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Adaptive Model Inversion Flight Control for Tilt-Rotor Aircraft

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Neural-network augmented model inversion control is used to provide a civilian tilt-rotor aircraft with consistent response characteristics throughout its operating envelope, including conversion flight. The implemented response type is Attitude Command Attitude Hold in the longitudinal channel. Conventional methods require extensive gain scheduling with tilt-rotor nacelle angle and speed. A control architecture that can alleviate this requirement, and thus has the potential to reduce development time and cost, is developed. This architecture also facilitates the implementation of desired handling qualities and permits compensation for partial failures. One of the powerful aspects of the controller architecture is the accommodation of uncertainty in control as well as in the states. It includes an online, i.e., learning-while-controlling, neural network that is initialized with all weights equal to zero. Lyapunov analysis guarantees the boundedness of tracking errors and network parameters. Performance of the controller is demonstrated using a nonlinear generic tilt-rotor simulation code.

Nomenclature

$\hat{f}^{-1}$ = linear inversion at nominal operating point
K_{AC} = mechanical or rigging gain
K_{PD} = transfer function of proportional and derivative gains, $K_P + s \cdot K_D$
$U_{AD\theta}$ = network compensation
$U_{\mathrm{PD}\theta}$ = proportional+ derivative tracking error dynamics
U_θ = pseudocontrol; a desired angular acceleration, defined in Eq. (2)
X = aircraft states; body rates
$\bar{X}$ = aircraft states; scaled for neural network input
$\hat{\delta}_{LON}$ = commanded actuator deflections
δ_P = pilot stick displacement
Θ_C, Θ = filter output; commanded state vector and actual state vector, $\Theta = [\theta \;\; \dot{\theta}]^T$
$\tilde{\Theta}$ = tracking error, $\Theta_C - \Theta$
θ = aircraft pitch angle
θ_{COM} = filter input; Euler pitch attitude command
$\ddot{\theta}_C$ = filter output; commanded pitch acceleration

Introduction

BOEING, Bell Helicopter Textron, Inc., and NASA are jointly working on a civilian tilt-rotor aircraft (CTR) that builds on the XV-15 and V-22 technologies and that they will extend to civilian applications. A CTR provides a unique challenge for flight-control augmentation because it displays a variety of handling characteristics as it converts from cruise flight to helicopter configuration. This paper suggests a powerful low-cost method to provide the CTR with consistent Level 1 responses throughout its operating envelope.

Feedback linearization is a popular method used in nonlinear control applications,[1] and there have been several advanced flight control demonstrations.[2] Dynamic model inversion is the feedback linearization method employed in this study. This method is very effective in applications to high angle-of-attack fighter aircraft.[3–5] The main drawback of dynamic model inversion is the need for high-fidelity nonlinear force and moment models that must be inverted in real time, which implies a detailed knowledge of the plant dynamics, and the approach tends to be computationally intensive. In general, dynamic model inversion is sensitive to modeling errors.[6] The application of robust and/or adaptive control can alleviate this sensitivity and therefore the need for detailed knowledge of the nonlinearities.[1,7,8] However, to date, the adaptive control literature has assumed linearity in control. This assumption is not valid over the CTR operating envelope. The neural-network-based adaptive scheme applied here allows for nonlinearities and uncertainties in the controls as well as in the states.

Dynamic model inversion control is applied based on a single nominal operating point of the tilt-rotor aircraft operating in helicopter configuration, 30 kn, sea level at maximum gross weight. Operation at any other flight condition or configuration will result in an inversion error. Augmenting the model inversion with a linear online neural network that is learning while controlling compensates for this error. The network update law is derived from a Lyapunov stability analysis based on tracking error and network performance.[9] This ensures boundedness of both the tracking error as well as the network weights. In this work Euler angles were used to implement commanded acceleration response and attitude stabilization. A rate command application, combined with timescale separation of translational and rotational dynamics, was used to provide trajectory control for an AH-64 helicopter in Ref. 10. Furthermore, we employ a network architecture that is linear in the weights, as in Refs. 9 and 10, but note that the guarantee of boundedness was extended to nonlinearly parameterized network structures in Ref. 11. A linearly parameterized network is simpler to implement and appears to be adequate for this application.

The augmentation architectures presented here are applied to the XV-15 represented by the high fidelity Generic Tilt-Rotor Simulator[12] (GTRS) used at the NASA Ames Research Center. A comparison is made with the original stability and control augmentation system (SCAS)[12,13] to illustrate the performance improvements in comparison with that obtained using conventional gain-scheduling methods.

By design, a bandwidth separation between the tracking error dynamics and the command filter allows for easy implementation of the Aeronautical Design Standard-33D[14] (ADS-33D) requirements for the different channels. The present work specifically addresses the implementation of Attitude Command Attitude Hold in the longitudinal channel.[15] A similar architecture for Rate Command Attitude Hold augmentation and Turn Coordination in the lateral channels is presented in Ref. 16.

The first section contains a description of desired handling characteristics and associated terminology. The following section outlines the implementation of the augmented-model inversion control architecture. The neural network structure used for this work is described next. Numerical results and evaluative remarks with respect to ADS-33D are included in the final section.

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Flight-Control Augmentation for a Civilian Tilt-Rotor

Two common types of control augmentation for aircraft are referred to as Rate Command Attitude Hold (RCAH) and Attitude Command Attitude Hold (ACAH). A good overview of various types of augmentation for the different control channels as used in the V22 are provided in Ref. 17. Reference 18 represents an example of the considerations involved in an approach procedure, including 1) a schedule for the conversion of mast angle with speed, from airplane to helicopter in the regular approach and vice versa for a missed approach procedure; 2) deployment or retraction of flaps depending on nacelle angle, speed, and glide slope; 3) switching between augmentation types; and 4) desired altitude and speed trajectories.

The tilt-rotor provides a unique challenge because its control responses change as it converts from forward flight in aircraft configuration to slow flight as helicopter. Starting in airplane configuration, the throttle is used for speed, and the longitudinal control (cyclic or stick) is used to initiate climb and descend. As the aircraft decelerates and converts into a helicopter configuration, these controls trade roles. The throttle now represents the collective, controlling climb and descend; the longitudinal control results in changes in speed. In all flight conditions the primary effect of longitudinal control is a change in pitch attitude. The attitude response to a longitudinal control input is therefore of considerable interest. A detailed report on the augmentation is provided in Ref. 15.

ADS-33D[14] prescribes Attitude Hold as the pitch attitude angle returning to $\pm 10\%$ of the peak excursion in less than 10 s following a pulse input. Similarly, Attitude Command implies that a step pitch command shall produce a proportional pitch attitude change within 6 s. ADS-33D contains quantitative handling qualities for military rotorcraft. These requirements are implemented through design of a command filter (Fig. 1).

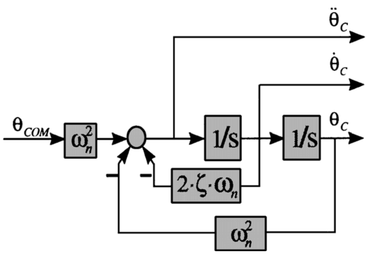

Fig. 1 Command filter.

Neural-Network Augmented Model Inversion Architecture

This section details the architecture of the neural-network (NNW) augmented-model inversion as applied to the tilt-rotor aircraft, which is based on the applications as described in Refs. 9 and 10. Figure 2 contains a schema of the architecture used for implementation of ACAH control in the pitch channel. The presented architecture provided for excellent results in the longitudinal application. Preliminary results in the lateral channels have shown similar performance.

Dynamic model inversion is used as the feedback linearization method of choice. The true aircraft is represented by the GTRS nonlinear model for the XV-15. The model inversion control is based on the linearized dynamics at 30 kn, in helicopter configuration, with the rotor dynamics residualized.

$$\begin{Bmatrix} \dot p \\ \dot q \\ \dot r \end{Bmatrix} = A_1 \cdot \begin{Bmatrix} u \\ v \\ w \\ \delta_{COL} \end{Bmatrix} + A_2 \cdot \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} + B \cdot \begin{Bmatrix} \delta_{LAT} \\ \delta_{LON} \\ \delta_{PED} \end{Bmatrix} \tag{1}$$

where A_1, A_2, and B represent, respectively, the aerodynamic stability and control derivatives at the nominal operating point. One of the objectives of this paper is to demonstrate that the NNW is capable of adapting to errors caused by the linearized inverted model. Unmodeled dynamics originate from the linearization used in the derivation of the nominal inverting controller, which may include linearization of dynamics nonlinear in the control. Any cross-coupling between fast rotational states and slow translational states is neglected in the inversion.

For the ACAH augmentation in the longitudinal channel, pitch attitude θ and its primary control δ_{LON} are of particular interest. We consider inversion control using Eq. (1); this involves replacing the left-hand side of the equation with commanded angular accelerations and solving for the control perturbations. From the control architecture in Fig. 2, the pseudocontrol for the three rotational degrees of freedom is designed in terms of Euler angles as

$$U = \begin{Bmatrix} U_\phi \\ U_\theta \\ U_\psi \end{Bmatrix} = \begin{Bmatrix} U_{\mathrm{PD}\phi} \\ U_{\mathrm{PD}\theta} \\ U_{\mathrm{PD}\psi} \end{Bmatrix} + \begin{Bmatrix} \ddot\phi_C \\ \ddot\theta_C \\ \ddot\psi_C \end{Bmatrix} - \begin{Bmatrix} 0 \\ U_{AD\theta} \\ 0 \end{Bmatrix} \tag{2}$$

$U_{AD\theta}$ is an adaptive signal that represents the NNW augmentation in the pitch channel. The proportional-derivative (PD) dynamics for the longitudinal channel are designed as

$$U_{\mathrm{PD}\theta} = K_D \cdot (\dot\theta_C - \dot\theta) + K_P \cdot (\theta_C - \theta) \tag{3}$$

The gains K_P and K_D are used to define the error dynamics. Bandwidth separation between the PD dynamics and the command filter ensures that the handling qualities are not affected by these dynamics. Yet they are designed slow enough so as not to interfere with actuator dynamics. The quantities θ_C and $\dot\theta_C$ are outputs of the command filter. Thus the command filter serves both to limit the input rate and as a model for desired response, which allows for straightforward implementation of ADS-33D handling quality specifications. Similar construction applies to the lateral channels.

To use the pseudocontrol in Eq. (2), it needs to be transformed from the Euler frame to the body axes. In terms of the individual components and assuming control of Euler angular accelerations in all three channels, the equivalent body angular acceleration commands are computed as indicated in Eq. (4):

$$\begin{aligned} \dot p_C &= U_\phi - U_\psi \cdot s_\theta - \dot\psi \cdot \dot\theta \cdot c_\theta \\ \dot q_C &= U_\theta \cdot c_\phi - \dot\theta \cdot \dot\phi \cdot s_\phi + U_\psi \cdot s_\phi \cdot c_\theta \\ &\quad + \dot\psi \cdot \dot\phi \cdot c_\phi \cdot c_\theta - \dot\psi \cdot \dot\theta \cdot s_\phi \cdot s_\theta \\ \dot r_C &= -U_\theta s_\phi - \dot\theta \cdot \dot\phi \cdot c_\phi + U_\psi c_\phi c_\theta - \dot\psi \cdot \dot\phi \cdot s_\phi c_\theta - \dot\psi \cdot \dot\theta \cdot c_\phi s_\theta \end{aligned} \tag{4}$$

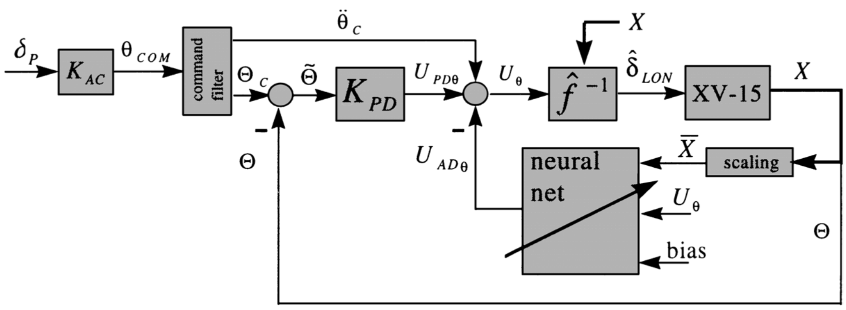

Fig. 2 NNW augmented model inversion architecture.

where s_ϕ is shorthand for $\sin(\phi)$, etc. Replacing the left-hand side of Eq. (1) with $\{\dot{p}_C \;\; \dot{q}_C \;\; \dot{r}_C\}^T$ and inverting gives

$$\begin{Bmatrix} \delta_{LAT} \\ \delta_{LON} \\ \delta_{PED} \end{Bmatrix} = B^{-1} \cdot \left\{ \begin{Bmatrix} \dot{p}_C \\ \dot{q}_C \\ \dot{r}_C \end{Bmatrix} - A_1 \cdot \begin{Bmatrix} u \\ v \\ w \\ \delta_{COL} \end{Bmatrix} - A_2 \cdot \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right\} \tag{5}$$

Because in practice A_1, A_2, and B are not represented exactly, we actually obtain $\hat{\delta}$.

$$\begin{Bmatrix} \hat{\delta}_{LAT} \\ \hat{\delta}_{LON} \\ \hat{\delta}_{PED} \end{Bmatrix} = \hat{B}^{-1} \cdot \left\{ \begin{Bmatrix} \dot{p}_C \\ \dot{q}_C \\ \dot{r}_C \end{Bmatrix} - \hat{A}_1 \cdot \begin{Bmatrix} u \\ v \\ w \\ \delta_{COL} \end{Bmatrix} - \hat{A}_2 \cdot \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right\} \tag{6}$$

The inversion error in this case is defined as

$$\varepsilon \equiv \begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} - \left\{ \hat{A}_1 \cdot \begin{Bmatrix} u \\ v \\ w \\ \delta_{COL} \end{Bmatrix} + \hat{A}_2 \cdot \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} + \hat{B} \cdot \begin{Bmatrix} \hat{\delta}_{LAT} \\ \hat{\delta}_{LON} \\ \hat{\delta}_{PED} \end{Bmatrix} \right\} \tag{7}$$

We may equivalently represent the effect of ε in the pitch attitude dynamics as

$$\ddot{\theta} = U_\theta + \varepsilon_\theta \tag{8}$$

Combining Eqs. (2), (3), and (8), we have

$$\ddot{\tilde{\theta}} + K_D \cdot \dot{\tilde{\theta}} + K_P \cdot \tilde{\theta} = U_{AD\theta} - \varepsilon_\theta \tag{9}$$

where $\tilde{\theta} = \theta_C - \theta$ and ε_θ is the pitch component of the inversion error when represented in the Euler frame. Equation (9) represents the error dynamics with the network compensation error as the forcing function. In the ideal case the NNW output cancels ε_θ.

NNW Structure and Adaptation

The NNW can consist of any linearly parameterized feedforward structure that is capable of approximately reconstructing the inversion error. For this demonstration a two-layer sigma-pi network was used. The inputs to the network consist of the longitudinal state variables, the pseudocontrol, and a bias term. Figure 3 shows a general depiction of a sigma-pi network. The values v_i represent the weights associated with a nested Kronecker product of input signal categories, Eq. (14), and therefore they are (binary) constants. The values $\hat{w}_i$ are the variable network weights.

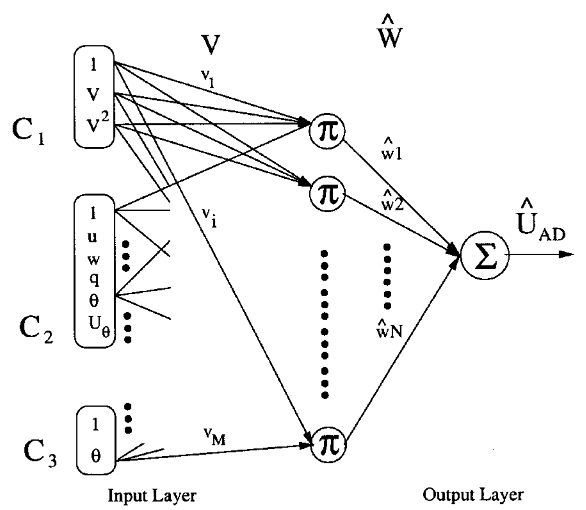

Fig. 3 NNW structure.

The input/output map of the neural network for the longitudinal channel may be represented as

$$U_{AD\theta} = \hat{W}^T \cdot \beta(\bar{X}, U_\theta) \tag{10}$$

where $\hat{W}$ is a vector of variable network weights, β is a vector of network basis functions, and $\bar{X}$ represents the normalized states. The basis functions are chosen from a sufficiently rich set of functions, so that the inversion error function ε_θ can be accurately reconstructed at the network output. The basis functions were constructed by grouping normalized inputs into three categories. The first category is used to model inversion error due to changes in airspeed because the stability and control derivatives are strongly dependent on dynamic pressure.

$$C_1: \{1, V, V^2\} \tag{11}$$

In allowing the plant to be nonlinear and uncertain in the control as well as in the states, the inversion error is a function of both state and pseudocontrol. These and a bias are therefore contained in the second category:

$$C_2: \{1, u, w, q, \theta, U_\theta\} \tag{12}$$

The third category is used to approximate higher-order effects due to changes in pitch attitude. These are mainly due to the transformation between the body frame and the inertial frame.

$$C_3: \{1, \theta\} \tag{13}$$

Finally, the vector of basis functions is composed of combinations of the elements of C_1, C_2, and C_3 by means of the Kronecker product:

$$\beta = \mathrm{kron}[\mathrm{kron}(C_1, C_2), C_3] \tag{14}$$

where

$$\mathrm{kron}(x, y) = [x_1 y_1 \quad x_1 y_2 \quad \cdots \quad x_m y_n]^T \tag{15}$$

For the Lyapunov analysis equation (9), the error dynamics can be rewritten as

$$\dot{e} = A \cdot e + b \cdot \tilde{W}^T \cdot \beta + b \cdot \left(W^{*T} \cdot \beta - \varepsilon_\theta\right) \tag{16}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -K_P & -K_D \end{bmatrix}, \qquad b = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \qquad e = \begin{bmatrix} \tilde{\theta} \\ \dot{\tilde{\theta}} \end{bmatrix} \tag{17}$$

and

$$\tilde{W} = W - W^* \tag{18}$$

W^* denotes the optimal weights, the precise nature of which is not essential for the proof of convergence. Because the input to the NNW includes the pseudocontrol signal U_θ, which in turn is a function of the output of the NNW U_{AD}, a fixed-point problem occurs (Fig. 4). We make the assumption that U_{AD} exists. The consequence is that the term $|W^{*T} \cdot \beta(z) - \varepsilon_\theta(z)|$ is bounded. As detailed in Refs. 9 and 10, the existence of the fixed point cannot be guaranteed when unbounded basis functions of U_θ are allowed. However, singularities can readily be avoided by proper choice of $\beta(\bar{X}, U_\theta)$, see e.g., Ref. 16.

The adaptation law is derived by using a Lyapunov energy function consisting of the tracking error e and the NNW-weights error $\tilde{W}$:

$$V = \frac{1}{2} e^T \cdot P \cdot e + \frac{\tilde{W}^T \cdot \tilde{W}}{2 \cdot \gamma} \tag{19}$$

A Lyapunov stability analysis[9] then suggests that the network weights be adapted on-line according to the following equation:

$$\dot{W} = -\gamma \cdot s \cdot \beta \tag{20}$$

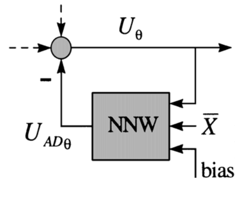

Fig. 4 Fixed-point assumption.

where $\gamma > 0$ is the adaptation gain and

$$s = \frac{1}{2 \cdot K_P} \cdot \tilde{\theta} + \frac{1}{2 \cdot K_D/(1 + K_P) \cdot K_P} \cdot \dot{\tilde{\theta}} \tag{21}$$

Though not necessary for stability, the implementation relies on the use of a dead zone in which the adaptation law is turned off when a weighted norm of the error signals is small. The purpose of the dead zone is to account for the fact that the network cannot exactly reconstruct the functional form of the inversion error. Alternatives to the dead zone and their effects are described in Ref. 11.

Numerical Results

The XV-15 itself is represented by the comprehensive nonlinear GTRS code. This code includes complete augmentation, here referred to as original SCAS. This SCAS is gain scheduled with speed and with mast angle (though not with altitude). In the longitudinal channel it provides ACAH and RCAH, depending on the mode selected by the pilot. The ACAH setting was used for the comparison in the following results.

Model inversion control, as given by Eq. (6), was applied to the XV-15 with the aerodynamics linearized about the 30-kn-level flight helicopter configuration. The linear model used for inversion is based on the assumption that the rotor was in a quasisteady state. The dominant complex poles of the command filter (Fig. 1) provide minimal overshoot ($\zeta = 0.8$) and a 5% settling time of 1.5 s ($\omega_n = 2.5$ rad/s), which provides Level 1 handling characteristics in the pitch channel.[14] The gains K_P and K_D were chosen so that the error dynamics settle in 0.5 s ($\zeta = 1.0$, $\omega_n = 6.0$ rad/s).

Figure 5 shows the response to a commanded-square-wave pitch input, shaped by the command filter. The aircraft is trimmed at the 30-kn-level flight helicopter configuration. During the first 30 s, the aircraft responds using the original gain scheduled SCAS design; the aircraft remains within 10 kn and within 250 ft of its altitude. At $t = 30$ s the model inversion SCAS is activated as evidenced by the NNW weight histories. The improvement in pitch response is clearly visible in Fig. 5.

Figure 6 shows the results of engaging the model inversion SCAS near one of the boundaries of the operating envelope. The XV-15 is flying in airplane configuration with 300 kn at 35,000 ft. Two remarks are important here. First, the original SCAS is not scheduled with altitude and merely serves to show the effects of operating at 35,000 ft. Second, the NNW is now suddenly engaged, which is not likely to be a normal operating procedure. However, it shows the essential effects of the adaptation of the weights initialized at zero. Figure 7 shows a detail of this process.

At the first second the aircraft is flying open-loop in approximate trim flight at 35,000 ft. At $t = 1$ s the model inversion SCAS is suddenly activated. The model inversion is based on the 30 kn trim values, and this instantaneously causes an actuator deflection that reflects this discrepancy. However, in the next 0.5 s the NNW, with the initial weights all zero, is able to adjust for the error caused by the model inversion. (Actuator dynamics are not modeled in GTRS, but similar applications with actuator dynamics modeled have not shown significant differences.)

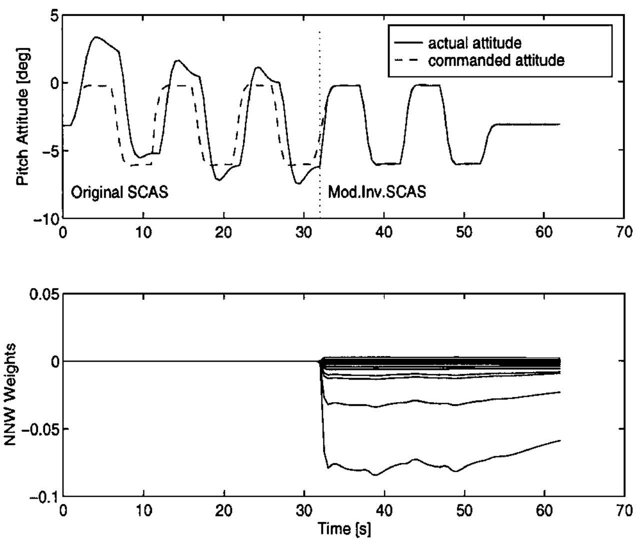

Fig. 5 Comparison near the nominal operating point.

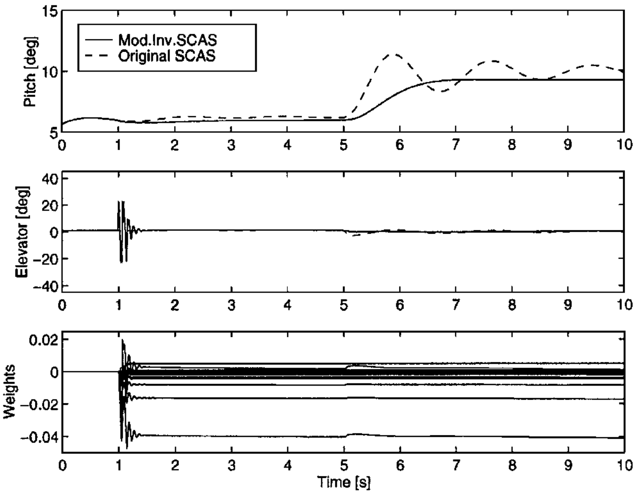

Fig. 6 Step response at 300 kn, 35,000 ft, aircraft configuration.

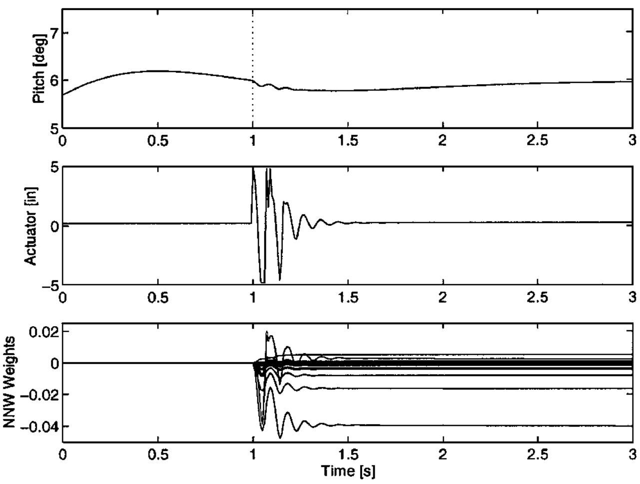

Fig. 7 Detail of step response shown in Fig. 6.

Evaluation

ADS-33D[14] states as one of the so-called Level 1 (most stringent) flying quality requirements: The pitch attitude shall return to $\pm 10\%$ of the peak excursion, following a pulse input, in less than 10 s (flight in Instrument Meteorological Conditions), and the attitude [.] shall remain within the specified 10% for at least 30 s. Figure 8 shows the results for the longitudinal channel at the nominal operating point in helicopter configuration. The model inversion SCAS provides a Level 1 response whereas the original SCAS does not.

With zero-commanded input the architecture in Fig. 2 provides the hold-part or stabilization-part of ACAH by the dynamics determined by K_P and K_D, i.e., the error dynamics as represented by Eq. (9). With reference to the two remarks made regarding Fig. 6, Fig. 9 shows the Attitude Hold performance at the 35,000-ft condition in aircraft configuration.

To further evaluate the performance of the NNW adaptive control, a pilot model was developed. This model is able to perform such tasks as 1) follow desired altitude profiles; 2) follow desired speed profiles; 3) operate on both sides of the power curve; 4) convert, including flaps as well as nacelle angle changes; and 5) operate with different SCAS modes. The pilot model can provide lead, lag, or act as a $P + I$ controller if necessary. Root locus methods were used to select desirable closed-loop characteristics. Reference 15 details the development of the longitudinal pilot model, which includes the mixing of control strategies mentioned earlier.

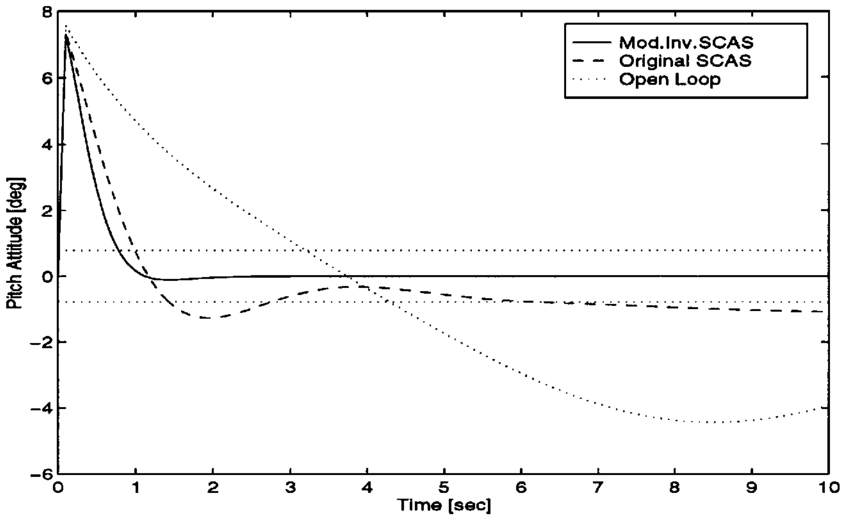

Fig. 8 Attitude Hold demonstration at nominal operating point, helicopter configuration.

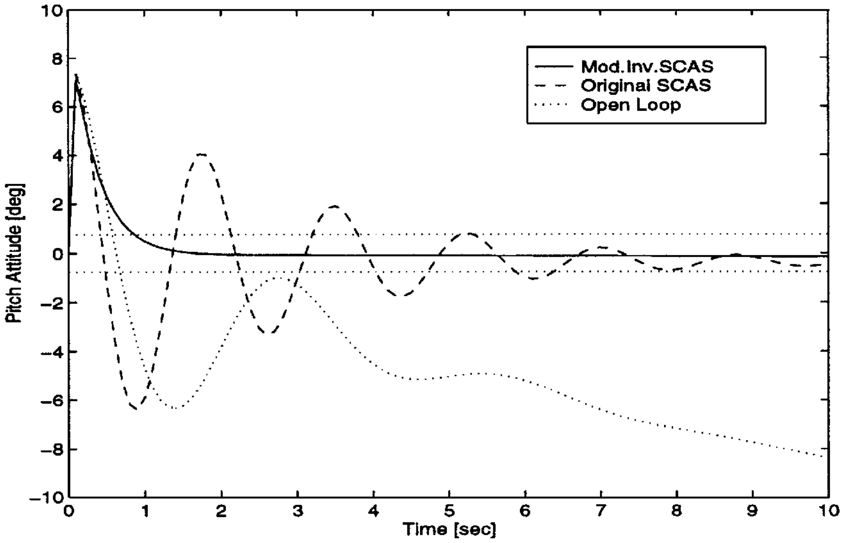

Fig. 9 Attitude Hold demonstration at a boundary of the flight envelope.

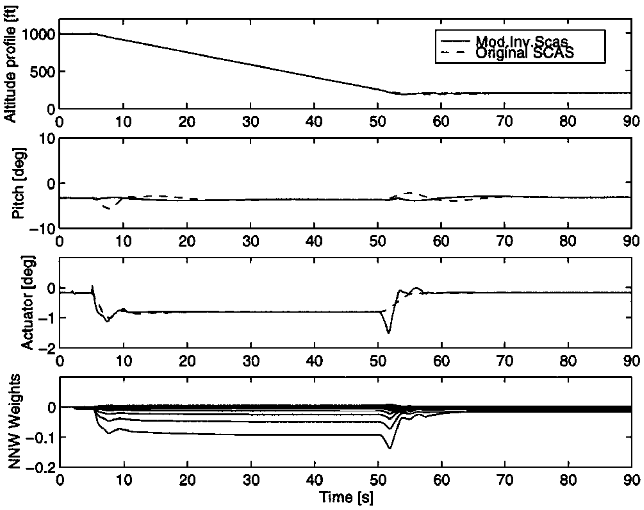

Fig. 10 Approach to landing.

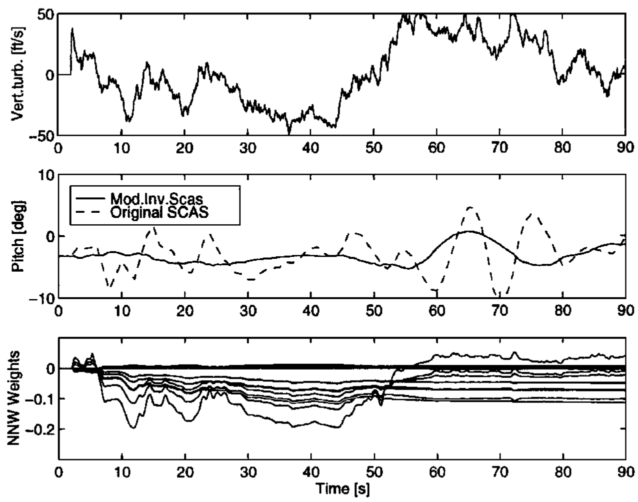

Fig. 11 Approach to landing with turbulence.

The NNW augmented control is evaluated in a nonlinear simulation of transition from forward flight in airplane mode to landing in helicopter mode. In addition, an indication of the performance and the pilot workload under turbulent conditions is possible. An example is provided in Figs. 10 and 11.

The figures show a comparison between the original SCAS and the model inversion SCAS. The data for the model inversion was recorded every 0.1 s; the original SCAS was recorded every second. (For both cases the GTRS uses an integration step size of 0.01 s.) The maneuver shown is a simulated approach to minimum descend altitude, starting at 1000 ft from the nominal operating configuration, i.e., 30 kn in the helicopter configuration. The desired descend rate is 1000 ft per min. The primary control for establishing the descend rate is the collective. However, the maneuver has an effect on the velocity, which is subsequently controlled by the pilot model through pitch commands. The pitch histories show that the model

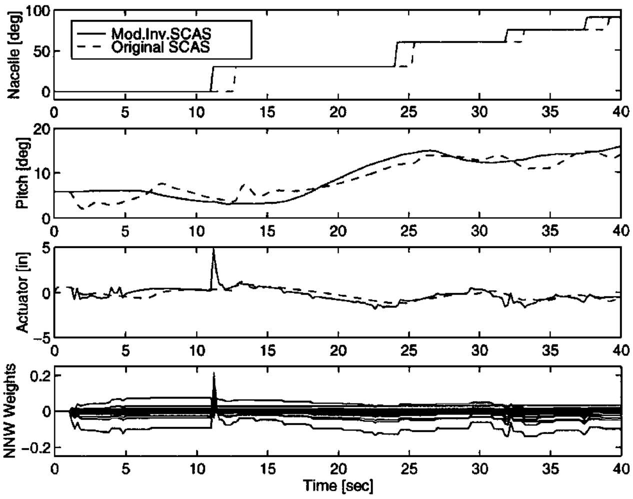

Fig. 12 -0.1 *g*-force decelerating conversion.

inversion SCAS provides some improvement in this benign maneuver. The model inversion control is based on the nominal operating point, and this is reflected in the first 5 s of the NNW weight histories. At $t = 0.5$ s the descent is initiated, and a new trim point is established. After approximately 50 s the desired altitude is reached and maintained. Subsequently, the aircraft is once more established close to the nominal operating conditions but this time at 200 ft. This is visible in the NNW weights as they are again reduced.

Figure 11 shows the same approach but now in turbulent conditions. The flight progresses through Dryden turbulence with a spatial turbulence intensity $\sigma = 5$ ft/s and a turbulence scale length of $L_W = 1750$ ft. The results suggest that the model inversion SCAS might provide for a reduction in pilot workload under these circumstances and perhaps increased passenger comfort.

Perturbations in pitch also occur when converting from aircraft to helicopter because of the changing angle of the rotor systems, i.e., the nacelle angle. The nacelle angle is 0 deg in aircraft configuration and converts to 90 deg for helicopter flight. Figure 12 contains the results of a -0.1 g-force decelerating conversion. The nacelle angles and flap settings were scheduled with airspeed. The results show a similar suppression of the pitch excursions as in the turbulence situation in the case of the model inversion SCAS. The NNW weights follow the changes in configuration as the aircraft converts.

Conclusion

A tilt-rotor aircraft is a prominent candidate for augmentation of the longitudinal channel. The NNW augmented model inversion control is a valuable method for providing ACAH augmentation throughout the operational envelope of a tilt-rotor aircraft. The tracking errors and network parameters converge fast by design, and this provides for bandwidth separation with both the command filter as well as with actuator modes. The desired handling qualities can be implemented readily through the command filter. A relatively simple NNW is sufficient to provide stability for the operations considered. Similar strategies as applied to the pitch channel have been shown to provide good performance in the lateral channels. Because of the allowance of uncertainties and nonlinearities both in control as well as in the state of the plant, a fixed-point assumption is necessary, which is a mild assumption in the case of the tilt-rotor aircraft and with a proper design of the network. Further work will include an extension of the architecture, which should lead to fully automated trajectory following.

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