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RECONFIGURABLE FLIGHT CONTROL USING RPM CONTROL FOR HELI-UAV'S

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RECONFIGURABLE FLIGHT CONTROL USING RPM CONTROL FOR HELI-UAV'S

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Abstract

The fact that current Helicopter Uninhabited Aerial Vehicles (Heli-UAVs) are unable to handle exceptional situations and combinations of simple failures makes it necessary to find remedies for such cases. A Heli-UAV will most likely crash under circumstances like a basic control failure, unless a remote pilot is at control or alternately, a solution is provided for its control reconfiguration. This paper investigates the use of main rotor speed variation as a fault tolerant feature for a Heli-UAV. Specifically, it is shown that the use of main rotor speed, i.e., RPM variations combined with advanced adaptive control architectures can successfully compensate for partial loss of main rotor collective control. The overall concept is illustrated using simulation results for example failure scenarios.

1. Introduction

Traditional helicopter controls consist of four controls, viz., collective, longitudinal cyclic and lateral cyclic controls of the main rotor and collective control of the tail rotor. Collective control is used to regulate the required thrust, whereas the main rotor longitudinal and lateral cyclic controls and the tail rotor collective control are used for control of the body pitch, roll and yaw, respectively. The variation of rotor RPM is not typically a desired control option in conventional helicopters as it may introduce unfavorable effects on rotor stability, loads and vibration. Moreover, the limits imposed by the transmission system may not permit large variations of the rotor speed above its nominal value.

A few investigations in the past have analyzed the effect of rotor speed variations on helicopter flight mechanics. Linearized helicopter equations of motion including rotor RPM degree of freedom[1,2] were obtained and analyzed in the early 1950's. Also, previous studies showed some benefits in varying the rotor RPM by using fuel flow control, but pointed out that it could result in high frequency oscillations and stability problems[3]. Degraded handling qualities in piloted flight due to large fluctuations in rotor RPM[4] suggest the regulation of rotor RPM as a desirable feature in full size helicopters. A speed governor is introduced to keep the rotor speed nearly constant. However, for a small size Heli-UAV, it is possible to vary the rotor RPM significantly above its nominal value. Hence, the rotor RPM may be used as a redundant control in Heli-UAVs.

In an ongoing study under the DARPA sponsored Software Enabled Control (SEC) program, the Georgia Institute of Technology is teamed with the Boeing Company to advance SEC technologies. The objective is to develop SEC methods for complex dynamic systems with the application focus on intelligent UAVs.[5] One emphasis in this project is to develop mid-level fault tolerant control algorithms and combine them with flight control reconfiguration in the lower level. The low level controller architecture being considered is a neural network based adaptive nonlinear flight controller, which makes use of the model inversion technique in a two-time scale architecture.[6,7]

Figure 1 illustrates a possible arrangement for how the mid-level controller for mode transition and fault tolerant control interfaces with the low level flight controller. An internal abnormal condition is identified by the fault tolerant control algorithms using information from the sensor suite, which in turn may trigger control reconfiguration and/or transition to a new flight mode. The RPM Control option in the low-level flight controller is used as a control reconfiguration strategy.

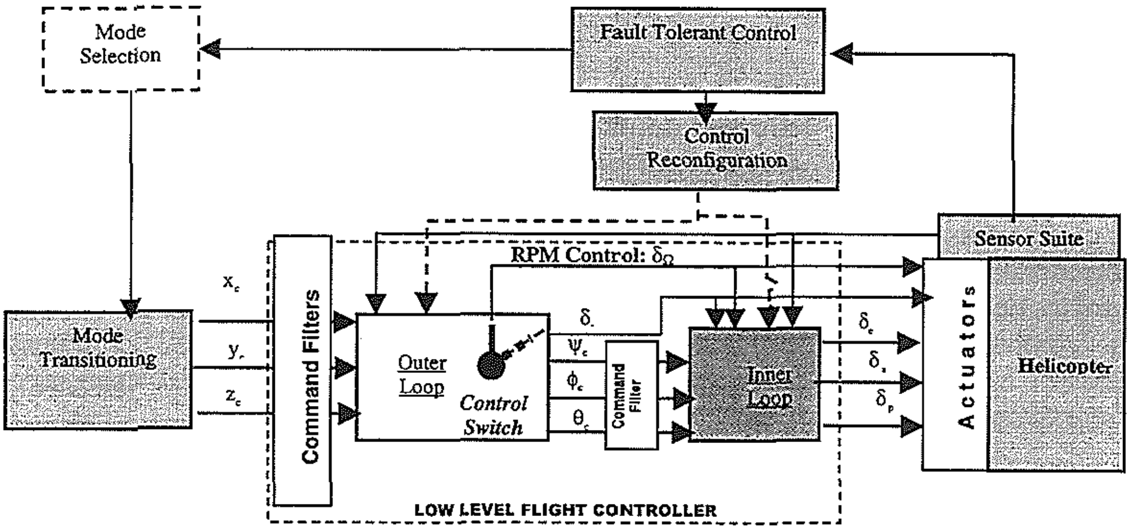

Figure1: Fault Tolerant Controller Architecture

This paper presents modeling, analysis and simulation evaluations for using main rotor RPM as a substitute control in case of partial failure of main rotor collective control. Also, coupling effects of RPM changes on other control channels are investigated.

2. Simulation Model

In order to adequately model the RPM dynamics of a Heli-UAV, a component based high fidelity simulation model is required. For this purpose, a helicopter model is formed based on the physically based, object oriented modeling approach using the FLIGHTLAB[8]. The FLIGHTLAB provides the capability to build models for separate components and then bring the pieces together in a seamless fashion under a common framework. Such an approach offers considerable flexibility for the modeling of individual components required for a realistic simulation of rotor RPM variations.

The model used is a generic helicopter model with articulated main rotor with rigid blades, fuselage, tail rotor, drivetrain, engine, governor and rotor inflow models. The rotor RPM variation is regulated by the fuel flow change (w_f) in the engine. Normally this is controlled by the main rotor speed governor to keep the rotor speed at a constant value (Ω_{ref}). However, by sending commands to the governor, it is possible to control the fuel flow to the engine and therefore, control the engine output torque. This in turn changes the rotor RPM through the engine transmission. The fuel change is represented as a single lag[8]

$$\tau_1\dot{\omega}_f + \omega_f = k_1\Delta\Omega \qquad (1)$$

where τ_1 and k_1 are the time constant and the gain, respectively, and $\Delta\Omega=\Omega-\Omega_{ref}$. The engine drivetrain component is modeled as a second order model[8] as

$$(\tau_1\tau_2)\ddot{Q}_e + (\tau_1 + \tau_1)\dot{Q}_e + Q_e = k_3\left[\Delta\Omega + \left(\Omega_{ref} + \Omega_i\right) + \tau_2\dot{\Omega}\right] \tag{2}$$

where Q_e is the engine output torque, Ω and $\dot{\Omega}$ are the rotor rotational speed and the rotor angular acceleration, respectively, Ω_{ref} is the rotor reference speed, Ω_i is the rotor idle speed, τ_l, τ_2 and τ_3 are engine time constants, and k_3 is the engine droop law constant.

3. Adaptive Nonlinear Flight Controller including

The Flight Controller, referred to as the 'low-level controller' in Figure 1, used is a model inversion based adaptive nonlinear controller[6,7] with a neural network block in the feedback path to account for inversion errors. This controller architecture has been developed under the Georgia Tech Center of Excellence in Rotorcraft Technology (CERT) program, and is applied through simulations to diverse set of airframes. These include fighters, helicopters, tiltrotor aircraft, missiles, and munition.[9-12] This technology is leveraged to the SEC Program by including rotor RPM as an additional control.

The overall setup for the low level flight controller is shown in Figure 2. The controller consists of an outer loop and an inner loop. The outer loop receives trajectory commands along with vehicle yaw attitude command as inputs and makes use of vehicle force equations to convert them to specific force, pitch attitude and roll attitude commands. A simple integral controller is used to obtain the required input to the main rotor collective control actuator for tracking of the specific force commands during normal operation. The pitch and roll attitude commands from the outer loop along with the vehicle yaw attitude command are received by the inner loop as inputs and it makes use of vehicle moment equations to obtain the required inputs to the main rotor longitudinal and lateral cyclic and the tail rotor collective control actuators. A neural net block is used in the feedback path in the inner loop to account for inversion errors and to guarantee closed loop stability. A block diagram representation of the inner loop controller is shown in Figure 3. Command filters are used at various places for the purpose of command smoothing. More details on the inner and outer loop controllers along with control law derivations are given in Refs. [6] and [7]. Additional design details, derivation of network update law and a proof of closed loop stability can be found in Refs. [9] through [12].

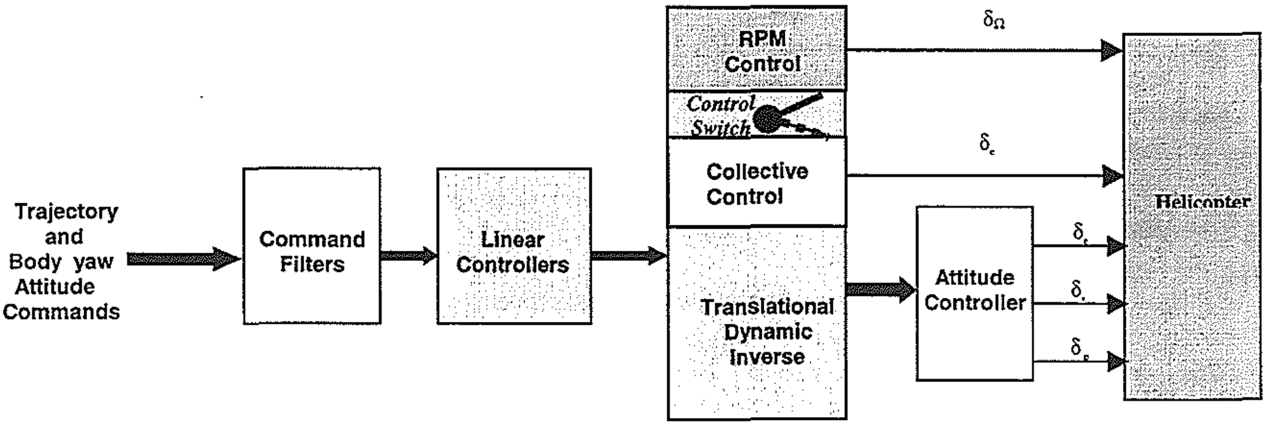

Figure2: Overall Flight Controller

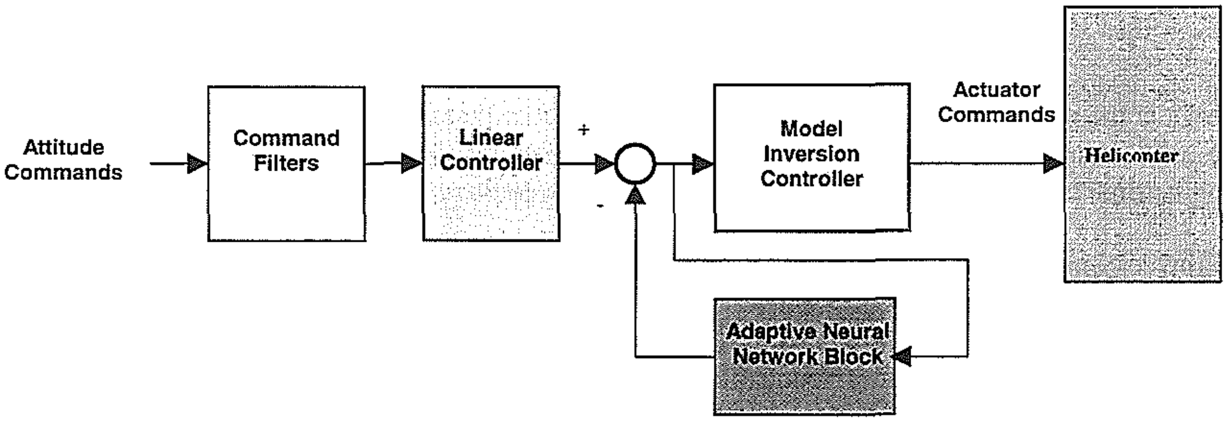

Figure3: Inner Loop Attitude Controller

In case of a failure in the collective channel, the specific aerodynamic force command computed in the outer loop is redirected to the rotor RPM control channel instead of the collective control channel. Once again, a simple integral control law is used to arrive at the required input to the RPM governor, which can be written as

$$\Omega_c = \Omega_{nom} + K_I \int (A_c - A) dt \qquad (3)$$

where A is the specific force magnitude which can be measured using a three-axis accelerometer measurement unit and A_c is the specific force command computed in the outer loop. The value of the controller gain K_I is adjusted based on results from initial simulations with the RPM controller. The commanded rotor speed (Ω_c) from Equation (3) is used as the reference rotor speed (Ω_{ref}) for the RPM governor.

The linear models required for the model inversion part of the inner loop are obtained using the linearization feature in FLIGHTLAB. The linearized model is obtained for hovering at 300ft altitude flight condition.

4. Simulation Results and Discussion

The performance of the controller is evaluated using the FLIGHTLAB simulation model of the generic helicopter model. Both the inner and the outer loop controller gains are set to same as those used in Ref. 6. The gain K_I of the RPM controller in Eq. (3). is set to 0.22.

4.1. Failure Scenario#1

In the first scenario, the unmanned helicopter starts at hover at 300ft altitude. Beginning at time t=1sec, the helicopter is commanded to descend to an altitude of 200ft with a descent rate of 10 ft/sec, and then hover at 200 ft altitude. To demonstrate the effectiveness of the RPM Controller, a failure is introduced halfway during the descent at t=7sec as a stuck collective control actuator. The fault tolerant controller (see Figure 1) is assumed to recognize this failure condition and it immediately sends a command to the control reconfiguration module to switch to the RPM controller. A sketch of this failure scenario is shown in Figure 4.

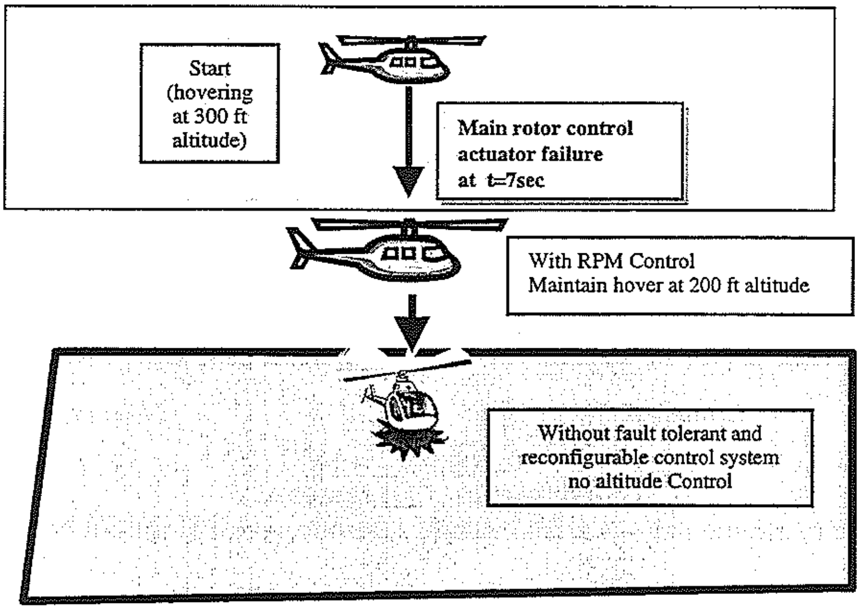

Figure 4. Scenario #1: Stuck Collective in Bob Down Maneuver

Figure 5 presents simulation results for components of inertial velocity and position of the vehicle along with their commanded values. It is seen from Figure 5 that in spite of a switch to the RPM control at t=7 sec, the command tracking is quite good. The pitch, roll and yaw attitude responses are shown in Figure 6. Note that the pitch and roll commands are calculated in the outer loop whereas the body heading command is specified as input to the controller. Due to the sudden switch to the RPM Control at t=7sec, fluctuations arise in the angular rate responses but die out with adaptation of the network weights .

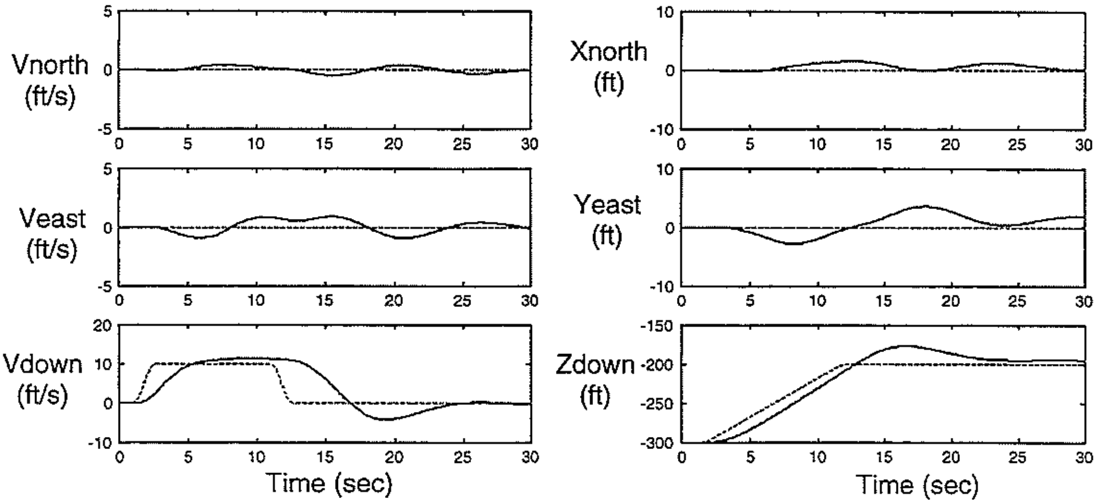

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Figure 5. Inertial Velocity and Position Response for Failure Scenario#1.

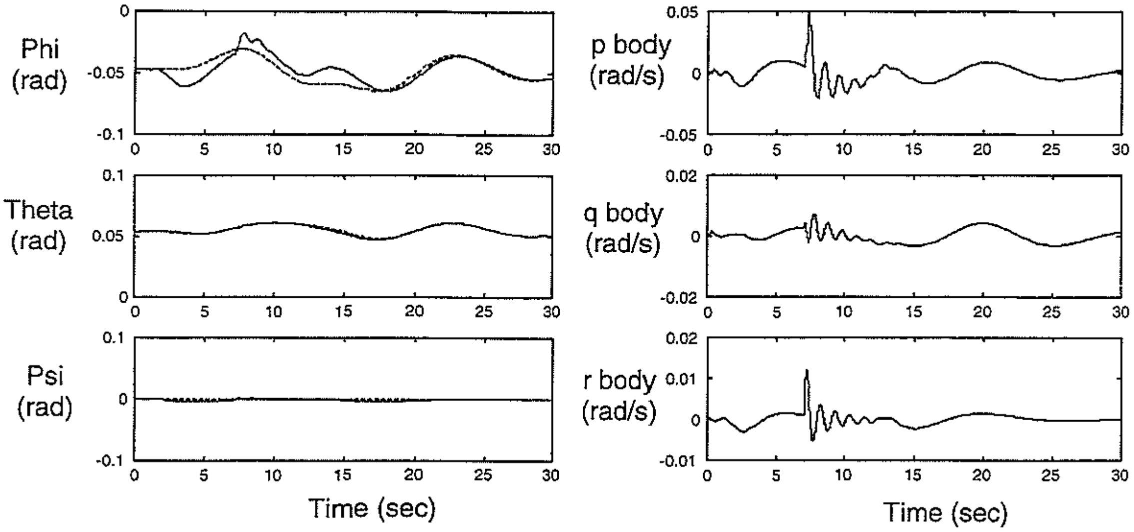

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Figure 6. Attitude and Angular Velocity Responses for Failure Scenario#1.

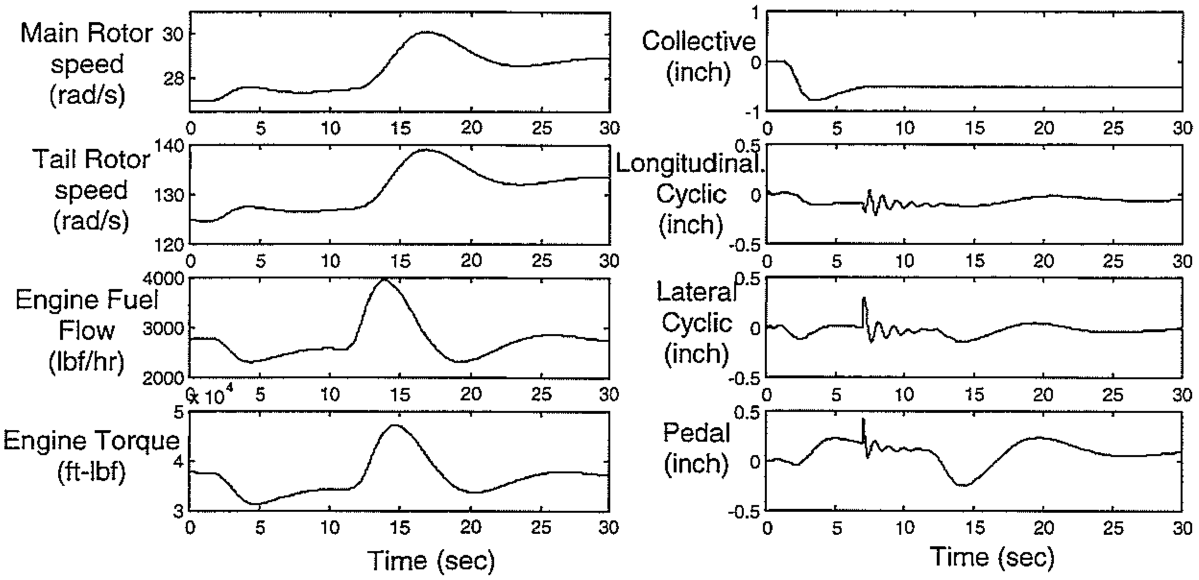

Figure 7. Control Variations for Failure Scenario#1.

Figure 7 shows the variations of the main rotor RPM, tail rotor RPM, engine fuel flow rate and the generated engine torque. Figure 7 also shows the variations of main rotor collective, longitudinal and lateral cyclic and tail rotor collective controls from their trim values. Immediately after the collective pitch actuator is stuck at t=7sec, the rotor RPM varies in order to track the commanded descent trajectory. Also, the main rotor longitudinal and lateral cyclic and tail rotor collective controls vary accordingly in the new control configuration bringing the helicopter to a hovering condition and avoiding a fatal crash.

4.2. Failure Scenario#2

The second scenario consists of a sinusoidal speed change to investigate the effect of coupling between control channels in forward flight in the event of a collective control actuator failure. The vehicle starts from hover at 300ft altitude and is commanded to a sinusoidal speed variation of 20 ft/sec amplitude along the inertial X-axis (North). At t=8sec, a stuck collective control actuator condition is introduced and the controller is reconfigured with the RPM control.

Figure 8 shows the variations of components of inertial velocity and position of the vehicle along with their commanded values. Although the vehicle is able to follow the commands in the horizontal direction very well, some degradation in command tracking along the inertial Z-direction is observed. The pitch, roll and yaw attitude responses are shown in Figure 9. Once again, after an initial adjustment of the net work weights right after the failure of the collective control actuator, the tracking of the inner loop is quite good. The control variations are shown in Figure 10. Right after t=8 sec when the collective control actuator failure is introduced and with control reconfiguration, the rotor RPM is allowed to change to track the sinusoidal horizontal speed command.

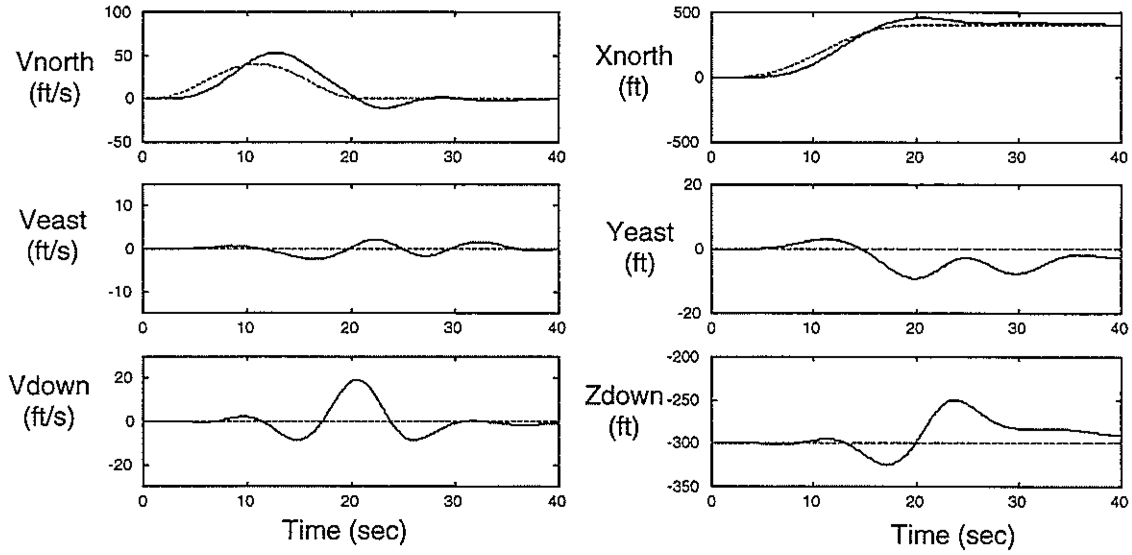

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Figure 8. Inertial Velocity and Position Response for Failure Scenario#2.

5. Summary and Conclusions

A fault tolerant flight controller using the rotor RPM control for a Heli-UAV is proposed. A control reconfiguration with RPM control in an adaptive neural net based nonlinear controller structure is synthesized. For a realistic simulation of the proposed reconfigurable flight controller scheme, a component based simulation model which includes engine and governor dynamics is formulated using the FLIGHTLAB. Simulation evaluations of the reconfigurable flight controller are carried out using two command maneuvers, viz., a bob down maneuver and a sinusoidal speed change maneuver from hover. A failure of the main rotor collective control actuator is introduced during each maneuver and the effectiveness of the reconfigured flight controller with RPM control is evaluated using simulation results. The results indicate that the main rotor RPM control when

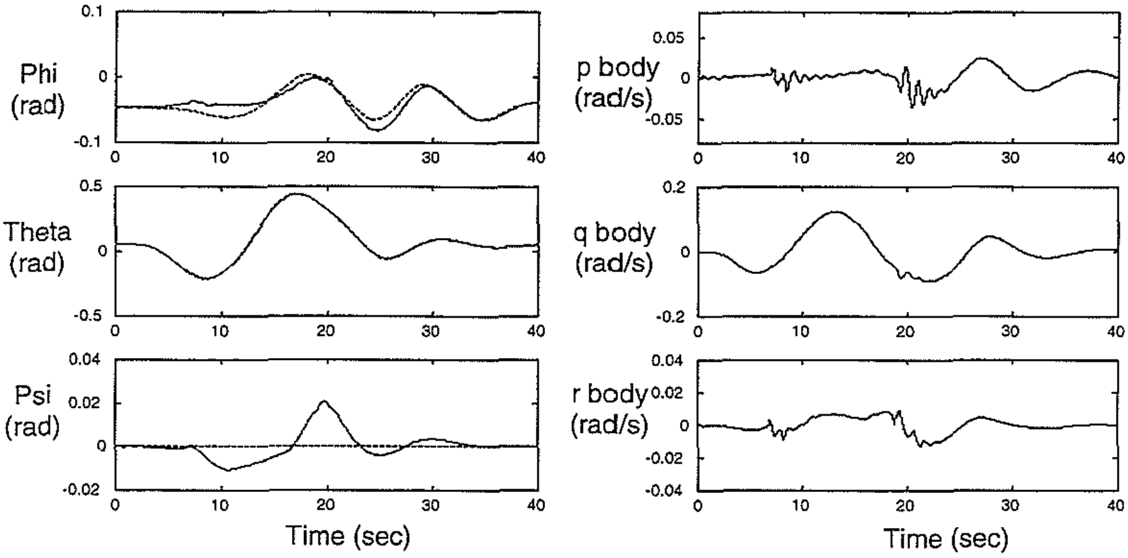

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Figure 9. Attitude and Angular Velocity Response for Failure Scenario#2.

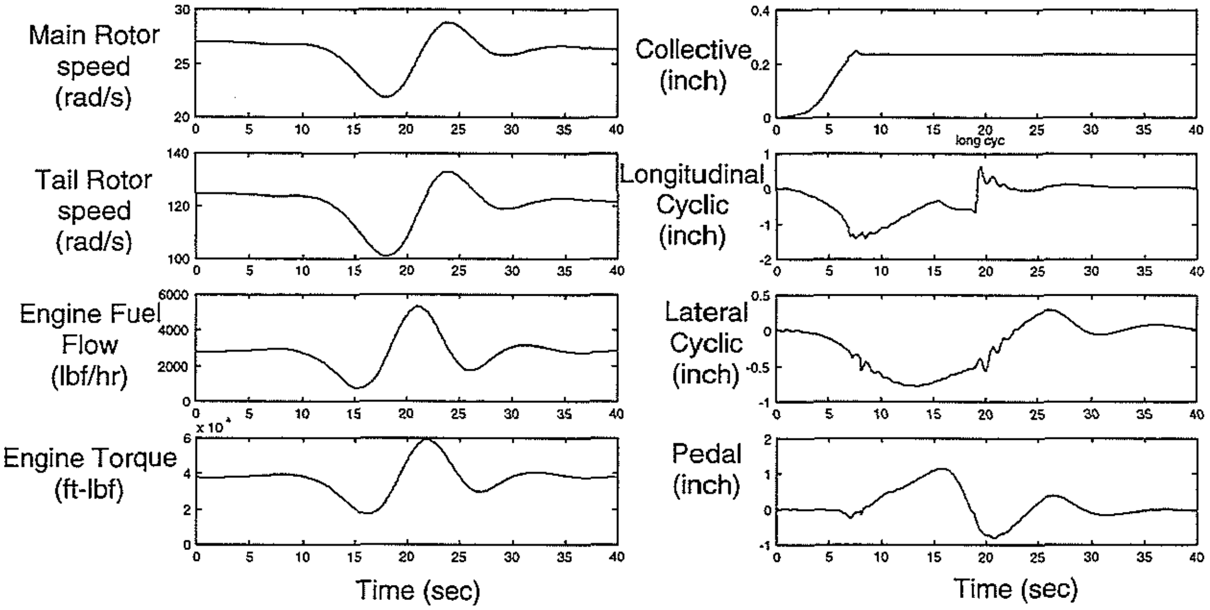

Figure 10. Control Variations for Failure Scenario#2.

combined with an advanced adaptive control architecture can successfully compensate for partial loss of main rotor collective control. The use of rotor RPM control along with the four traditional controls of a Heli-UAV for achieving extreme maneuver performance is being pursued as part of an ongoing investigation.

6. Acknowledgments

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7. References

[1] Schuck H. and Warsett P., “Equations of Motion for a Nominally-Hovering Helicopter with Rotor RPM Degree of Freedom,” AD 5143-TR7, June 1953.

[2] Warsett P., Maze R. and Schuck H. “Equations of Motion Including Rotor RPM Degree of Freedom for the Helicopter in Cruising Flight,” AD 5143-TR13, August 1955.

[3] Tamura J., “Control of Altitude and Rotor RPM of the Single Rotor Helicopter with Free-Turbine Turbo-Prop Engine in Hovering Flight,” AD 5143-TR15, January 1956.

[4] Corliss, L. D. , Blanken, C. L. and Nelson, K., “Effects of rotor inertia and rpm control on helicopter handling qualities,” AIAA PAPER 83-2070, Aug 01, 1983.

[5] Schrage D.P. and Vachtsevanos G.,”Software-Enabled Control for Intelligent UAV’s,” Proceedings of the IEEE Control Applications Conference, Hawaii, Augst 1999.

[6] Carbon, J.E., Calise, A.J. and Prasad, J.V.R., "Implementation of Adaptive Nonlinear Control for Flight Test on an Unmanned Helicopter,” Proceedings of the 37th IEEE Conference on Decision and Control, December 1998.

[7] Prasad J.V.R., Calise A.J, Yubo, P. and Corban J.E., “Adaptive Nonlinear Controller Synthesis and Flight Test Evaluation on an Unmanned Helicopter,”. Proceedings of the IEEE Control Applications Conference, Hawaii, Augst 1999.

[8] Advanced Rotorcraft Technology, Inc., FLIGHTLAB Theory Manual, July,1998.

[9] Kim, B.S. and Calise, A.J., "Nonlinear Flight Control Using Neural Networks," AIAA Journal of Guidance, Control and Dynamics, Vol. 20, No. 1, 1977.

[10] Leitner, J., Calise, A.J. and Prasad, J.V.R., "Analysis of Adaptive Neural Networks for Helicopter Flight Control," AIAA Journal of Guidance, Control and Dynamics, Vol. 20, No. 5, Sept.-Oct., 1997.

[11] Calise, A. J. and Rysdyk, R.T., "Nonlinear Adaptive Flight Control Using Neural Networks,” IEEE Control Systems Magazine, Vol.18, No.6, pp.14-25, December 1998.

[12] McFarland, M. B., and A. J. Calise, "Multilayer Neural Networks and Adaptive Nonlinear Control of Agile Anti-Air Missiles,” Proceedings of the AIAA Guidance, Navigation and Control Conference, Paper No. AIAA 97-3540, August 1997.