TRAJECTORY TRACKING FOR A NON – CONVENTIONAL UAV

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Abstract

The aim of the present paper is the design of a flight control system for a Tandem – Canard UAV, useful in the whole flight envelope, both Out of Ground Effect (OGE) and In Ground Effect (IGE) conditions. Because of the particular arrangement of the studied aircraft, a general mathematical model has been built in order to obtain non-linear analytical equations for longitudinal aerodynamic coefficients both in OGE and in IGE flight. So the dynamic behaviour of the UAV may be studied during every flight phases i.e. in the whole range of altitude. To consider the strong variation of aerodynamic parameters due to the ground effect presence, a robust control technique (LQG/LTR) has been used to design the control system. Because Phugoid mode is strongly affected by ground effect, a Stability Augmentation System has been implemented in order to increase Phugoid damping. The controller has shown suitability to track both out of ground effect and in ground effect trajectories. Besides, it possesses robustness properties either in presence of wind disturbances.

1 Introduction

Modern UAVs are often applied in missions which require an accurate tracking of the imposed flight paths [1], [2], [3]. In order to achieve this goal, usually, it is necessary to design the following systems:

1. Navigation: to estimate linear and angular positions and velocities;
2. Guidance: to process reference flight path data;
3. Control: to generate the deflections of the control surfaces that are required to drive the actual velocity and attitude of the UAV to the value imposed by the guidance system.

Traditional guidance and control schemes used to steer the aircraft along the imposed trajectories may be successfully used [4].

Generally, for guidance purposes proportional navigation or line-of-sight (LOS) command strategies are employed [4]. The most commonly employed form of command guidance is the LOS trajectory also called three-point guidance. For such a guidance, the aircraft is guided so as to remain on the LOS during the whole period of the flight. By a double integration of acceleration, the flight path is obtained. For longitudinal trajectories, usually, a pitch acceleration control system is used to perform the desired path [4].

Papoulias [5] has shown that traditional schemes may be inadequate in presence of wind. Therefore, he shows that such a strategy leads to finite trajectory tracking errors, the magnitude of which depends on the type of path to be tracked (vehicle desired speed, for example). Instead of the classical approach [6], an alternative methodology is proposed to design the guidance and control systems of an Autonomous Vehicles. By using such a methodology, the resulting trajectory steady state tracking errors are reduced to zero about any flight path, also in presence of wind velocity. In fact, instead of defining the desired path in terms of space and time coordinates [7], [8], [9], the linear position of an Autonomous Vehicles is given in terms of its location with respect to the closest point on a desired trajectory, together with the arc length of an imaginary curve traced along that trajectory.

The problem of trajectory tracking is posed and solved in the framework of gain scheduled control theory.

The subject of trajectory tracking has also been approached by using multiple interconnected control loops to track command states [10]. This approach requires fine tuning of controller gains and does not assure robustness properties. Many authors use a numerical approach called inverse simulation. This is an iterative algorithm that performs stepwise dynamic simulations. The feedforward control solution is based on an internal model of the aircraft dynamics [11], [12], [13].

Nonlinear control techniques have been applied to the aircraft tracking problem. In Refs [14], [15], input/output linearization is combined with classical proportional integral derivative control in outer command loops to obtain good performance over an expanded flight envelope and stability robustness to modelling errors. This approach also requires complex gain tuning when applied to the full multivariable tracking problem.

Boyle et al. [16] presents a flight control strategy capable of high-performance tracking of a given three-dimensional Earth-fixed flight trajectory in the presence of nonlinear dynamics and parameter uncertainty. This is achieved by dividing the control task into three parts, a simple three-dimensional guidance loop, a six-degree-of-freedom feedforward manoeuvre control law, and a robust inner-loop command-following controller. An advantage of this separation is that dynamic nonlinearities are handled by the manoeuvre logic, while the inner-loop controller accounts for parametric uncertainty. Tabulated aircraft stability and control derivatives are used.

In this paper, a different flight control strategy is presented in order to achieve accurate flight path tracking. In fact:

1. Instead of tabulated stability and control derivatives [16], a non linear model of aircraft dynamics is used;
2. Instead of gain scheduling [4], [17], [18], [19], or proportional integral derivative control [14], [15], a robust control technique is employed;
3. A Stability Augmentation System is inserted into an inner loop in order to improve Phugoid damping.

The aim of the present research is to track the desired flight path, or to reject disturbances due to atmospheric turbulence by using only a controller in the whole flight envelope.

In fact, modern UAVs are often applied in missions, like surveillance and/or patrolling as a consequence, they need to operate at very low altitude, under the influence of extreme ground effect [20], [21], [22]. This involves the necessity to consider ground effect influence both on the modelling phase and during the Flight Control System design phase [23], [24], [25], [26].

As it is well known, the stability characteristics of an aircraft are strongly correlated to the ground distance, since, when an aircraft flies near the ground, the lift increases, the induced drag decreases, the neutral point shifts and the pitching moment at zero lift varies [27].

Usually, to cope with this problem, two different mathematical models are used to study dynamic stability characteristics of aircraft in OGE or in IGE conditions [23], [24], [26], [28], [29].

Besides, the variation of aircraft parameters, in IGE operations is the critical problem in the design of the control system.

Usually, to make up this variation, suitable controller gains are determined at several equilibrium points over a flight envelope and the gain scheduling approach is used [17], [18], [19].

Nevertheless, the flight control system is designed in order to operate only in OGE conditions, because IGE operations are limited to landing and touch down flight phases.

In previous papers of the same authors [30], [31], [32], by means of classical methodologies [17], [18], [33], [34], a general mathematical model has been built to obtain non – linear analytical equations for longitudinal aerodynamic coefficients both Out of Ground Effect and In Ground Effect conditions. In the present paper, such a mathematical model is used to perform the tracking of the flight path for a particular UAV in Tandem – Canard architecture [35], [36], [37]. Since a mission is usually performed in turbulent air, and because of the relevant parametric variations due to ground effect, robustness properties have been imposed to the Controller.

In particular, FCS has been designed by using the Linear Quadratic Gaussian/Loop - Transfer Recover (LQG/LTR) design technique, [38], [39], [40], [41]. Moreover, measurement noise has been considered and, according to MIL-F-8785C, the turbulence has been modeled via Dryden Spectrum. Finally, to take into account the noticeable influence of the ground effect on the Phugoid mode, a Stability Augmentation System has been applied.

Because of the stability robustness of such a controller in spite of both aircraft parameter variations and external disturbances, the designed flight control system allows either to track the desired flight path, both in OGE and IGE operations, or to reject disturbances due to atmospheric turbulence.

2 Technical Characteristics

The studied UAV, as previous stated, has a tandem – canard arrangement; it is particularly suitable to very low altitude missions (for example forest fire detection, volcanoes monitoring and/or battle field surveillance).

The peculiar aerodynamic and the geometric configuration of the UAV considered, make the longitudinal stability characteristics very different from conventional aircrafts [31]. In detail, it has a canard configuration with fixed tail surface that is identical to the main wing. The elevator has the same wing span of the main wing. Moreover, the UAV has been designed with a non-trimming stabilizer, so that the elevator has a zero deflection when the airplane flies at cruising speed. This particular configuration gives to the UAV both an excellent damping rate and good capability of atmospheric disturbances rejection. Finally, this airplane has also a pusher propeller, which produces a better stabilizing effect around the pitching axis and yawing axis than a tractor propeller. The geometric characteristics of the aircraft are:

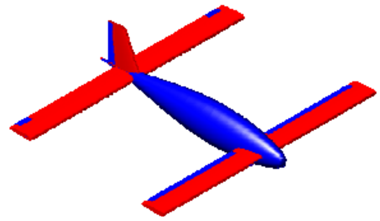

Fig.1. Studied UAV

- $S_f = S_b = 3{,}1 m^2$;
- $\lambda_f = \lambda_b = 10$;
- $b_f = b_b = 5{,}56 m$;
- $c_f = c_b = 0{,}55\ m$;
- $W = 344.43 kg$;
- V_{maxOF}=50 m/s (OGE condition);
- h_{nf} =1.361 m: forward wing's aerodynamic center - mass center distance;
- h_{nb}=2.083m: backward wing's aerodynamic center – mass center distance;
- I_y = 204.61kg m^2
- *Wing airfoil section:* *NACA 23012;*
- *Fin airfoil section:* *NACA 0012;*
- Fuselage:
  - *Longitudinal airfoil section:* *NACA 641-018;*
  - *Plan airfoil section:* *NACA 631-012.*
- *Installed power: 34kWatt.*

(the subscripts "*f*" and "*b*" mean forward and backward wing).

3 Problem Formulation

Because of the typology of their missions, it is very important that UAVs could operate fully autonomous from take off to landing.

As previous stated, the present research deals with the trajectory tracking for a tandem-canard UAV. As it is well known, to obtain an accurate tracking of the flight path, it is essential to have a mathematical model which describes appropriately the behaviour of the aircraft.

Because of the particular aerodynamic and geometric configuration of the studied UAV, the same authors have considered [31] a non-linear model to study its dynamic behaviour out of ground effect. Moreover, to study dynamic stability in ground effect, stability and control derivates have been evaluated by using the general model built in previous researches [30], [32]. In the present study a non linear mathematical model has been implemented [31], taking into account also the variations of the aerodynamic characteristics due to the influence of ground effect. In fact this model has to reproduce the UAV behaviour both in OGE and in IGE conditions.

It is known that, when an aircraft flies close to the ground, the downward flow of air (associated with the lifting action of wing and tail) is inhibited. It implies that there is a reduction of the downwash effect, which generates:

1. a reduction in the downwash angle at the tail;
2. an increase in the wing-body lift slope;
3. an increase in the tail lift slope;
4. an increase in the aircraft lift slope;
5. a reduction in the induced drag;
6. a rearward shift of the neutral point (when the variation of $\frac{\partial \varepsilon}{\partial \alpha}$ is large enough).

Because of these effects, the equations of lift, drag, and pitching moment are different from the equations of an aircraft flying out of ground effect, so they have to be properly modelled.

3.1 Mathematical model for aerodynamic coefficients

All the aerodynamic coefficients have been evaluated in function of classical variables and including also the flight altitude. Obviously, because of the strong nonlinearities due to the ground effect presence, the superposition principle is not applied.

In previous studies, a mathematical model of the lift coefficient versus angle of attack has been built by using experimental data, so the variations of both state and control variables have been considered as a function of angle of attack [31].

The influence of ground effect on aerodynamic coefficient has been evaluated as an angle of attack variation, as a downwash variation and as an aspect ratio variation due to flight altitude [27], [42]. So, the equations of Lift, Drag and Pitching Moment are:

$$L = \frac{1}{2}\rho V_w^2 S\left(\frac{1}{2}c_{Lf} + \frac{1}{2}c_{Lb}\cdot\cos\varepsilon\right) \qquad (1)$$

$$D = \frac{1}{2}\rho V_w^2 S\begin{pmatrix} c_{D0} + \Delta c_{D0}\left(\delta_{el}\right) + \\ + \frac{1}{2}\frac{c_{Lf}^2}{\pi\lambda_f} + \frac{1}{2}\frac{c_{Lb}^2}{\pi\lambda_b}\cos\varepsilon \end{pmatrix} \qquad (2)$$

$$\begin{aligned} M = \frac{1}{2}\rho V_w^2 Sc\Bigg(&-\frac{1}{2}\frac{h_{nb}}{c}\Bigg(c_{Lb}\cos\left(\alpha_g-\varepsilon\right)+ \\ &+\left(\frac{1}{2}c_{D0}+\frac{c_{Lb}^2}{\pi\lambda_b}\right)\sin\left(\alpha_g-\varepsilon\right)\Bigg)+ \\ &+\frac{1}{2}\frac{h_{nf}}{c}\Bigg(c_{Lf}\cos\left(\alpha_g\right)+ \\ &\left(\frac{1}{2}c_{D0}+\frac{c_{Lf}^2}{\pi\lambda_f}\right)\sin\left(\alpha_g\right)\Bigg)-c_{m0}\Bigg)\end{aligned} \qquad (3)$$

Obviously, c_{Lf} and c_{Lb} (respectively forward and backward wing lift coefficient) depend on angle of attack of the single wing:

$$\alpha_f = i_t + \arctan\left(\frac{w - q\cdot h_{nf}}{u}\right) + \Delta\alpha_{IGE} \qquad (4)$$

$$\begin{aligned}\alpha_b = &\arctan\left(\frac{w+q\cdot h_{nf}}{u}\right) - \\ &+\left(\varepsilon - \left(\left.\frac{\partial\varepsilon}{\partial\alpha}\right|_{OGE}\left(1-\Delta\varepsilon_{IGE}\right)\cdot 4q\frac{h_{nf}+h_{nb}}{V_w}\right)\right)+\Delta\alpha_{IGE}\end{aligned} \qquad (5)$$

$\Delta\alpha_{IGE}$ is the angle of attack variation due to ground distance.

In a previous research [30], a mathematical general model has been built to evaluate the variation of the aerodynamic characteristics laws due to altitude; this methodology permits the calculation of aerodynamic coefficients both in OGE and in IGE conditions.

It has been found that aerodynamic coefficients can be expressed by the hyperbolic equation:

$$\Delta\alpha_{IGE} = \left(\frac{3.3574 + 0.0045 \cdot \left(\frac{h}{b}\right)^{-1.748}}{3.3574} - 1 \right) \cdot \left(1 + 0.001317 \left(\frac{h}{b}\right)^{-1.75} \right) \cdot \alpha_{OGE} \qquad (6)$$

$$\Delta\varepsilon_g = \varepsilon \frac{b_{eff}^2 + 4(H_h - H_w)^2}{b_{eff}^2 + 4(H_h + H_w)^2} \qquad (7)$$

where b^2_{eff} is the wing span in IGE and it has been evaluated by Roskam [34], [43].

Moreover:

$$\begin{aligned} H_w &= \frac{h}{b} b - h_{nb} \sin\alpha_g \\ H_h &= \frac{h}{b} b + h_{nf} \sin\alpha_g \end{aligned} \qquad (8)$$

In order to evaluate the aspect ratio variation due to altitude, the variation of the induced angle of attack caused by the altitude has been evaluated for each wing:

$$-\frac{1}{\pi\lambda_e} = \frac{c_{L\alpha_{IGE}}}{c_{L\alpha_{OGE}}} \cdot \frac{1}{c_{L\alpha_{airfoil}}} \left(1 - \frac{c_{L\alpha_{airfoil}}}{\pi\lambda_{OGE}} \right) - \frac{1}{c_{L\alpha_{airfoil}}} \qquad (9)$$

By inserting Equations (6), (7), (9) into Equations (1) to (5), $\frac{h}{b}$ becomes a main parameter to study the dynamic behaviour of an airplane. Furthermore, Equations (1) to (5) may be used to evaluate aerodynamic forces and momentum which have to be inserted into the classical equilibrium equations [33] in the whole flight envelope, both in OGE and in IGE conditions.

3.2 Flight Control System Synthesis

Generally, to synthesize a Control System for a non linear mathematical model, it's necessary to linearize the model and to build the controller associated to the linearized model [17], [19], [33]. To consider the variations of the aircraft parameters, it is, often, necessary to apply a gain scheduling approach, so that the control laws can be modified in function of flight conditions [17], [18], [19]. Therefore, in presence of ground effect, the gains should be modified in function of the ground distance.

A different approach has been considered in this paper, in fact the LQG/LTR robust control technique has been employed to design the controller for the previous described UAV. This technique guarantees the proper working condition of the controller also in presence of consistent parametric variations, external disturbances (i.e. atmospheric turbulence), measurement noise, unmodelled dynamics, etc.

As it is well known, LQG/LTR is a robust control technique based on the separation principle, such that a state observer and a controller can be separately designed in order to obtain state estimate and the control actions can be computed from the above-mentioned state estimate. The Control System Synthesis has been carried out on a linearized model obtained from a particular altitude. Because of the aircraft considerable parameters variations in ground effect, the Kalman Filter and the Controller have been designed by using an altitude which corresponds to fully extended ground effect conditions (h/b=0.5).

After the verification of the robustness property, the controller has been applied on the non linear model, in this way it has been possible to obtain a single Control System efficient in every flight condition.

In order to determine both the gain matrix of the Kalman filter and the gain matrix of the control law, the dynamic equations of the studied UAV have been modelled by using the classical state-space formulation:

$$\begin{aligned} \dot{x}(t) &= \boldsymbol{A}x(t) + \boldsymbol{B}u(t) + \boldsymbol{\Gamma}w(t) \\ y(t) &= \boldsymbol{C}x(t) + \boldsymbol{n}(t) \end{aligned} \qquad (10)$$

with:

- ***A*** stability matrix
- ***B*** control matrix
- ***C*** state – output matrix
- ***Γ*** disturbance-state matrix
- ***w(t)*** process noise
- ***n(t)*** measurement noise

- $\boldsymbol{x}(t)$ state vector
- $\boldsymbol{u}(t)$ control input vector

The Kalman filter gain matrix $\boldsymbol{L}$ has been chosen to minimize the performance index:

$$PI_L = \frac{1}{2}\mathrm{tr}(\boldsymbol{P}_L) \qquad (11)$$

where $\boldsymbol{P}_L = \boldsymbol{E}\left\{\tilde{\boldsymbol{x}}(t)\tilde{\boldsymbol{x}}^{\mathrm{T}}(t)\right\}$ is the covariance matrix of the observation error $\tilde{\boldsymbol{x}}(t) = \boldsymbol{x}(t) - \hat{\boldsymbol{x}}(t)$, and tr($\boldsymbol{P}_L$) is the trace of the matrix $\boldsymbol{P}_L$. The solution of this optimization problem is given by:

$$\boldsymbol{L} = \boldsymbol{P}_L\boldsymbol{C}^{\mathrm{T}}\boldsymbol{R}^{-1} \qquad (12)$$

Where $\boldsymbol{P}_L$ is the constant steady state error covariance matrix, solution of the Algebraic Riccati Equation (ARE):

$$\boldsymbol{AP}_L + \boldsymbol{P}_L\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{\Gamma Q}_L\boldsymbol{\Gamma}^{\mathrm{T}} - \boldsymbol{P}_L\boldsymbol{C}^{\mathrm{T}}\boldsymbol{R}_L^{-1}\boldsymbol{CP}_L = \boldsymbol{0} \qquad (13)$$

with $\boldsymbol{Q_L}$ and $\boldsymbol{R_L}$ weighting matrixes. The control law gain matrix $\boldsymbol{K}$ has been computed with the expression:

$$\boldsymbol{K} = \boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} \qquad (14)$$

by the minimization of the performance index:

$$PI_K = \frac{1}{2}\int_0^{\infty}\left(\boldsymbol{x}(t)^T\boldsymbol{Qx}(t) + \boldsymbol{u}(t)^T\boldsymbol{Ru}(t)\right)dt \qquad (15)$$

where $\boldsymbol{P}$ is the unique positive semidefinite solution of the following ARE:

$$\boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{PA} + \boldsymbol{Q} - \boldsymbol{PBR}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} = \boldsymbol{0} \qquad (16)$$

The following expressions have been used for $\boldsymbol{Q}$ and $\boldsymbol{R}$ [14]:

$$\boldsymbol{R}=\rho^2\,\boldsymbol{I}\,;\,\boldsymbol{Q}=\boldsymbol{C}^T\boldsymbol{C} \qquad (17)$$

Since altitude is the most important parameter in IGE conditions, the selected controlled variables are airspeed and altitude, instead of the classical choice of airspeed and climb gradient. So, the Flight Control System is based on speed and altitude errors; as consequence, the ground distance is the variable that mainly influences aerodynamic forces and moments.

3.3 Stability Augmentation System Implementation

To improve the precision of the Flight Control System, and to suppress the effect of overshoot due to Phugoid mode, a Stability Augmentation System has been implemented.

When an aircraft flies close to the ground, the Phugoid mode is strongly affected by ground effect presence. The long period oscillations could cause considerable tracking errors, especially during the first phases of the manoeuvres. Therefore, it is very important that overshoot due to this mode should become as little as possible. In a previous paper of the same authors [36], it has been shown that in some manoeuvres the maximum overshoot value in the altitude error is about 0,80m. To decrease this value, it is necessary to increase the Phugoid damping ratio.

Classically, a technique of Phugoid Suppression would be applied [18], but in IGE conditions, such a technique cannot be successfully applied. In fact, since Phugoid characteristics are strongly influenced by altitude variations, several systems with variable transfer function parameters would be designed. For the reasons given above, a unique Stability Augmentation System (SAS) has been implemented. This system allows to modify damping characteristics in order to obtain the desired overshoot value. Generally, as it is well known, an SAS is designed using classical techniques to compute a fixed feedback gain for each flight condition. Stability augmentation is achieved by a system which controls one or more flight control surfaces or engines. Since the studied aircraft has a low-powerful engine and since it has a very efficient elevator (small deflections of elevator imply strong variations of pitching moment), the SAS has been implanted on the elevator. Therefore, a gain has been put in the elevator line and it has been multiplied by the pitch rate.

To select the correct value of the gain, it is necessary to fix the desired value for the overshoot and in consequence for the Phugoid damping ratio. In fact, as it is well known, for a second order system, overshoot and damping ratio are linked by the following equation:

$$S = e^{-\frac{\pi\zeta}{2\zeta\sqrt{1-\zeta^2}}} \qquad (18)$$

The dynamic equation for the elevation angle becomes:

$$\ddot{\vartheta} + 2\zeta\omega_n\dot{\vartheta} + \omega_n^2\vartheta = c_{m\delta}\left(\delta_{basic} + k\dot{\vartheta}\right) \qquad (19)$$

In this way, in presence of an SAS, the angle of elevator equation becomes:

$$\delta_e = \delta_{basic} + k\dot{\vartheta} \qquad (20)$$

where k is the gain put in the elevator line. Equation (18) becomes:

$$\ddot{\vartheta} + \left(2\zeta\omega_n - c_{m\delta}k\right)\dot{\vartheta} + \omega_n^2\vartheta = c_{m\delta}\delta_{basic} \qquad (21)$$

So, the relation between the Phugoid damping ratio with and without the SAS is:

$$\left(2\zeta\omega_n\right)_{SAS} = \left(\left(2\zeta\omega_n\right)_{basic} - c_{m\delta}k\right) \qquad (22)$$

Finally, by fixing damping ratio (related to the selected value of the overshoot), it is possible to calculate a value for the elevator gain which assures the imposed precision maintaining the stability of the system.

To improve the precision of the system and to cope with the dynamics of the actuator (inserted in the elevator line) a Lead Compensator has been put in the feedforward line of elevator inner loop.

Because, as previous stated, the aim of the present paper is to effectively control the system in the whole range of flight altitude by using one controller, both the SAS sensitivity and the time constants of the Lead Compensator have been selected by imposing a constrain to the maximum overshoot of the altitude errors.

In particular, it has been fixed to halve the maximum errors obtained in Ref [36].

The block diagram of the controller is showed in Fig. 2.

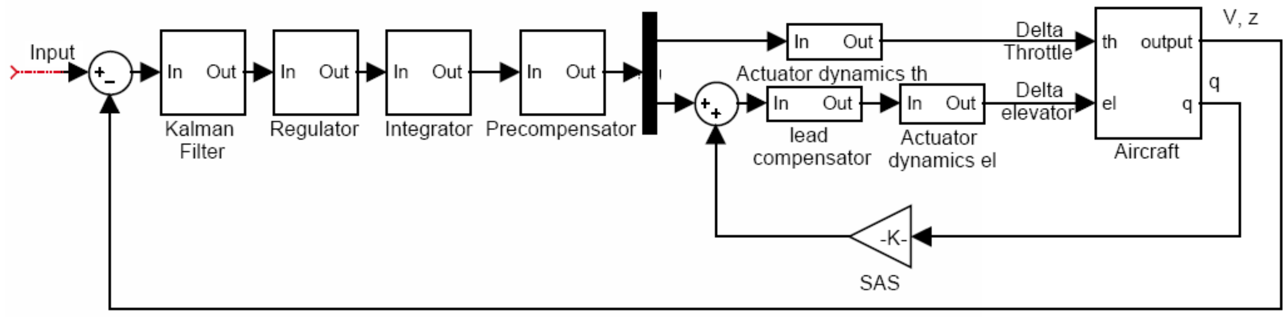

Fig.2. Controlled system architecture

4 Simulation Results

A Simulink model has been built for the Flight Control System and many simulations have been carried out.

Different trajectories have been tested, modifying several parameters, like speed, radius of curvature, starting altitude, etc.

Simulations have shown that the maximum trajectory tracking errors happen during pull up manoeuvres starting from a condition of horizontal flight.

The maximum error has been found for a pull up manoeuvre at an altitude of 0,6m with a speed of 45m/s and a load factor of 1,4. At this altitude, the error moves down when the speed decreases.

In the following tables, some of the simulations results are shown:

z *(m)*	**V** *(m/s)*	**Max Error** *(m)*
50	35	-0,3
	41,5	-0,28
	45	-0,27
2.8	35	0,29
	41,5	0,27
	45	0,26
0,6	35	0,27
	41,5	-0,32
	45	-0,35

Fig.3. Maximum altitude error in a pull up manoeuvre with radius of curvature of 700m

z *(m)*	**V** *(m/s)*	**Max Error** *(m)*
50	35	-0,25
	41,5	-0,21
	45	-0,19
2.8	35	0,24
	41,5	0,20
	45	0,19
0,6	35	0,2
	41,5	0,26
	45	0,31

Fig.4. Maximum altitude error in a pull up manoeuvre with radius of curvature of 1000m

These values show that the error decreases as speed increases for altitudes higher than 0,6m.

In the light of these results, it is possible to conclude that the maximum error in the trajectory tracking has been reduced from a value of 0.8m to 0.35m [36], value that is lower than the imposed constrain.

Nevertheless, in many other trajectories we obtained better accuracy in their tracking.

In the following figure we show the altitude tracking error obtained during a landing manoeuvre.

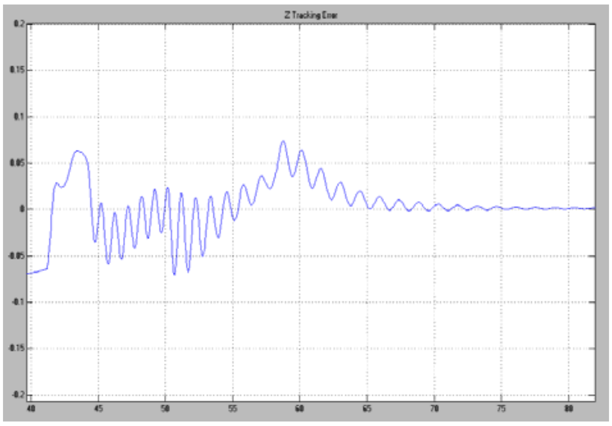

Fig.5. Altitude tracking error in landing manoeuvre

As it can be noticed, the maximum error during this manoeuvre is under 0,1m.

Finally, to verify the FCS attitude in atmospheric disturbances rejection. By using the turbulence Dryden form [44], several simulations have been carried out. The results have shown that the maximum error is about 0,15m with a strong turbulence intensity (10% of the airspeed).

The following figure shows the result obtained with the aircraft subject to turbulence at a flight altitude of 2,8m and an airspeed of 41,5 m/s.

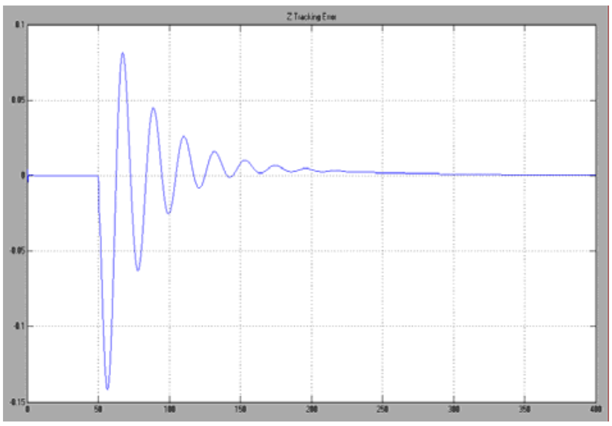

Fig.6. Altitude tracking error with atmospheric turbulence

As it can be seen from Fig. 6,the steady state errors decay quickly to zero, furthermore, it assures very small values despite of the strong turbulence intensity.

Conclusions

The carried out studies have shown the accuracy of the flight control system. In fact, the FCS allows an efficient trajectory tracking both in OGE and in IGE conditions and in the transition zone. The Controller architecture is very simple and easy to implement on board.

Moreover, the controller is efficient also in presence of strong parametric variation, even when the airplane flies in ground effect conditions. It also permits the rejection of disturbances due to atmospheric turbulence.

At the present, the authors are carrying out studies to apply the present approach to the Six Degree of Freedom UAV model.

Because the designed controller is a state feedback system, further developments of the present research deal with the synthesis of an Extended Kalman Filter, to perform both wind velocities and state estimation. Furthermore, it is possible to obtain more accurate state variables estimation and, consequently, it is possible to increase the accuracy in the flight path tracking.

Secondly, to make the altitude error smaller, an adaptive Stability Augmentation System will be designed.

Finally, since the collision avoidance is a weighty problem for UAV civil applications, the authors are studying an automatic collision avoidance system, in order to prevent impacts with immobile obstacles.

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