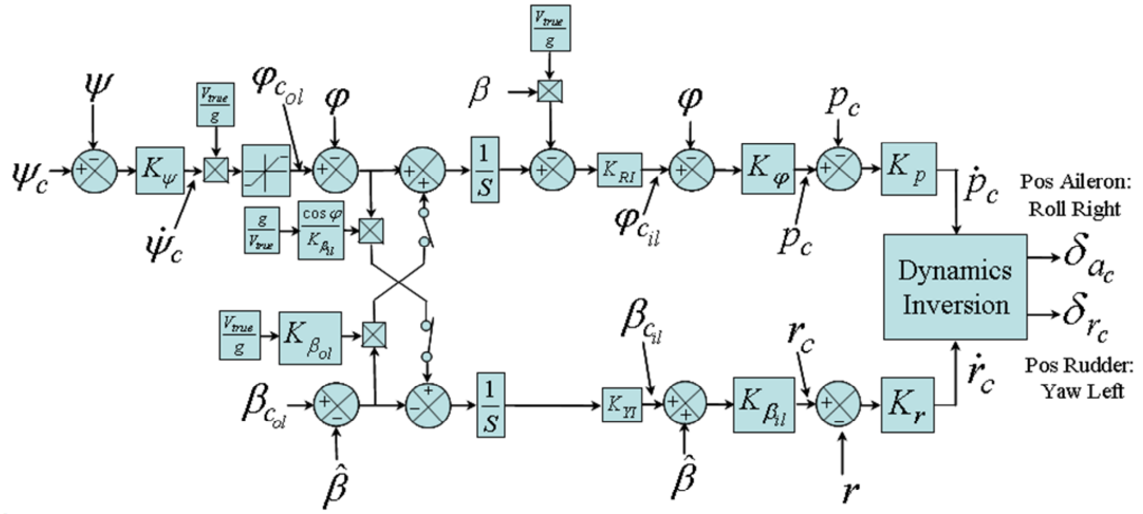

Figure 3.2 Restructured THCS Roll Attitude based Core controller

In order to maintain coordination between the $\varphi_{c_{il}}$ of the roll channel and r_c of the yaw channel innerloop in response to a $\varphi_{c_{ol}}$, a new gain $1/K_{\beta_{il}}$ has been inserted in the cross feed path from the outerloop φ-error to the yaw channel, as shown Figure 3.1.

Decrab Control. For the earlier architecture of Figure 2.1 decrab capability was provided by a β_c cross feed term added to the input of the roll control channel integrator and a β_c feed forward term added to the rudder command. This approach required fairly complex β_c filters and gain schedules to achieve the precise roll-yaw coordination to quickly establish the commanded sideslip angle, without causing the airplane to drift sideways. For the updated design these complex ad hoc designed elements have been eliminated and replaced by a new β_c signal cross feed to the outerloop roll angle command and feedback summing junction, providing an incremental roll angle command $\Delta\varphi_{c_{ol}} = K_{decrab}.\beta_c$. The gain $K_{decrab} = \Delta\varphi_{c_{ol}} / \beta_c$ is now computed by solving the lateral directional equations of motion in near real time for the steady state roll angle $(p = r = 0)$, yaw and roll control surface deflections needed to achieve zero side acceleration with $\beta = \beta_c$ and zero acceleration along the y-body axis (no side drift). The computation is shown in Figure 3.3.

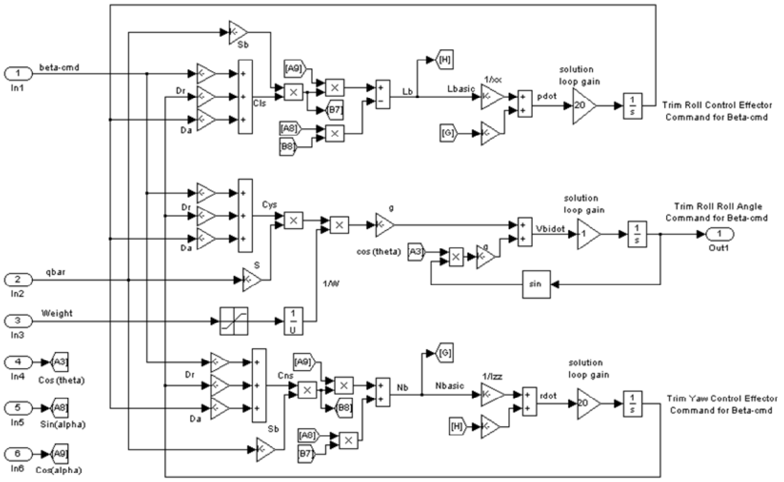

Figure 3.3 Computation of K_{decrab}

Final THCS Core Controller Configuration. In the final THCS architecture reconfiguration, shown in figure 3.4, the integrators are moved to the end of the control effector command processing string, which is now part of the Dynamics Inversion processing block. As a result the proportional signal paths now include a differentiation function. In this reconfigured architecture the output of the gain block K_{YI} may be considered a $\beta_{c_{il}}$, just like the output of the gain block K_{RI} in the roll channel may still be regarded as a $\varphi_{c_{il}}$. The only reason why in Figure 3.4 $\beta_{c_{il}}$ and the yaw channel innerloop β -feedback are not combined in one summing junction is the new placement of the integrator and the end of the yaw effector command processing chain, which now terminates in the Dynamics Inversion processing block.

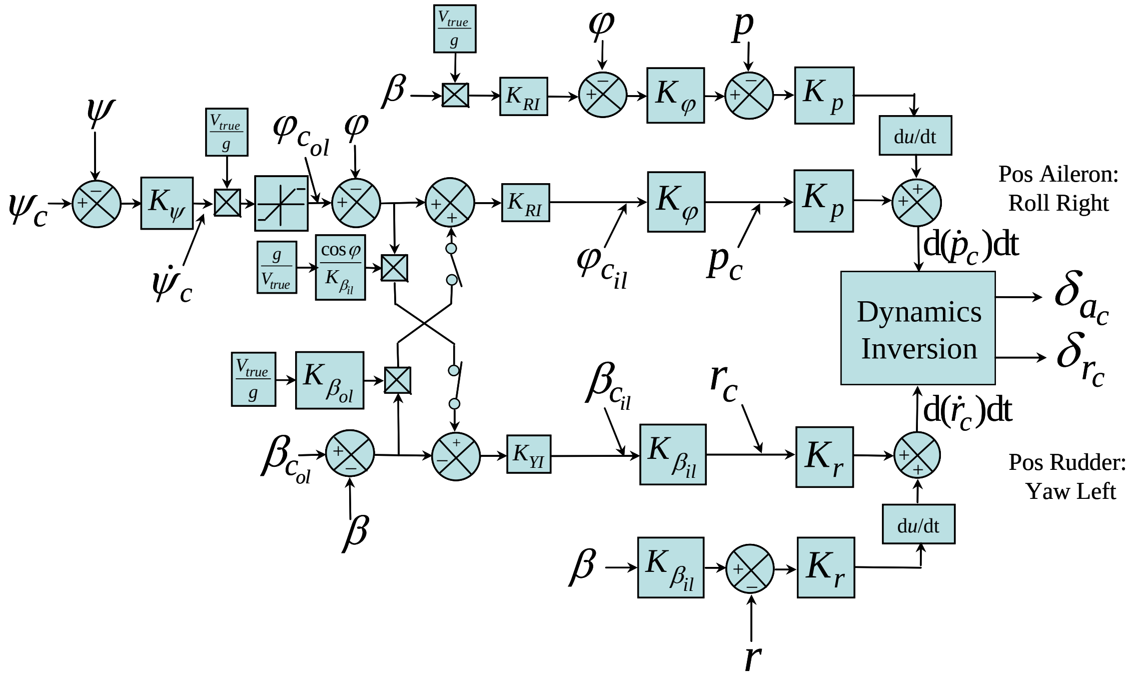

Figure 3.4 Final THCS Roll Attitude based Core Controller Architecture

Design of the THCS Core Controller feedback Gains

Applying Dynamics Inversion. The generalized design approach used for TECS Core Controller, including feedback normalization/concatenation, airplane dynamic model inversion and loop gain separation or pole placement, was also applied to the updated THCS Core Controller design. Only the Roll and Yaw dynamics are inverted. A simplified Dynamics Inversion approach is represented in Figure 3.5. This approach was used in combination with the architecture of Figure 2.1 with the output of the integrators representing the $(\varphi_{c_{ol}})$ and r_c for the roll and yaw innerloop control. In the processing of Figure 3.5 only the direct moment contributions due to airplane state feedback are inverted, under the assumption that the inertial coupling moments are insignificant. Clearly, for high rates of maneuvering, such as in case fighter planes this will not be a valid assumption. The inputs to the inversion process are a roll acceleration command and a yaw acceleration command, represented by the outputs of the gain blocks K_p and K_r in Figure 2.1. The outputs of the Dynamics Inversion processing (Figure 3.5) are the roll and yaw control effector commands. In this Inversion processing the actuator dynamics are not taken into account and for that reason, as explained in [3], the gain of the most innerloop roll and yaw control (K_p and K_r) are selected to accommodate the addition of actuator dynamics without significantly impacting the final system stability and response. The results achieved using the inversion approach of Figure 3.3 were quite satisfactory for all routine maneuvers, although the approach has not been tested for extremely high airplane maneuver rates.

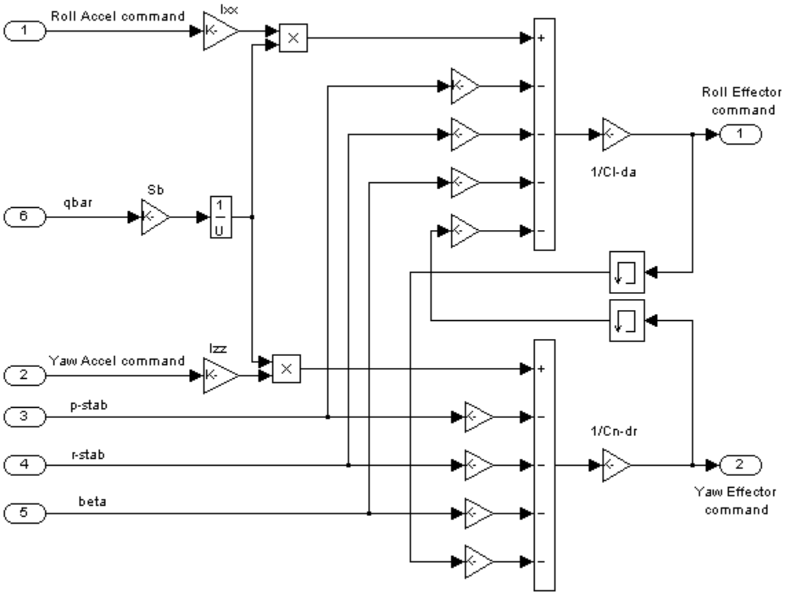

Figure 3.5 Simplified Roll Yaw Control Inversion

A slightly more elaborate Dynamics Inversion processing that includes inversion of the of the inertial coupling moments is shown in Figure 3.6. It applies to the architecture of Figure 3.4 where the integrators have been moved to the end of the control effector commands processing string. As a result the integrators now appear as the last processing step to generate the control effector commands in Figure 3.6. This approach has been used in all recent THCS work, including the simulation results shown below. The inputs to the inversion process of Figure 6 are *the rate of change* of the roll acceleration and *the rate of change* of the yaw acceleration command. Because the collective inversion term in Figure 3.6 associated with the moment dependencies on the state derivatives will also be integrated in the final processing step, a differentiation needs to be applied to. The inversion of the moments of inertia associated cross coupling terms are developed using as input the rate of change of the “pure decoupled “ rolling moment coefficient command and the rate of change of the “pure decoupled “ yawing moment coefficient command.

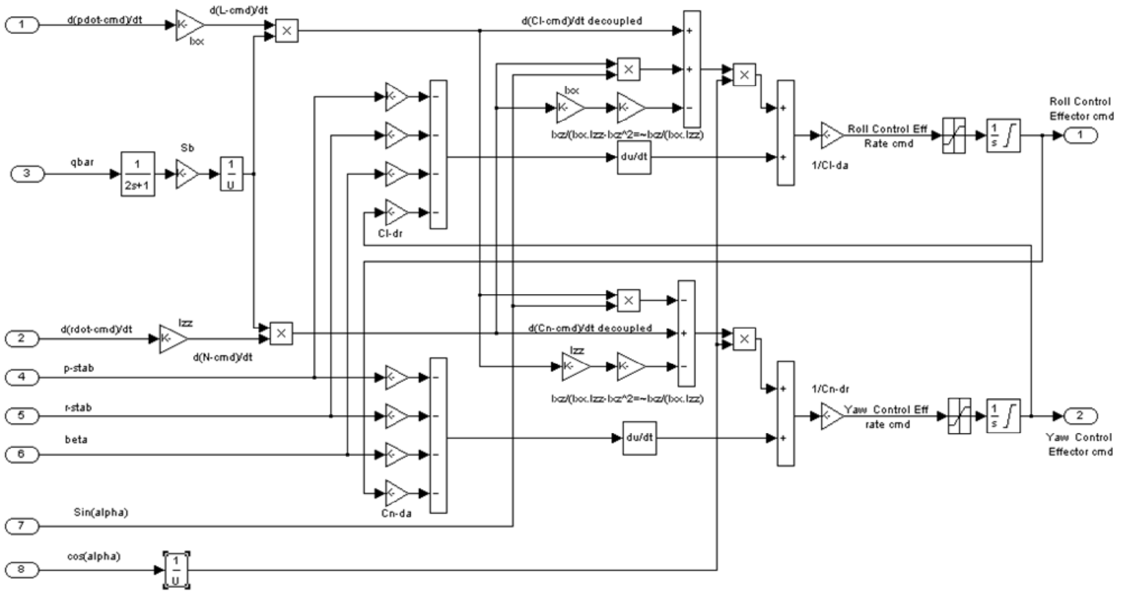

Figure 3.6 Extended Lateral Directional Inversion

The still less significant inertial coupling terms associated with products of the angular rates have been neglected. A final validation of the adequacy and correctness of the inversion process can be performed by modifying selected or all coefficients and cross coupling moments of inertia involved in the airplane model and in the inversion process and checking that the final augmented airplane dynamics remain unaffected for all realistic airplane maneuvers.

THCS Core Controller roll channel gains. Inversion of the roll dynamics, removes all cross axis coupling effects and leaves only the bare roll rate and roll angle integrators around which the new proportional concatenated roll rate and roll attitude loops are closed with the gains K_p and K_φ, to create the desired innerloop roll dynamics. In addition, a roll error integral control loop is closed around the innerloop roll dynamics to assure zero steady state roll command tracking error. The resulting THCS Core Controller roll control channel, shown in Figure 3.7, is functionally the same as the roll control channel of figure 3.1, 3.2, 3.3 .

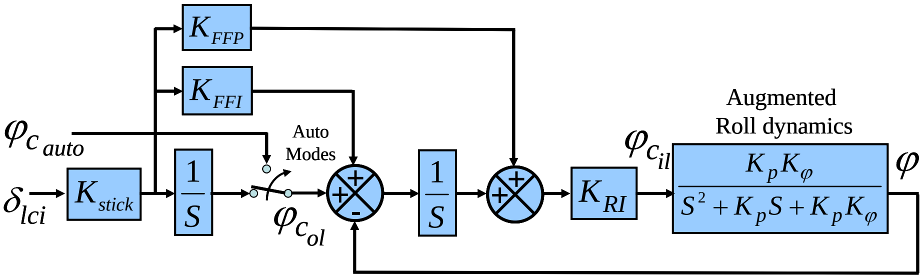

Figure 3.7 THCS Core controller Roll Channel.

The basic transfer function for the system of figure 3.7 with the switch in the “Auto Modes” position is:

$$\left[\frac{\varphi}{\varphi_{c_{ol}}}\right]_{auto} = \frac{K_p K_\varphi K_{RI}}{S^3 + K_p S^2 + K_p K_\varphi S + K_p K_\varphi K_{RI}} \tag{3.1}$$

The Dynamics Inversion process and the kinematic relationships built into the THCS Core controller take care of all needed real world gain scheduling. As an example, we use pole placement to define the dynamics of the basic $[\varphi / \varphi_{c_{ol}}]_{auto}$ transfer function:

$$\left[\frac{\varphi}{\varphi_{c_{ol}}}\right]_{auto} = \frac{1}{(.5S+1)^2(S+1)} \tag{3.2}$$

The resulting gains are $K_p = 5$ (rad/sec^2)/(rad/sec), $K_\varphi = 1.6$ (rad/sec)/rad and $K_{RI} = .5$ rad/rad. The $[\varphi / \varphi_{c_{ol}}]$ TF dynamics not only supports the closing the automatic control loops for the Heading, Track, the Localizer, or the LNAV mode, but was purposely designed to support augmented manual control mode design, as is shown below.

THCS Core Controller yaw channel gains. The yaw channel of the reconfigured architecture of Figure 3.2 or 3.4 is structured entirely analogous to the roll channel. Therefore, as discussed above, by selecting $K_{YI} = K_{RI} = .5$, $K_{\beta_{il}} = K_\varphi = 1.6$ and $K_r = K_p = 5$, the resulting dynamics of the $[\beta / \beta_{c_{ol}}]$ TF will be identical to the dynamics of the $[\varphi / \varphi_{c_{ol}}]$ TF , since the roll and yaw axes are fully decoupled as the result of the Inversion of the original airplane dynamics. For a lateral maneuver, the airplane will respond smoothly to a $\varphi_{c_{ol}}$ -command to establish $\varphi = \varphi_{c_{ol}}$, while the cross feed from the roll channel to the yaw channel commands the required yaw rate to ensure that the airplane will not develop a significant side acceleration and sideslip. Likewise, for a decrab maneuver, the airplane responds smoothly to a $\beta_{c_{ol}}$ -command to establish $\beta = \beta_{c_{ol}}$, while commanding a precisely coordinated roll angle through the cross feed $\Delta\varphi_{c_{ol}} = K_{decrab}.\beta_{c_{ol}}$, to prevent the airplane from drifting sideways. The $[\beta / \beta_{c_{ol}}]$ response dynamics are quick enough to avoid the need for additional augmentation.

Performance in Turbulence and Windshear

Balancing the control command tracking performance against the control effector activity for operation in turbulence and windshear conditions is a difficult problem for any flight control design. It is perhaps the easiest to do so for the autoland mode, where Localizer tracking performance is of paramount importance and all other performance metrics are secondary. Additional (secondary) performance objectives may include minimizing RMS of lateral acceleration at the airplane center of gravity and in the back of the passenger cabin, roll angle, yaw angle and control effector activity. Attempts to achieve additional (secondary) performance objectives, often leads to design conflicts that can only be resolved by making design compromises. For example, the specific feedback control architecture and the feedback signal synthesis by the use of Complementary Filters (observers) can greatly affect the relative outcome of the various performance measures. It is beyond the scope of this paper to address these issues in further detail.

4 THCS Automatic Modes Simulation Results

Final THCS Core Controller. The Core Controller architectures of Figure 3.2 and 3.4 represent the highest level of development of the Total Heading Control Concept reached so far. However, during performance evaluations it was found that the system responses were slightly smoother when the sideslip error cross feed to the roll and the sideslip feedback in the roll channel were removed. Therefore the merits of using $(\psi_{\varepsilon} + \beta_{\varepsilon})$ in the roll control channel, rather than for heading error, with or without a higher level lateral outerloop (e.g. Localizer or LNAV) mode feedback needs further studies, in particular for system performance in turbulence. Here, the simulation results were generated using a system configuration of Figure 3.4, without the sideslip error cross feed to the roll and the sideslip feedback in the roll channel. No further "system tuning" was used for any of the maneuvers shown below.

Simulation. A complete TECS/THCS system simulation capability was developed in MATLAB-Simulink. The simulation includes all TECS and THCS modes and design features discussed above in this paper, as well as a full flight regime six degrees of freedom nonlinear airplane simulation. Realistic 2nd order actuator models including rate and position limits were included, along with a rate limited 2nd order engine model. The airplane model represents a generic 100-125 passenger twin turbofan engine transport airplane at 120,000 lbs. Here only the results for the automatic Heading control mode and the augmented manual control mode are presented.

Track Angle Mode. Figure 4.1 left plot shows the airplane in level flight Altitude Hold and Track Angle mode responses to o step Track angle-command of + 90 degrees at t=20 seconds. The airplane rolls to the bank command limit of 25 degrees, stays there for nearly 30 second, then rolls out on the commanded track angle. The sideslip angle remains limited to ~.5 degrees.

Engine Out Control. Figure 4.1 right plot shows the airplane in Altitude Acquisition Track Angle mode in a climb from 5000 ft to 10000 ft, at an IAS-cmd = 200 knots. At t = 50 seconds, just after the engines reach maximum climb thrust, the left engine fails. The integrated Track Angle/Sideslip Angle control modes and the Altitude Acquisition/IAS control modes respond to thrust asymmetry induced yawing moment, rolling moment and thrust drop by immediately pitching the airplane down to stop the airspeed bleed off, control the track angle deviation and sideslip deviation and retrim the airplane ailerons and rudder. In the process the airspeed error peaks at -12 knots, the roll angle peaks at ~4 degrees, the sideslip angle at +2 degrees (wind from the right), the track angle error at -2 degrees and the Flight Path Angle reduces from 11 to ~2.5 degrees. Zero Sideslip Angle and zero Track Angle are reestablished ~25 seconds after the left engine failed. The roll angle trims out at a little over 2 degrees. The aileron deflection peaks at ~8 degrees and trims out at 4 degrees. The rudder smoothly deflects and re-trims to -7 degrees trailing edge right.

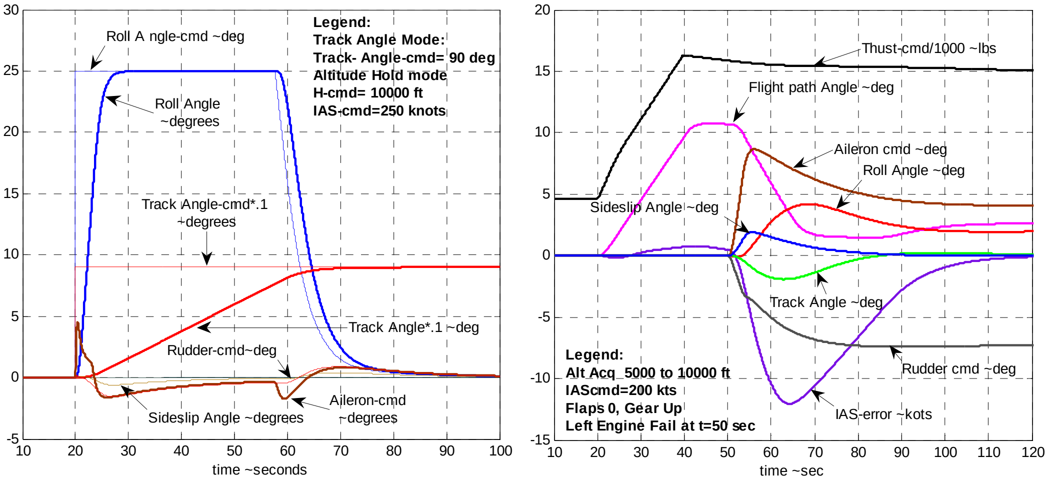

Figure 4.1 Left plot:Track Mode, Step-cmd = +90 degrees;
Right plot: Climb, Track Angle mode, Engine Failure at t=50 seconds

5 THCS Augmented Manual Roll/Yaw Control mode

Design Strategy

The design strategy for the augmented manual control mode is analogous to the strategy used for the TECS FPA based augmented manual control mode: the THCS Core controller provides the basic generalized roll attitude and sideslip control algorithm. When the pilot is not in the control loop this core controller maintains the airplane at the last roll angle established by the pilot. The roll control inceptor deflection commands a roll rate, which is integrated to develop the roll attitude command see figure 3.5. The roll control inceptor signal is normalized to +1 and -1 for full right and full left deflection. Full roll control inceptor deflection commands a roll rate equal to 30 degrees /sec, therefore $K_{stick_{roll}}$ = 30 degrees/second.

Basic Augmented Manual Roll Control. A Roll Rate Command/Roll Attitude Hold control strategy is used for roll attitudes less than 30 degrees, as shown in figure 3.5. For roll attitudes greater than 30 degrees, the lateral control inceptor deflection (δ_{lci}) still commands a proportional roll rate, but the $\varphi_{c_{ol}}$ is limited to (30 +30.δ_{lci}), so that a full roll stick deflection commands $\varphi_{c_{ol}}$ =60 degrees. Also, for roll angles greater than 30 degrees a positive spiral stability is introduced, so that the roll angle smoothly returns to 30 degrees when the δ_{lci} is returned to neutral. These high roll angle features are not shown in Figure 3.5. The basic $\varphi / \varphi_{c_{ol}}$ TF defined above for the automatic modes can easily be modified for the augmented manual mode by adding δ_{lci} feed forward command augmentation signal paths including the gains K_{FFP} and K_{FFI}. The TF for the a δ_{lci} input becomes

$$\left[\frac{\varphi}{\delta_{lci}}\right] = \frac{K_{lci}}{S}\frac{(K_{FFP}S^2 + K_{FFI}S + 1)K_p K_\varphi K_{RI}}{S^3 + K_p S^2 + K_p K_\varphi S + K_p K_\varphi K_{RI}} \tag{5.1}$$

or

$$\left[\frac{\varphi}{\delta_{lci}}\right] = \frac{K_{lci}}{S}\frac{(\tau_{R_1} S + 1)(\tau_{R2} S + 1)}{\{(1/\omega_R^2)S^2 + (2\zeta_R/\omega_R)S + 1\}(\tau_{D_R} S + 1)} \tag{5.2}$$

For example, using gains corresponding to the TECS example above: $K_p = 5$ (rad/sec^2)/(rad/sec), $K_\varphi = 1.6$ (rad/sec)/rad and $K_{RI} = .5$ rad/rad results in $\omega_R = 2$ rad/sec, $\zeta_R = 1$ and $\tau_{D_R} = 1$ and then by selecting $K_{FFI} = 1$ and $K_{FFP} = 0$ τ_{D_R} pole at -1 rad/sec cancel. This reduces the TF of (6.2) to a unity numerator and a second order denominator, producing an equivalent roll mode time constant $\tau_\varphi = 1$ second. In principle it is possible to cancel 2 poles, one at -1 rad/sec and one $\omega = -2$ rad/sec, by selecting $K_{FFP} = .5$ an $K_{FFI} = 1.5$. However this leaves an unnatural first order $\varphi / \varphi_{c_{ol}}$ TF. The effective roll mode time constant τ_φ can be changed by changing the gain K_{FFI} while maintaining the same feedback gains : K_p, K_φ and K_{RI}, but this results in a pole zero mismatch that will cause a roll angle bobble in response to a control inceptor command, thereby degrading the handling qualities in proportion to the pole zero mismatch. A better approach to adjusting τ_{φ} is the redesign the basic $[\varphi / \varphi_{c_{ol}}]_{auto}$ TF, (equation 3.1). More details on augmented manual control design strategies are presented in [5, 6, 7].

Manual Yaw Control. The yaw control inceptor (rudder pedal) deflection commands a proportional sideslip angle $\beta_{c_{ol}} = K_{pedal}.\delta_{pedal}$. The gain K_{pedal} is scheduled as function of $1/V_{true}$ or dynamic pressure ($\overline{q}$), such that full rudder pedal deflection provides adequate slideslip command authority for decrab and landing for a selected design level crosswind, while assuring that the maximum rudder deflection at high speed does not cause excessive vertical tail loads. The $\beta_{c_{ol}} = K_{pedal}.\delta_{pedal}$ produced by the rudder pedal is used in the same way as a $\beta_{c_{ol}}$ developed in the automatic landing mode to decrab the airplane prior to touchdown, without inducing a cross track acceleration. It also uses the same sideslip angle command to roll angle command cross feed gain K_{decrab}. Therefore, the airplane response to a pedal command in the augmented manual mode is in principle the same as for the $\beta_{c_{ol}}$ decrab command in the automatic landing mode, shown in figure 4.1 right plot. The pilot does not need to use manual roll cross control inputs during sideslip maneuvers in order to find and maintain the precise bank angle that produces zero cross track acceleration. However, the airplane continues to respond normally to the addition of δ_{lci} inputs. In response to a lateral gust the airplane will not roll significantly, because of the Roll Rate Command/Roll Angle Hold control strategy, but instead yaw into the side gust to reduce the induced sideslip.

Carefree Maneuver Control. For large simultaneous vertical and lateral control inceptor commands it was found necessary to design a NLF control authority allocation between pitch and roll control, because the TECS vertical control uses airspeed and NLF envelope protection functions. Therefore an ultimate bank angle limit is programmed as a function of $n_{z_{authority}}$, while reserving a certain portion of the available $n_{z_{authority}}$ for immediate vertical maneuvering and dividing op the remaining authority. It is beyond the scope of this paper to describe all these design details here. A more detailed discussion on Envelope Protection requirements and design for automatic and augmented manual control mode can be found in the companion paper **[4]**.

It is possible to further enhance the augmented manual lateral control mode to help the pilot maneuver the airplane and keep it “on Track” once the pilot releases the lateral control inceptor. The idea is to correct the commanded bank angle during a turn for the effect of wind on the airplane flight trajectory over the ground, so that the airplane will maintain a circular trajectory over the ground. This circular trajectory can then be displayed as the radius of turn arc on the NAV-display, sometimes referred to as “the noodle”. This can help the pilot with manual interception of programmed 3D track legs, without overshooting or turning short due to the change in cross wind caused by the heading change. Then when the pilot levels the airplane and the bank angle drops below a value that signals the intent to fly straight and level the Track Angle Hold function may be engaged. The result will be a reduction in pilot workload. These concepts, as reported in **[5],** were first explored during the NASA TCV program in the late 1970-ties, as part of the manual Velocity Vector Control mode which included a Track Hold submode for level flight. A limited in-flight pilot evaluation of this manual Velocity Vector Control mode on the NASA TCV B737 airplane indicated that transition logic for reversion from bank angle to level flight Track Angle control and vice versa presented some challenges, particularly when making small heading or track angle adjustments. Such a Track Angle Hold function has been incorporated in the Real Time Demonstration version of the THCS augmented manual lateral directional control mode, using less obtrusive transition logic.

6 THCS Manual Roll/Yaw Control simulation results

Figure 6.1 left plot shows the airplane response to a δ_{lci} =.1 for a duration of 10 seconds. As designed, the roll angle lags the roll angle command by an amount $\tau_{\varphi} = 1$ second. The response is smooth and overshoot free. Figure 6.1 right plot shows the airplane response to full right control inceptor input, starting at t=10 seconds and released back to zero deflection at t=30 seconds. The roll angle reaches the roll command limit of 60 degrees 5 seconds after the step inceptor command is applied. When the inceptor is released the roll angle decays back to 30 degrees over a period of ~7 seconds, due to programming of the roll angle limit: $\varphi_{c_{\lim}} = 30 + 30.\delta_{lci}$ degrees, thereby creating in effect spiral stability for $|\varphi| > 30$ degrees. As a result the pilot must hold a lateral control inceptor deflection, in order to maintain $|\varphi| > 30$ degrees.

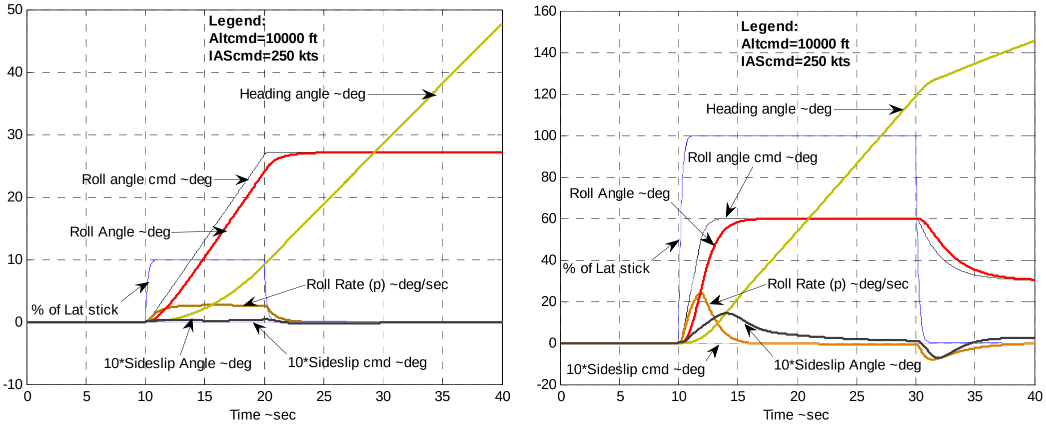

Figure 6.1 Left Plot: THCS Augmented Manual Mode responses to $\delta_{stick_{roll}}$ =.1; Right Plot: Augmented Manual Mode responses to $\delta_{stick_{roll}}$ =1 from t=10 to 30 sec

Figure 6.2 shows the airplane response to full left rudder pedal deflection at IAS=225 knots, Altitude =10000 ft.

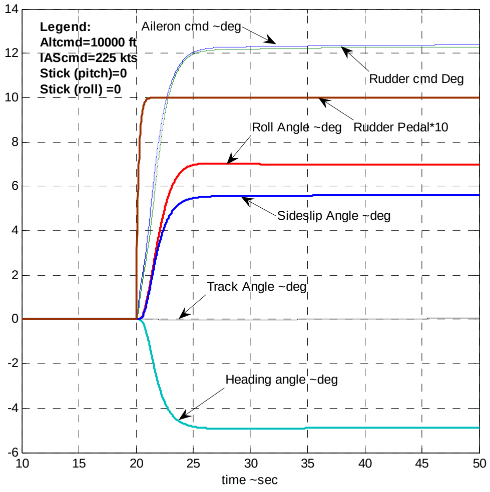

Figure 6.2 THCS Augmented Manual Mode responses to $\delta_{rudderpedal}$ =1

The airplane responds smoothly to establish a steady sideslip angle equal to 5.5 degrees, a heading angle equal to -5 degrees and a roll angle equal to ~7 degrees. The track angle stays virtually constant, as intended. It is interesting to note that this maneuver requires essentially equal magnitudes of aileron and rudder.

7 TECS THCS Interactive Real Time Simulation

An interactive Real-Time TECS/THCS Demonstration System was develop, using the Simulink Real Time Workshop program, including the twin engine transport airplane simulation, an interactive TECS/THCS Mode Control Panel (MCP) with integrated Controller Pilot Data link Communication functions, a joystick manual control capability and several versions of Primary Flight Displays (PFD) including a Flight Mode Annunciation display function. The interactive TECS/THCS Mode Control Panel and the enhanced TECS/THCS inspired "Energy Management" PFD are discussed in more details below.

8 TECS THCS Interactive Mode Control Panel

Layout and Functionality of the TECS/THCS Modes. The interactive Virtual TECS/THCS Mode Control Panel is depicted in figure 8.1. It was developed to be able to demonstrate TECS/THCS mode operations and capabilities and conduct effectiveness research on possible future MMI concepts.

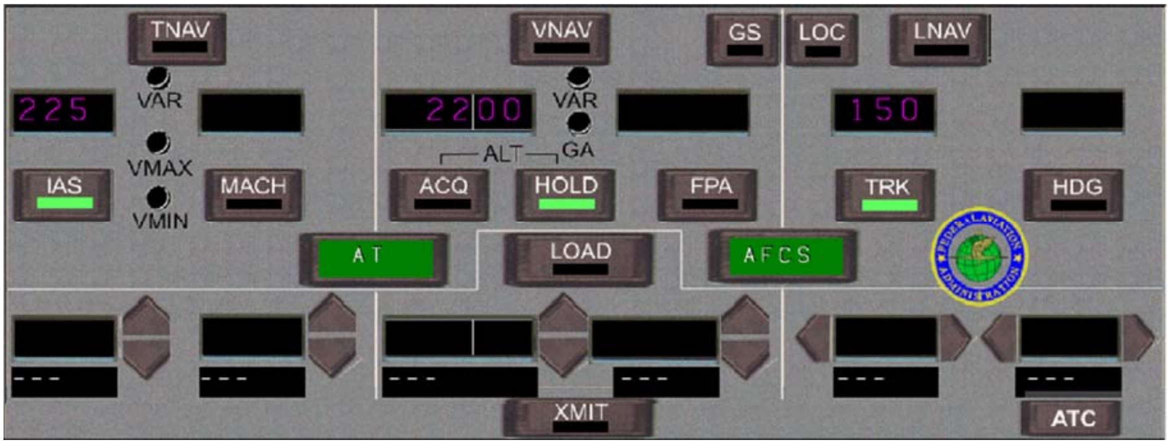

Figure 8.1. TECS/THCS Research Mode Control Panel

It does not represent a "production ready" configuration. The upper section of the panel, above the white line, provides mode control and engage status indication for all Airspeed, Vertical and Lateral Guidance and Control modes in respectively the left, middle and right sections of the panel. The airspeed and vertical path control modes have been laid out next to each other, because there are numerous energy control strategy related interactions between these modes. The mode hierarchy is reflected by locating the most complex "Managed Modes" on the top of the panel and the lower level "tactical command" modes below. Only one airspeed, vertical path and lateral path mode can be engaged at the same time and the mode buttons for the engaged modes light up in green. The "Managed Modes" modes may take inputs from the Flight Management System (FMS) such as waypoint information or from external Guidance systems such as ILS or MLS. The "TNAV" mode provides waypoint time of arrival control, sometimes referred to as the 4th dimension of "4D" airplane trajectory control.

The lower part of the panel, below the white line, represents a Cockpit-Pilot Data Link Communications (CPDLC) interface with Air Traffic Control (ATC) for the Guidance and Control functions.

TECS/THCS Mode Engagement. The green button labeled “AFCS” as shown indicates the system automatic modes are engaged. Pushing this button causes reversion to the augmented manual (FBW) control mode and changing the button label to “MAN” (indicating manual control) and the color to blue in this demo panel. Automatic Speed control normally remains engaged at all times. Pushing the mode button for any of the tactical automatic vertical path or lateral path modes when the Augmented Manual mode is engaged causes that mode and the other default modes (FPA and Track Angle) to engage. The reference commands for the tactical command modes can be changed using the CPDLC panel, as described below. The left green button labeled “AT” indicates the automatic thrust control is engaged. Pushing this button disengages the automatic thrust control and causes the vertical automatic mode – if engaged - to be dropped, so in that case by default the automatic speed control remains in effect. The button label changes to “MAN T” and the color will change to blue. It is possible to then override (disengage) the speed mode by selecting a desired vertical path mode, but this operation is only intended for emergency operations. If the augmented manual mode is engaged at the time the autothrust control is disengaged, the augmented manual control mode remains engaged and the automatic speed control mode will disengage. Operations with the automatic vertical path or the augmented manual control modes engaged with Autothust OFF are protected by the Vmin/Vmax speed envelope protection functions. Pushing the mode button for any of the “Managed Modes” causes that mode to be “Armed” (indicated by the mode button lighting up in amber), if the appropriate guidance information has been provided. The “Armed” mode will then automatically engage when the airplane reaches the correct position relative to the guidance reference information to initiate a transient free capture of the guidance reference target. The “LOC” and “GS” are armed simultaneously, but engagement generally occurs at different times. The exact Mode Engagement status is also indicated on the PFD Mode Annunciation Panel, discussed below.

Airspeed Control. The airspeed control mode is assumed to be engaged at all times. The command window shows the command speed for the mode that is engaged. Pushing the “MACH “ button causes the Mach mode to be engaged. This action memorizes the current Mach number and displays it in the command window as the current Mach command. Going from the Mach mode back to IAS mode is analogous to changing from IAS to Mach mode. The IAS and Mach modes are served by the same airspeed control algorithm. The IAS to Mach command and feedback signals are first converted into true airspeed command and feedback signals, before being used by airspeed control algorithm. The control algorithm includes automatic mode reversion from IAS to MACH during climb and vice versa during descent, triggered by reaching the internal set point Mach or IAS engage values. The IAS or Mach-Command can be selected using the CPDLC panel, but the range is limited to Vmin-auto on the low end and Vmax-auto on the upper end. Typically, Vmin-auto = 1.2Vstall and Vmax-auto = Vmo/Mmo is used.

Vertical Flight Path Control. The lowest level vertical path mode is FPA. When the FPA mode is engaged the actual PFA is memorized and used as the FPA command and displayed in the FPA command window. The reference FPA-command can then be changed, as desired, using the associated command slew buttons of the CPDLC panel. Dialing in a FPA command in excess of the airplane capability at the commanded airspeed will result in climb or descent at maximum or idle thrust, with speed controlled through the elevator. The FPA mode can only be used to command the airplane to fly toward the reference Altitude-command of the Altitude Acquire mode as shown in the Altitude-command window of the MCP. This window is typically used to dial in the ATC clearance altitude. The Altitude Acquire and Altitude Hold modes use the same control algorithm, only the reference Altitude-command is different. The Altitude Acquisition mode is always armed, except when the Glide Slope/Localizer mode is armed or engaged, and will engage automatically when climbing or descending in the FPA mode to smoothly capture the altitude shown in the altitude command window. The Altitude Acquisition mode can also be engaged directly by pushing the associated mode button. When the Altitude Acquisition mode is engaged, changes to the reference altitude-command displayed in the window are executed immediately. The Altitude Acquire mode commands a normal acceleration limited climb or descent toward the reference altitude command. The commanded climb angle will be proportional to the difference between the current airplane altitude and the reference altitude command. If the resulting flight path angle command is in excess of the airplane capability at the commanded airspeed, the airplane will climb or descent at maximum or idle thrust, with speed controlled through the elevator, until the final capture of the commanded altitude. The Altitude Acquisition mode automatically reverts to Altitude Hold when the altitude error drops below 100 ft. At that point the Altitude Acquisition reference altitude command is memorized to serve as the reference altitude command for the Altitude Hold mode. The Altitude Hold mode can be engaged manually at any time during vertical maneuvering by pressing the associated mode button on the MCP. In that case, the reference altitude-command is computed at the time the Altitude Hold button is pushed, to produce a smooth transition to level flight. The Go Around mode does not have a dedicated engage button on the MCP. This mode is normally engaged by pressing the "Go Around" switch on the Throttle levers. Go Around engagement is indicated on the MCP by the "GA" light.

Operation of the MCP "VAR" lights. When the FPA or Altitude Acquisition mode is engaged and the flight path angle command is in excess of the airplane capability for the commanded airspeed, the airplane will execute a "best effort climb or descent" at maximum or idle thrust, with the airspeed controlled through the elevator. In that case the climb/ descent rate will depend on the prevailing thrust and drag and the VAR light in the Vertical mode section of the MCP will light up to indicate that the vertical flight path is not actively controlled. When during the final capture of the reference altitude command the thrust command comes off the Tmax or Tmin limit the VAR light extinguishes. Similarly, the Glide Slope and augmented manual control mode use a flight path control priority when during vertical maneuvering the thrust command reaches Tmax or Tmin, leaving the airspeed to respond open loop, as long as the Vmin or Vmax airspeed envelope protection is not invoked. In that case the "VAR" light in the airspeed control section of the MCP will light up.

MCP "Vmin" and "Vmax" indication lights. Whenever the airplane operates with the Vmin or Vmax command as the active speed control command reference this condition will be indicated by lighting the "Vmin" or "Vmax" light in the airspeed control section of the MCP, whichever applies.

Lateral Flight Path Control. The "HDG" (Heading) and "TRK" (Track) angle modes use commands that the memorized heading or track angle at the time of mode engagement. These commands can be changed through the CPDLC panel. A bank angle limit is imposed during execution of the command. The TRK mode is used as the default mode because it is most effective, e.g. for missed approach.

CPDLC Functions. The integrated CPDLC can be operated with or without ATC data link connection, using the selection button in the lower right corner of the panel. When connected to ATC, the panel receives the own-ship ATC commands for airspeed, altitude and possibly FPA, Track or Heading and the color of the associated numerical display will be green. Any green CPDLC command can be uploaded directly into the FG&C panel by pressing the LOAD button. The pilot can edit any received command before he loads it into the FG&C panel. This will change the color of the edited command to amber and prevent it from being uploaded. The pilot must then download it to ATC for approval by pressing the "XMIT" button. If ATC approves the edited command, ATC will resend the command(s) back to the airplane, causing the affected CPDLC display windows to turn green again.

9 Energy Management PFD and Flight Mode Annunciation

Energy Management PFD. The TECS energy based control strategy and the THCS Heading control strategy can be implemented into the Primary flight Display (PFD), to bring out control guidance cues for using manual Thrust, Pitch and Roll control. This will help the pilot to efficiently and simultaneously capture and track airspeed, altitude and heading targets in an efficient exponential and overshoot-free manner. This display concept may reduce or eliminate the need for a Flight Director, while enhancing pilot awareness of the airplane dynamic state and how to control it in and (energy) efficient manner with minimal effort. This display concept is shown in Figure 9.1. In this display the airspeed and altitude scales have been normalized to represent the same delta energy per unit scale length and all the other scales have been normalized to conform to this scaling concept. The scaling of airspeed in terms of ft/sec true airspeed per unit scale length is fixed. Therefore, in order to maintain the proper energy scaling relative to the airspeed scale, the altitude scale in terms of ft of altitude per unit scale length increases in proportion to true airspeed. So at low speed the altitude scale exhibits a higher resolution. This scaling choice facilitates tight vertical path control at low speed, e.g. during final approach. The vertical speed and the acceleration scales have been located on the inside of the altitude and indicated airspeed scales respectively and a convenient scaling ratio, here 10:1, has been adopted between altitude and vertical speed and indicated airspeed and acceleration. So, for example, a scale length that represents 1000 ft of altitude on the attitude scale, represents 100 ft/sec or 6000 ft/min on the vertical scale and a scale length that represents 10 knot of indicated airspeed on the speed scale, represents 1 knot/sec acceleration scale.

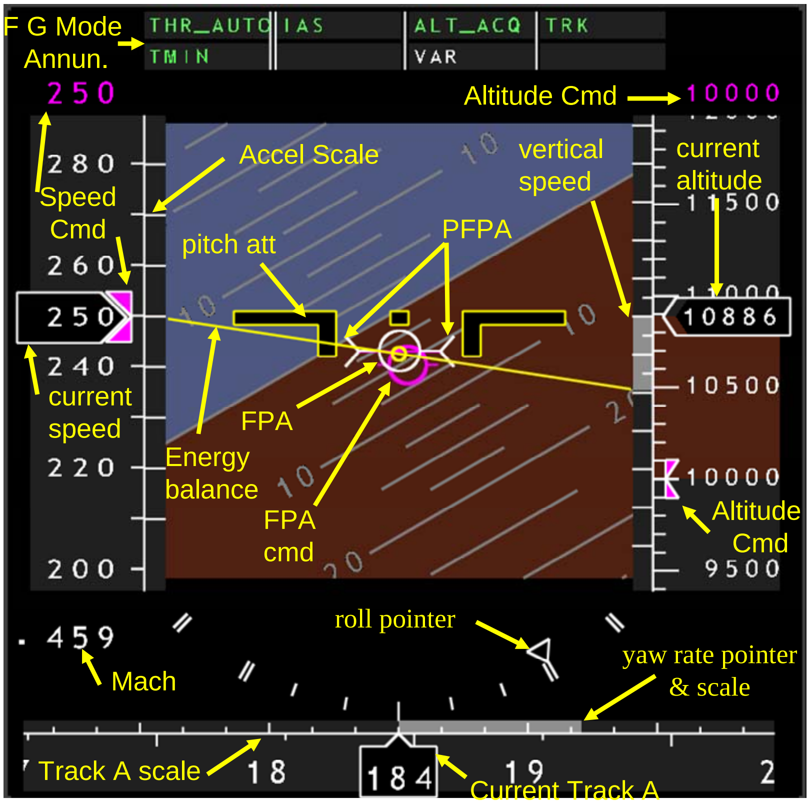

Figure 9.1. Energy Management PFD

The ”Energy Balance” line is not part of the display, but serves only to illustrate how the current thrust (energy rate) is being used. This ”Energy Balance” line connects the current vertical speed indication and the current acceleration. The PFPA (Potential Flight path Angle=$(\gamma + \hat{\dot{V}} / g)$) lies on the center pivot point. As shown, the energy rate is negative, represented entirely by the descent rate (the acceleration is zero). Application of nose up elevator causes the ”Energy Balance” line to rotate counter clock wise about its center, increasing the vertical speed and causing a deceleration of the same magnitude in terms of the change in energy rate. Application of positive thrust causes the ”Energy Balance” line (and thus the PFPA symbol) to shift up. Thrust can be trimmed for level flight by moving the throttles until the center the ”Energy Balance” line (the PFPA symbol) falls on the horizon, but then in order to maintain speed constant pitch control needs to be applied simultaneously to bring the vertical speed back to zero. In general, to capture and track a speed and altitude target simultaneously, pitch control is applied to equalize the speed and altitude errors, as indicated by the ”Energy Balance” line. Then thrust needs to be applied to shift the ”Energy Balance” line until the end points line up with the airspeed and altitude targets. Keeping the ”Energy Balance” end points lined up with the airspeed and altitude targets results exponential capture of the speed and altitude targets with a 10 second time constant. Then, if the TECS automatic speed and altitude control modes use the same 10:1 guidance ratio (by selecting Kv=Kh=.1), the manual and automatic control strategies are essentially the same. Hence the pilot can use the same "mental model" for manually controlling airspeed and altitude and for monitoring automatic execution of airspeed and altitude commands. Furthermore, the EMPFD indicates at all time how much altitude the airplane can gain for a certain amount of speed loss, e.g. the speed margin to Vmin. In the scenario shown the thrust is at idle, the airspeed is constant and the airplane is in a steady state descent reducing the altitude error. Thus the altitude command bug will soon line up with the vertical speed indication. At that point, the final exponential capture of the altitude command will begin, with the thrust coming up out of the idle limit and the vertical speed maintaining alignment with the altitude command bug, while the altitude error goes to zero. When during the execution of a large altitude and/or speed command the vertical speed and/or acceleration indication does not line up with the altitude and/or speed command bug, it indicates that the command is being executed with a "best effort", meaning that the trust is at the upper or lower limit, while the complementary speed or altitude control objective is also being addressed at the same time. This way the pilot can anticipate the start of the final speed and/or altitude capture.

An equivalent guidance strategy is also implemented for lateral control. In Figure 9.1 the airplane is shown in a turn to the right, executing a large Track Angle command. The Track Angle command bug is still out of view on the right. The automatic Track Angle control mode has a 30 degree bank angle maneuver limit, resulting in a corresponding Track Rate indication. When the track angle error reduces to the point where the Track Angle command bug lines up with the Track Rate indication, the final Track Angle Command capture maneuver will be initiated and from that point on both the Track Angle error and Track rate will go to zero simultaneously. Thus the pilot can use this display to execute the same guidance strategy as the automatic Track Angle control mode uses. The development of the EMPFD is described in more details in **[8].**

Flight Mode Annunciation. An enhanced TECS/THCS Flight Mode Annunciation Panel (FMA) is provided at the top of the EMPFD of figure 9.1. On the top line most left column it indicates the automatic control mode status for autotothrust (THRUST_AUTO or "blank" when the autothust is disengaged). On the right of the autothrust mode indication is the automatic speed mode indication (IAS or MACH). On the right of the automatic speed mode indication is the vertical flight path mode indication (FPA, ALT_ACQ, VNAV, GL SL, GO AR, or "blank" when the augmented manual control mode is engaged). The right most column top line indicates the automatic lateral control mode status (TRK, HDG, LOC, LNAV). The second line of the thrust mode column is used to annunciate when a thrust limit condition is in effect (Tmax or Tmin). The second line of the airspeed mode column is used to annunciate that the speed control is "open loop" (not controlled directly) displayed by the mnemonic "VAR" (meaning variable), when the thrust is at the upper or lower limit and the **PoECP** (l Path on Elevator Control Priority) is in effect. On this line the mnemonic "Vmin" or "Vmax" is indicated when the Vmin to Vmax protection overrides a **PoECP** control mode. The second line of the vertical mode column is used to annunciate that the vertical path control is "open loop" (not controlled directly), displayed by the mnemonic "VAR" (meaning variable), when the thrust is at the upper or lower limit and the **SoECP** (Speed on Elevator Control Priority) is in effect. It is also used to announce the arming status of the Glide Slope or VNAV mode when one of these modes has been armed. The second line of the lateral mode column is used to annunciate the arming status of the Localizer or the LNAV mode when one of these modes has been armed.

8 Conclusion

The generalized MIMO based Total Heading Control System has been developed to functionally integrate all lateral directional automatic and augmented manual control modes, using one common multi variable control strategy to achieve consistent system operation and performance for all modes. This paper describes more recently developed features, including the application of Airplane Dynamic Model to further enhance the ease reuse of the design on different airplanes. Further studies need to be conducted to evaluate the system functional and performance capabilities in the augmented manual control mode and to optimize the performance in turbulence and windshear and establish the preferred trade off between various performance indicators. Finally, short descriptions are included of the operational capabilities of a virtual TECS/THCS real time simulation demonstration system, including a Mode Control Panel, a CPDLC panel and an advanced Energy Management Primary Flight Display. All these system component are developed using one common control and operating strategy, such that pilots can use one mental model for all automatic and augmented manual mode operations.

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