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TRANSITION CONTROL AND REDUNDANCY MANAGEMENT FOR A TILT ROTOR UAV USING GENETIC ALGORITHMS

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Abstract

The design of Flight Control Systems for tilt-rotor UAVs can be challenging for the management of the hovering to forward flight transition and vice-versa and for the presence of redundancy in the control actuators. The preliminary design phase for the E-Pteron tilt-rotor UAV was almost completed and a first estimate of the inertial and dynamic characteristics of the aircraft was carried out. A dynamic model simulating both hovering and forward flight conditions was formulated and a preliminary control logic was identified. The proposed Flight Control System architecture is based on a non-linear fixed structure controller articulated in two main blocks isolating control laws from control allocation. The non-linear fixed structure was devised through engineering considerations on the dynamics involved, while the gain tuning was performed formulating a non-linear constrained optimization problem, its solution having been found running genetic algorithms. Local stability around flight conditions of interests was imposed as a hard constraint, performance were formulated using quadratic functions. Numerical simulations of the transition phases were carried out showing that the resulting controller exhibits promising responses.

1 Introduction

The Vertical Take Off and Landing (VTOL) capability is an important feature of an aircraft which adds great flexibility in its spectrum of operations. Unfortunately this comes at the expense of performance and efficiency in the forward flight regime; helicopters are limited in their cruising speed and are affected by dramatically higher fuel consumption which leads to poor range and endurance performance compared to fixed wing aircraft.

Extensive research activity has been conducted in the past to shorten the performance gap between VTOL and CTOL (Conventional Take Off and Landing) aircraft. Thrust vectoring and tilt rotor configurations are the most popular and promising solutions for jet and propeller aircraft respectively, though only very few projects have finally made it to the production line. The main reasons for the little success of VTOL aircraft lie in the complexity and associated costs of the configuration, reliability and safety concerns, control problems in the transition phase between hovering and forward flight.

Two manned tilt rotor configurations have been developed in the recent years: the V-22 Osprey is now in service with the military and the AW-609, intended for civilian use, is currently being tested and certification issues are being investigated. The two designs share a common control strategy: in hovering, control is achieved through cyclic and collective actuators, as in tandem rotor helicopters, while, in forward flight, conventional aerodynamic surfaces ensure controllability over the three axes. While this approach offers good performance and controllability in the entire flight envelope, it exhibits some undesirable features for small

UAV (Unmanned Aerial Vehicle) applications in terms of complexity of the rotor head, limited wing aspect ratio and propulsion efficiency; indeed small UAV operational requirements are typically driven by costs, loitering performance and, often, noise levels.

The configuration proposed in the *E-Pteron* project, carried out by the Second University of Naples, for flight mechanics and control, the REDAM company and the University of Naples, for aerodynamic and structural studies, tackles the issues by adopting all electric motors, two fixed pitch propeller tilting rotors placed at the tip of a canard and a dual counter-rotating ducted fan immersed in the fuselage. This design choice allows for a high wing aspect ratio and an optimization of the characteristics of the front motors and propellers for the forward flight mode; in hovering mode power is mostly provided by the ducted fan, leaving only control functions to the front rotors.

The conversion phase between the two flight regimes poses many controllability issues arising from:

- highly non-linear dynamics involved;
- difficult modeling of the performance of propellers invested by large flow angles;
- control allocation to the effectors with severe couplings and dramatic changes in the control effectiveness over different axes depending on flight conditions and tilt angles;
- uncertainties in the aircraft dynamic model and mutual interactions between propeller flow and wing aerodynamic field;
- large sensitivity to atmospheric conditions during hovering and transition.

Different approaches have been proposed in the literature to the FCS design of small scale tilt rotor UAVs. Most of them have been tested in simulation with few advanced flying platforms for real experiments, [9] and [10].

Ta et al. [22] propose a control architecture based on adaptive PID controllers whose gains are tuned with the aid of neural networks, Chowdhury et al. [3] and [4], Krishnamurthy and Khorrami [13], Kendoul et al. [12], Kulhare et al. [14] explore the possibility of adopting a nonlinear back-stepping control approach, whereas Yu et al. [23] and [24], Amiri et al. [1], Chen et al. [2], Rysdyk et al. [20], adopt nonlinear adaptive techniques. Papachristos et al. [17] propose the use of a model predictive control technique, Fang et al. [6] propose a dynamic inversion scheme for controlling the transitional mode of tilt-rotor UAVs. Papachristos et al. [18] also investigate the possibility to employ linear analysis techniques for the design of PID compensators for the hover regime.

The main problems for the application of nonlinear model based control techniques are the difficulty to have a reliable dynamic model of the tilt rotor and the complexity of the design procedure which requires many trials and, in some cases, provides control algorithms which do not have an easy and physical interpretation.

The first problem can be in part resolved adopting CFD, wind tunnel and flight tests, or adaptive structures such as Neural Networks providing a continuous refinement of the model.

As for the complexity of the controller, it would be desirable to have a fixed structure control law giving a clear understanding of all the feedback control actions. This is even more important in those cases, as ours, where also a control allocation problem, due to the redundancy of actuators, has to be solved. The last problem is particularly critical in the transition phases, when careful blending of the redundant effectors demands is required.

As a first step in the *E-Pteron* FCS design, in this paper we try to use a fixed-structure non-linear controller with tunable PID gains. Fixed structure gains, as well as dynamic allocator gains, are optimized using genetic algorithms. The choice of genetic algorithms was dictated by the complexity of the problem which drastically narrowed the available options. The optimization of the proposed fixed structure non-linear controller was a non convex problem with the presence of local non-differentiabilities (discontinuities in the partial derivatives) induced by mode transitions, saturations and rate limits, precluding the use of gradient based methods. The flight control literature is not new to the use of evolutionary optimization techniques for fixed structure controllers. In Feng et al. [7], Le Mauff et al. [16], Zhang et al. [26], genetic algorithms are proposed to design control gains for fixed wing aircrafts. The use of genetic algorithms is extended in Zhang et al. [25] to the problem of having an integrated aircraft-flight control system design. Karimi and Lofti-Forushani [11] use a PSO (particle swarm optimization) approach to the design of a fixed structure controller. A PSO approach is also adopted in Lee at al. [15] to the FCS of a tilt rotor aircraft.

2 Overall Design Description

The proposed UAV is a tactical uninhabited vehicle capable of Vertical Take Off and Landing and primarily intended for medium endurance and medium-short range patrolling missions.

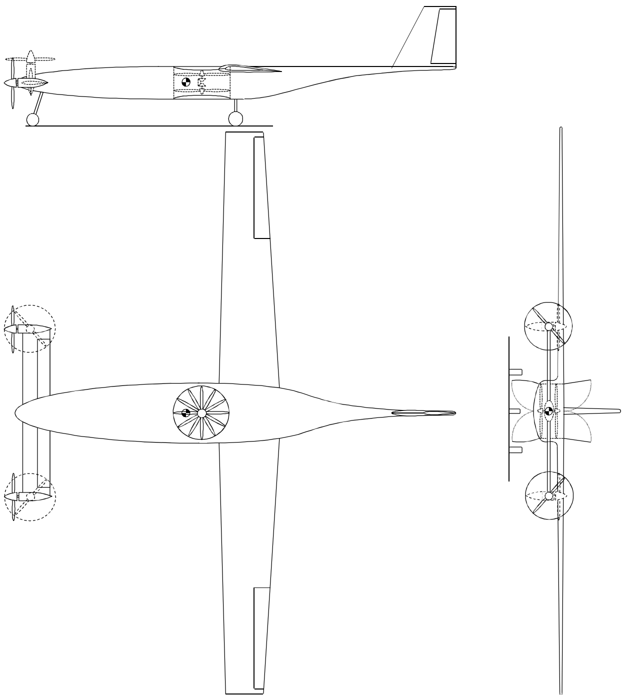

Fig. 1. *E-Pteron* UAV Three View

The aircraft will be powered by two propellers located at the tip of a canard and a central ducted fan with dual counter-rotating rotors. The aircraft configuration will be tricycle fixed gear with high aspect ratio canard and with high aspect ratio, straight, slightly tapered, untwisted, high mounted wing with no dihedral. The fuselage will be a lifting body with approximately elliptical cross section, hosting a ducted fan in the central part. All propellers will be fixed pitch and powered by electrical brushless Direct Current motors. All actuators will be stepper motors. Electrical power will be provided by fuel cells and Lithium-Polymer (Li-Po) batteries. Fuel cells will generate enough power to sustain forward flight during cruise and loitering phases, while partially recharging the Li-Po batteries. Large power demands during hovering will be absorbed by the Li-Po batteries. Main sensors feeding information to the FCS will be: an Inertial Measuring Unit (including three accelerometers, three rate gyros, GPS, magnetometer), an air data system (measuring calibrated airspeed and pressure altitude), and a laser altimeter. Additionally an analog camera will capture the video signal of the forward field of view, which will be transmitted to the ground for pilot's visual feedback (during remote piloting) and situational awareness (during autonomous operations). A telemetry system will ensure bi-directional communication between ground station and aircraft, for system and payload command and control.

General characteristics and performance of the proposed UAV are summarized below:

Length:	14.44 ft (4.40 m)
Wing span:	19.43 ft (5.92 m)
Aspect Ratio:	12
Wing Area:	31.46 ft^2 (2.92 m^2)
Height:	3.90 ft (1.19 m)
Maximum Take Off Weight:	100 lb (45.4 Kg)
Payload:	10 lb (4.54 Kg)
Operational Radius:	50 NM (92.6 Km)
Loitering Time:	6 hr
Cruise Speed:	35 knots (18 m/s)
Cruise Altitude:	5,000 ft (1,524 m)
Dive Speed:	80 knots (41.16 m/s)

3 Control Strategy

During forward flight the front propellers are tilted forward (the thrust line is aligned with the longitudinal axis) whereas the central fan is not powered and the duct doors are closed. Aircraft control about the three axes is provided by conventional aerodynamic surfaces: canardvator for pitch control, aileron for roll control and rudder for yaw control. Independent actuation of all moving surfaces has the potentials for providing some degree of redundancy for better transient response and tolerance to actuator failures.

In hover most of the thrust is provided by the central fan, while the front propellers are mainly used for control. Reaction torques from the motors are minimized by the design choice of counter-rotating rotors both for the ducted fan and the two front propellers. The three rotational degrees of freedom are controlled as follows: pitch control is achieved with symmetric power modulation on the front propellers (tilted upward), roll control is achieved with asymmetric power modulation on the front propellers and yaw control is obtained by differentially tilting the front rotors. The three translational degrees of freedom are controlled through the central fan power for vertical speed control, the symmetric tilting of the rotors for longitudinal speed control and the bank angle for lateral speed control.

Transition between hover and forward flight is a crucial phase which requires a careful blending of the control laws in the two regimes. For instance during acceleration or deceleration the front nacelles are partially tilted forward or backwards, thus producing strongly coupled responses: at intermediate tilt angles, symmetric power modulation or nacelle tilting produce pitching moment, lift and forward thrust at the same time, while differential power modulation or nacelle tilting simultaneously generate rolling and yawing moments.

The piloting logics change with the flight phases. During hovering, with their inceptors (stick and lever), the pilot controls vertical speed (longitudinal stick deflection), lateral ground speed (lateral stick deflection), yaw rate (stick rotation) and forward ground speed (throttle lever). In forward flight the pilot controls vertical speed (longitudinal stick deflection), bank angle (lateral stick deflection), angle of sideslip (stick rotation) and equivalent air speed (throttle lever). Smooth transition between the two logics is achieved by scaling and merging the control inputs as a function of a derived parameter called blended speed; the blended speed coincides with the ground speed below 15ft/s, with the equivalent air speed beyond 45ft/s and varies quadratically in between.

4 Mathematical Model of the Tilt Rotor

A preliminary aerodynamic model of the UAV was obtained using three approaches for the computation of the stability and control derivatives: Datcom [8], Roskam [19] and Vortex Lattice [5]. Results from the three methods were compared and the Roskam approach was assessed to be the most reliable (based on engineering considerations and on reasonable agreement with at least one of the other two methods). The stability and control derivatives were calculated for a single forward flight condition, but the same set has been used for any flight phase in the preliminary model; provided that angles of attack and sideslip remain small, no dramatic changes in the stability derivatives are expected and furthermore aerodynamic forces are obviously less and less effective with decreasing dynamic pressure, compared to the propulsive forces.

At the moment the aerodynamic model is only valid at small angles of attack and sideslip (below stall). Thus it cannot reproduce forces and moments at larger angles (relevant for lateral, backward, vertical flight and for proper simulation of hovering conditions in the presence of wind and turbulence). Furthermore mutual airstream interactions between propellers and airframe during nacelle tilting are not simulated in the present model. A more suitable model for VTOL aircraft is currently being developed based on a component buildup approach [21] as opposed to traditional stability and control derivatives methods. The model will be further refined using more sophisticated numerical tools (CFD analysis) and, when a scaled mock-up and a prototype are available, through wind tunnel experiments and flight testing.

Wind tunnel testing will also be done in order to explore the behavior of propellers and fans working at large flow angles (intended as the angle formed by propeller spin axis and relative wind), this being a big concern for tilt rotor applications.

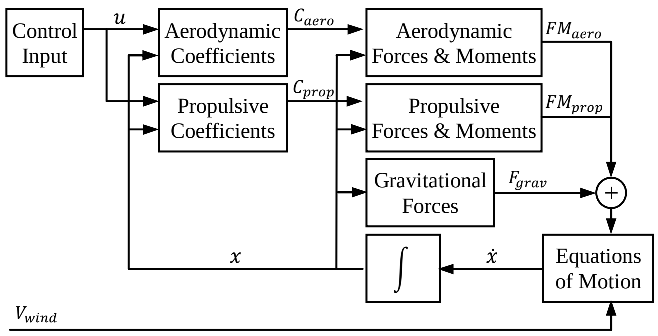

Fig. 2. Top Level Aircraft Dynamics Block Diagram

5 Flight Control Architecture

The Flight Control System architecture proposed in this paper is structured in two main blocks: one defining the control laws and the other for the control allocation. The control laws block receives inputs from the pilot (or autopilot) and the sensors, and outputs virtual controls (representative of forces and moments to be generated for tracking the desired reference). The control allocation block computes commands for the aerodynamic and propulsive effectors that will produce the required forces and moments.

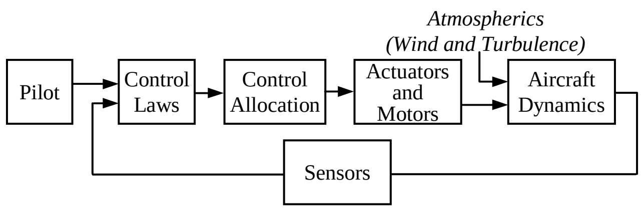

Fig. 3. Top Level Model Block Diagram

The control laws are basically PID controllers with integrator anti-windup filters. Reference signals are blended speed and vertical speed for the longitudinal motion (both hover and forward flight). In other terms the pilot controls vertical speed with the longitudinal stick deflection and blended speed (entirely ground speed below 15ft/s and entirely equivalent airspeed beyond 45ft/s) with throttle position. Control logic about the lateral-directional axes change with the flight regime. In hovering the stick lateral deflection commands a horizontal lateral ground speed, and the stick rotation controls the yaw rate. In forward flight reference signals are bank angle and lateral acceleration (highly correlated to the angle of sideslip). A transition parameter (function of the blended speed), ranging from zero to one, determines the blending of virtual commands from the hovering and the forward flight logics.

Most of the FCS non-linearities are found in the control allocation block. This block receives inputs from the control laws block, which computes all required virtual forces and moments except for the pitching moment: the pilot directly controls the vertical speed (not the pitch attitude), thus the required pitch angle change is indirectly calculated to achieve the desired rate of climb in forward flight (the virtual vertical force is divided by dynamic pressure and scaled by a gain closely related to the lift curve slope to generate the necessary angle of attack change). In hover the vertical speed is not controlled through the aerodynamic lift (vertical acceleration is directly produced by the fan thrust), thus a reference pitch attitude (level flight) is commanded. In the transition phase the two pitch angle change signals (forward flight and hover logics) are blended according to the transition parameter. The resulting pitch angle change command goes through a PID controller to compute the proper pitching moment. Longitudinal force and pitching moment are created through symmetric nacelle deflection and symmetric propeller speed, depending on the nacelle tilt angle: when the nacelles are aligned with the fuselage, nacelle deflection controls pitching moment and propeller speed controls longitudinal force, and vice-versa when the nacelles are pointing upwards. At intermediate positions the contributions vary sinusoidally with the tilt angle, thus they are blended accordingly. Furthermore the blended forces are scaled by the inverse of the square of the propeller speed to produce the symmetric tilt deflection to be commanded while the square root of the blended forces is taken to compute the commanded propeller speed. This is physically justified by the consideration that thrust is proportional to the square of the rotation speed. Pitching moment is controlled exclusively with front propellers in hover and exclusively with symmetric canardvator deflection in forward flight; during transition the allocator progressively distributes the effort among the effectors. Similarly vertical force is controlled by modulating the fan speed in hover and through the attitude in forward flight, as previously described.

In forward flight, rolling moment is produced with aileron deflection and yawing moment with rudder deflection; both are scaled by the inverse of the square of the equivalent airspeed. In hover, rolling and yawing moments are obtained by differential nacelle deflection and differential power modulation. Similarly to the longitudinal motion, the effects of nacelle deflection and power modulation are functions of the tilt angle, thus the contributors are blended according to sinusoidal laws.

One of the benefits of separating control laws and control allocation resides in the ability to simplify the distribution of the control effort among the redundant actuators or the reconfiguration of the allocation strategy in case of faults or failures. In the current model effectors redundancy is not yet exploited to enhance performance or to achieve fault tolerance, which will be investigated in the future.

6 Controller Gains Optimization

The non-linear fixed structure Flight Control System comprises many parameters (mostly PID gains in the control laws block and proportional gains in the control allocation block) to be optimized to achieve adequate performance and robustness.

The approach adopted for tuning the controller gains involved two steps:

- an initial parameter setting was found based on the knowledge of the mathematical model and according to the physics of the problem; an iterative process was followed to refine the initial setting through simulation and adjustment;
- once a satisfactory preliminary set of parameters was found, a genetic algorithm was run trying to converge towards an optimal solution.

In both steps the problem was split in two simpler separate tasks: the longitudinal gains were set first, then the issue of lateral-directional tuning was tackled.

Genetic algorithms are quite popular for the optimization of fixed-structure controllers, however they pose many challenges when applied to complex non convex highly dimensional problems. Three major issues arose when the method was applied to the proposed control scheme:

- the fitness function was quite complicated, involving monitoring of many signals and requiring a large number of maneuvers to be simulated;
- a large number of parameters was to be tuned;
- genetic algorithms have a tendency to converge toward local optima, as opposed to the global optimum.

These concerns were mitigated by carefully managing the sequence of maneuvers, posing meaningful hard constraints and attempting several combinations of settings, initial populations and ranges for different optimization runs, aiming at enhancing the likelihood that the result fell as close as possible to the global minimum in the domain of interest.

The number of parameters to be optimized was quite large: 15 parameters for the longitudinal response and 12 parameters for the lateral-directional response. The considerable number of variables and the complexity of the FCS and the vehicle dynamic model raised the issue of computational burden for the genetic algorithm. An effort was made to reduce the computational time by setting constraints on the eigenvalues of the linearized models for hovering and forward flight regimes respectively. The two linearized models were derived in a parametric form (the state matrix was expressed as an explicit function of the FCS gains) and a large cost was imposed to parameter settings causing divergent responses (positive real part of the eigenvalues of the state matrix) without even running the non-linear full simulation. The stability of the linearized models in the two extreme flight regimes did not guarantee stability of the non-linear system during transition from hover to forward flight. Bounds (although large) were set on the integrators of the non-linear dynamic model to prevent divergence and consequent crash of the simulation during the genetic algorithm optimization.

The objective function to be minimized comprised quadratic terms representative of the response deviation from the reference signal, the oscillatory trend of other relevant dynamic parameters and the control effort (number of overshoots and rate saturation). More specifically the number of sign changes of the signals derivatives (representative of overshoots and oscillations) and the amount of time in which the controls were saturated were penalized in the cost function.

For the longitudinal parameters optimization, the chosen reference signals were ramp inputs. Several maneuvers contributed to the final cost: leveled accelerations and decelerations from 0 to 50ft/s and back both in one step and at increments or decrements of 10ft/s, and climbs and descents at different speeds.

For the lateral parameters optimization, deviations from the reference signals were computed only in hover and forward flight, because during transition the responses are the result of blending between different control logics; however overshoots and saturations were weighted in all flight regimes. Reference signals were ramp and step inputs (at different speeds): lateral ground speed and yaw rate in hover, bank angle and lateral acceleration in forward flight.

7 Numerical Simulations

The proposed fixed structure controller with the best gain setting obtained with genetic algorithm optimization exhibited satisfactory dynamic responses, good tracking of the reference signals and pleasant blending of the control logics during transition, with acceptable control effort.

Examples of responses at different flight regimes (hover, transition and forward flight) are presented below. The simulator included realistic actuators and motors limitations, in terms of bandwidth, saturation and rate limits. The first sets of graphs are referred to the nominal behavior, while the last four figures show the effect of disturbances and model uncertainties on the resulting responses. More specifically the injected uncertainties were 50% reduction of the most important derivatives (C_{L_α}, C_{m_α}, C_{m_q}, C_{l_β}, C_{n_β}, C_{l_p}, C_{n_r}, $C_{m_{\delta_{cv}}}$, $C_{l_{\delta_a}}$, $C_{n_{\delta_r}}$) and 20% reduction of the propeller coefficients of thrust. Atmospheric disturbances were simulated using the Dryden turbulence model and introducing a 10ft/s constant wind. Although a thorough robustness evaluation has not yet been performed, the controller behavior in the presence of uncertainties and disturbances is promising.

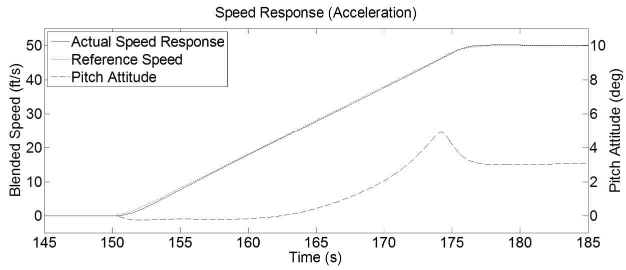

Fig. 4a. Throttle acceleration input (speed response)

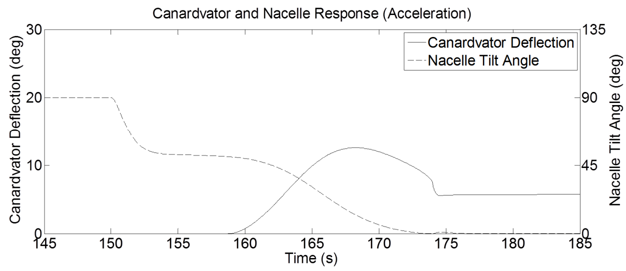

Fig. 4b. Throttle acceleration input (effectors position)

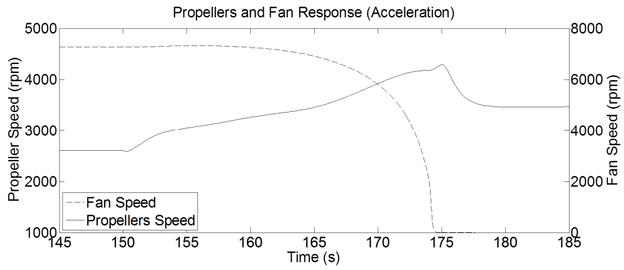

Fig. 4c. Throttle acceleration input (engines speed)

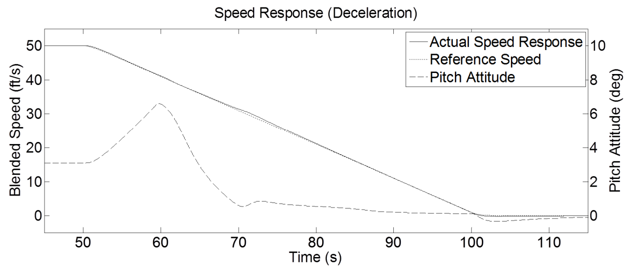

Fig. 5a. Throttle deceleration input (speed response)

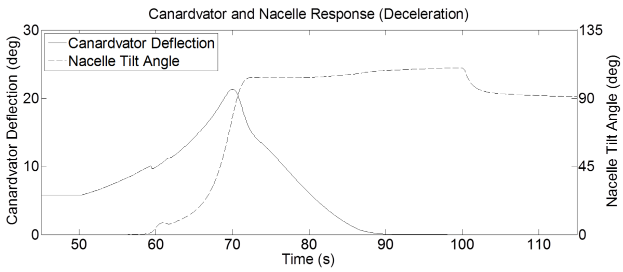

Fig. 5b. Throttle deceleration input (effectors position)

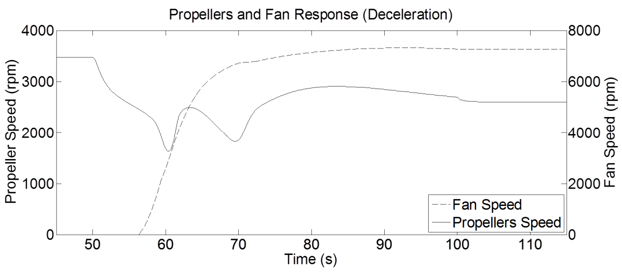

Fig. 5c. Throttle deceleration input (engines speed)

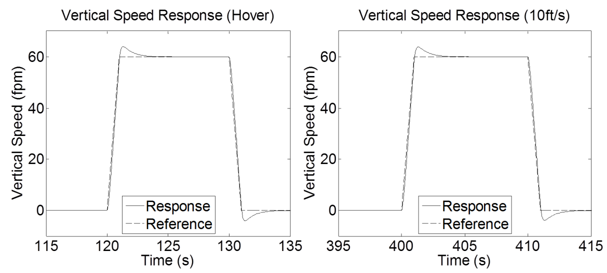

Fig. 6a. Aft stick input (hover and low transition speed)

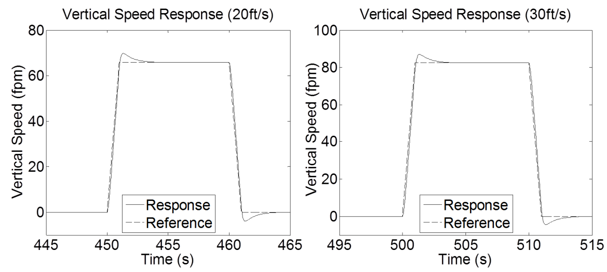

Fig. 6b. Aft stick input (intermediate transition speeds)

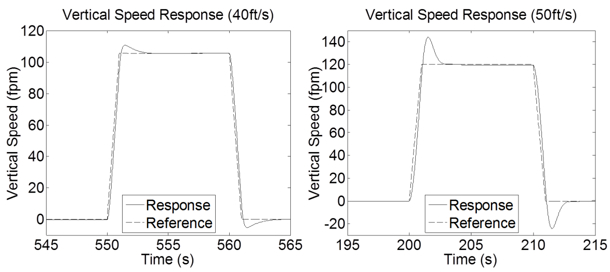

Fig. 6c. Aft stick input (high transition and forward flight)

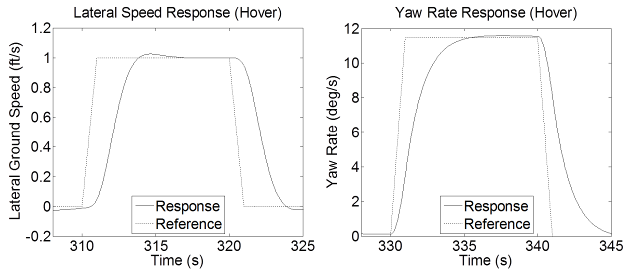

Fig. 7a. Right stick displacement and rotation (hover dynamic responses)

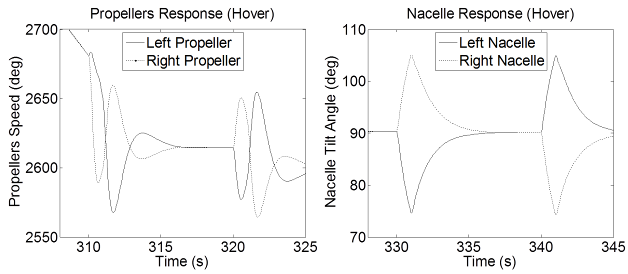

Fig. 7b. Right stick displacement and rotation (hover effectors responses)

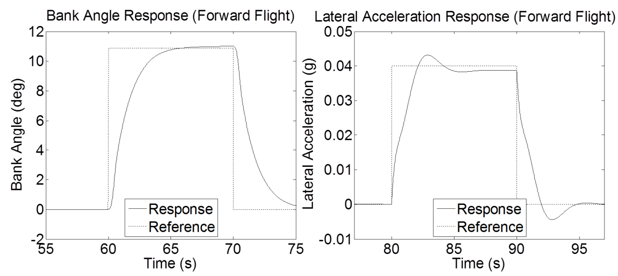

Fig. 8a. Right stick displacement and rotation (forward flight dynamic responses)

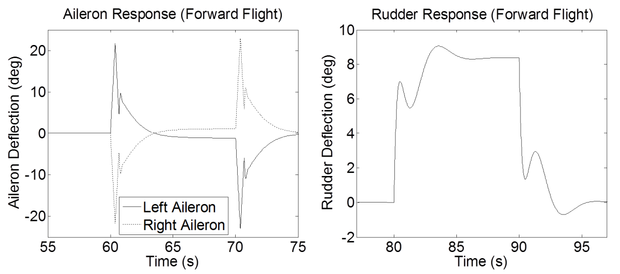

Fig. 8b. Right stick displacement and rotation (forward flight effectors responses)

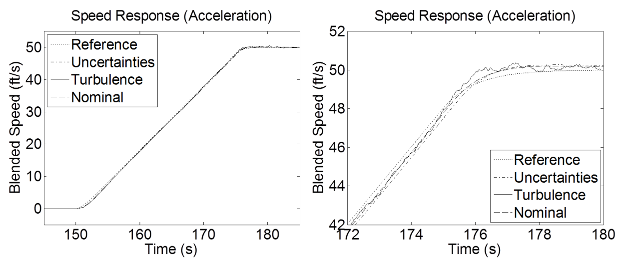

Fig. 9. Throttle acceleration input (with uncertainties and turbulence)

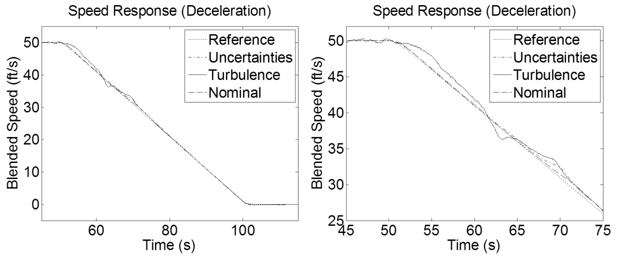

Fig. 10. Throttle deceleration input (with uncertainties and turbulence)

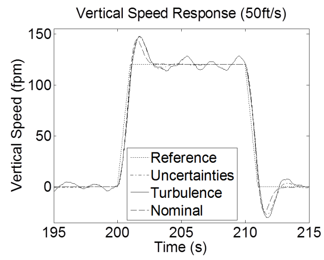

Fig. 11. Aft Stick input (with uncertainties and turbulence)

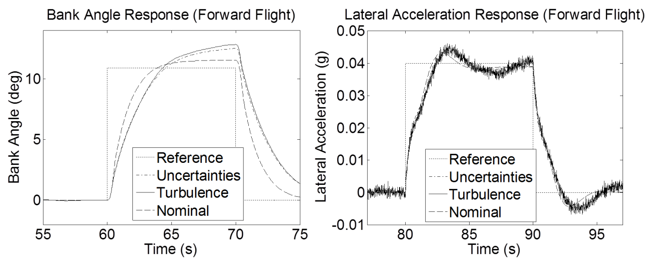

Fig. 12. Right stick displacement and rotation (with uncertainties and turbulence)

Gain and phase margins were calculated for the linearized models in the two extreme flight phases (forward flight and hover) to gain preliminary confidence in the robustness and noise rejection properties of the proposed control scheme.

Forward Flight

Input	Output	*Gain Margin (dB)*	*Phase Margin (deg)*
Throttle	Blended Speed	26.8	70.9
Long. Stick	Vertical Speed	26.3	49.0
Lat. Stick	Bank	31.3	83.7
Rot. Stick	Lateral Accel.	Inf	42.5

Hover

Input	Output	*Gain Margin (dB)*	*Phase Margin (deg)*
Throttle	Blended Speed	36.4	72.6
Long. Stick	Vertical Speed	22.5	78.1
Lat. Stick	Lateral Speed	13.2	64.3
Rot. Stick	Yaw Rate	43.5	84.2

Table 1. Gain and Phase Margins

8 Conclusions

A fixed structure non-linear Flight Control System for a tilt-rotor UAV was synthesized based on the dynamic model obtained in the preliminary design process. A genetic algorithm was used for tuning the controller gains. The proposed controller exhibited satisfactory responses with the nominal model including actuators and motors physical limits and also proved promising in the presence of uncertainties and disturbances. Following steps in this project will include:

- refinement of the dynamic model;
- testing of the controller robustness;
- synthesis of different controllers and comparison of performance and robustness;
- enhancement of control prioritization to augment performance;
- introduction of fault tolerant logics;
- manufacture of a prototype and flight testing of different control laws.

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