ROBUST CONTROLLERS DESIGN STRATEGIES FOR UNMANNED AIR VEHICLES: H∞

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Abstract

In this paper, an H∞ robust synthesis method is used to design a UAV lateral and longitudinal realistic model controller. The aircraft model is presented and analyzed. The control-law synthesis and controller structure is explained and applied to the aircraft model. Next, simulations are presented and discussed. Finally, controller robustness is demonstrated using simulations. They show the efficiency of the method since the closed-loop system meets a set of realistic specifications in time domains.

The results have been obtained in the frame of SISCANT project, whose main goal is designing a low cost FCS which enables the extensive use of UAVs. More information of SISCANT project can be encountered in http://www.tcpsi.com/siscant/.

1 Introduction

The objective of Robust Control is to design control systems that guaranties the desired performances in presence of disturbances, uncertainties and noise. Developing multivariable Robust Control methods has been the focal point in the last two decades in the control community. The challenge of this work is to apply these methods to obtain a practical realization of a robust controller, which fulfills a complete specification set, resolving the implementation issues.

Several uncertainties and disturbances sources as center of gravity position variations, time varying dependence of the mass, model simplifications, unmodeled high order dynamics, wind gust (see Dryden model [9]), etc., have been taken into account in this work. On the other hand, the controller has to be able to reject the sensor noise, wind-gusts effects and so on.

2 Aircraft description

The UAV is a 1/3 scaled down model of a Diamond Katana DA-20 shown in Fig. 1.

Fig. 1. KUAV scale model

The main characteristics of the aircraft are:

- Span 3.9 m.
- Wing surface 1.47 m.
- Mean aerodynamic chord 0.39 m.
- Mass 18-30 kg.
- Cruise velocity 130 km/h.
- Maximum velocity 200 km/h.
- Engine power 8 HP.
- Centre of gravity between 15 and 31 % of mean aerodynamic chord.

This aircraft is only slightly unstable at nominal center of gravity position. The robust controller design is justified taken into account the fact that the center of gravity movement strongly unstabilizes the aircraft.

3 Aircraft model

The first step is to obtain a mathematical model who describes the behavior of the real aircraft. First of all a complete identification flight set through the full envelope was performed to estimate the main parameters of the aircraft. Later, a 6 DOF model was build. This model was developed using the MATLAB- SIMULINK environment.

$$x = \begin{bmatrix} V_T \\ \alpha \\ \beta \\ \phi \\ \theta \\ \psi \\ P \\ Q \\ R \\ p_N \\ p_E \\ h \\ pow \end{bmatrix} \quad y = \begin{bmatrix} a_x \\ a_y \\ a_z \\ P \\ Q \\ R \\ lon \\ lat \\ h \\ \dot{p}_N \\ \dot{p}_E \\ \dot{h} \end{bmatrix} \quad u = \begin{bmatrix} \delta_{tl} \\ \delta_e \\ \delta_a \\ \delta_r \end{bmatrix} \qquad (1)$$

The state variables are respectively: true airspeed, angle of attack, sideslip angle, roll angle, pitch angle, yaw angle, roll rate, pitch rate, yaw rate, north position, east position, altitude and power. The output variables are respectively: the three components of the acceleration, roll rate, pitch rate, yaw rate, longitude, latitude, altitude, north position derivative, east position derivative and altitude derivative. The control variables are throttle position and elevator, aileron and rudder deflections.

A large set of simulations has been completed using this model and the results were compared with the real aircraft behavior encountering a high fidelity degree.

Later, the model is linearized around the nominal condition in order to use the selected optimization technique.

The nominal condition is

- True airspeed: 30 $\frac{m}{s}$.
- Centre of gravity position: 25% of mean aerodynamic chord.
- Roll angle: 0 deg.
- Yaw angle: 0 deg.
- Yaw rate angle: 0 $\frac{\text{deg}}{s}$.
- Roll rate angle: 0 $\frac{\text{deg}}{s}$.
- Pitch rate angle: 0 $\frac{\text{deg}}{s}$.
- Rate of climb: 0 $\frac{m}{s}$
- Lateral acceleration: 0 $\frac{m}{s^2}$

The state space linear model is:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \qquad (2)$$

4 Specifications

The goal of this work is to design a robust controller that fulfills predefined specifications. These specifications are usually set in terms of rise time, settling time, etc. Due to the limitation of available space on this paper, a complete description of the specifications is not possible. Only the specifications related to the experimental results included in this paper will be described.

Altitude response:

- The controlled system should be able to track altitude commands, hc, with rise time tr < 5 s.
- Settling time ts < 20 s.
- There should be very little overshoot (Mp) in the response to unit steps in altitude commands at altitudes above 305 m (1000 ft), i.e., Mp < 5%.
- At lower altitudes Mp may increase to 30% in order to obtain higher tracking performance.
- In the final phase of flight (landing approach glide path) the vertical

deviation from the desired flight path should not exceed that given in the next figure.

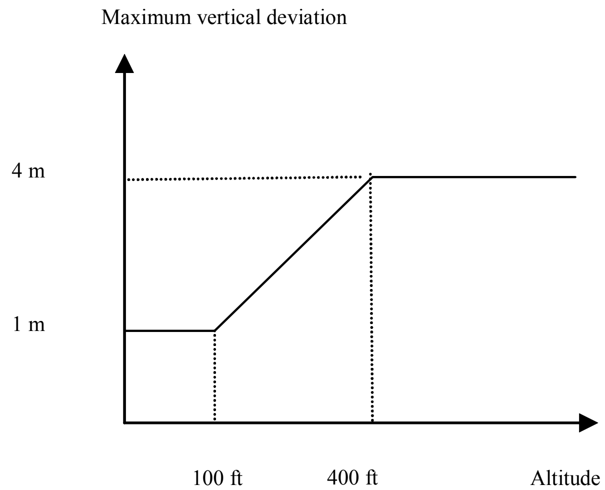

Fig. 2. Altitude response limits

Flight path angle response:

- The commanded flight path angle, γ_c , should be tracked by the actual flight path angle, γ , with a rise time tr < 1 s.
- Settling time ts < 5 s.
- There should be very little overshoot in the response to unit steps in flight path angle commands at altitudes above 305 m (1000 ft), i.e., Mp < 5%.
- At lower altitudes Mp may increase to 30% in order to obtain higher tracking performance.

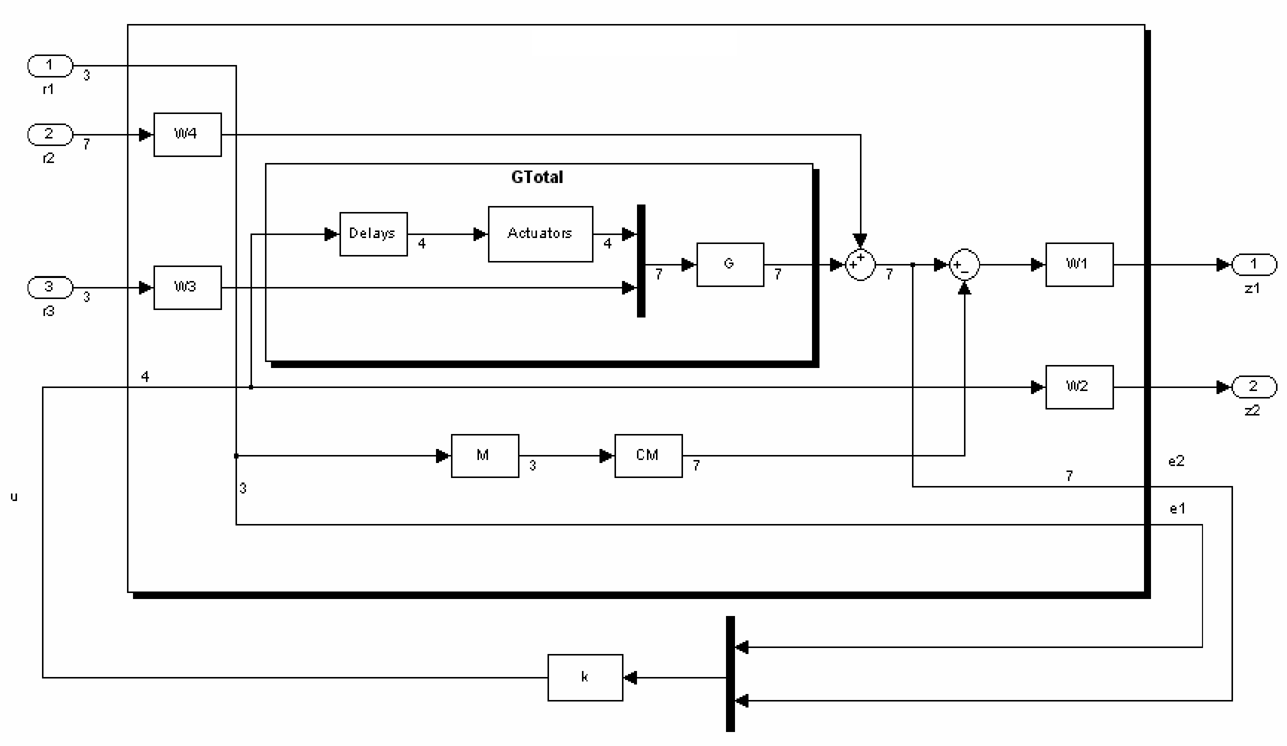

Fig. 3. Inner loop architecture

5 Architecture selection

The proper architecture selection is one of the most time consuming task during the controller synthesis. In our case, the architecture selected is based in that proposed by Tucker and Walker [10]. This architecture is formed by an inner and an outer loop.

The inner loop controller is designed to meet the performance and robustness specifications. The reference inputs are vertical speed, airspeed and roll angle. The goal is to design a controller that minimizes the deviation to desired output and the control effort. This architecture proposes a non traditional way to pilot the aircraft. The pilot doesn't deal with the traditional control inputs (throttle position and control surfaces deflection). He uniquely informs the controller the desired vertical speed, airspeed and roll angle and it, automatically, calculates the adequate input.

The inner loop feedback variables are vertical velocity, airspeed, roll angle, pitch rate, yaw rate, roll rate and sideslip.

The plant Gtotal (Fig. 3) is composed by the plant, an actuators model (first order linear approximation) and the corresponding delays modelized using a first order Padé approximation.

M is a matching model that acts on vertical velocity, true airspeed and heading angle respectively. The elements of M are selected using a simplified second order models that fulfil the performance requirements.

$$M = \begin{bmatrix} \frac{4^2}{s^2+2\cdot 4s+4^2} & 0 & 0 \\ 0 & \frac{1.5^2}{s^2+2\cdot 1.5s+1.5^2} & 0 \\ 0 & 0 & \frac{2.25^2}{s^2+2\cdot 2.25s+2.25^2} \end{bmatrix} \qquad (3)$$

The criteria used to select the elements of the M system are based on the performance specifications. Now, the selection of the first element of M model is depicted. The "specifications" section describes the performance specification related to flight path angle. The flight path angle γ is defined by the expression:

$$\sin(\gamma) = \frac{-V_v}{V_T} \qquad (4)$$

Where V_v is the height derivative and V_T is the true velocity. If small angles are considered then:

$$\gamma = \frac{-V_v}{V_T} \qquad (5)$$

This result allows applying the vertical velocity specifications to flight path angle behavior. Finally, a model that fulfills the specifications has to be built. For simplicity, a second order model is selected:

$$\frac{4^2}{s^2+2\cdot 4s+4^2} \qquad (6)$$

The step response is:

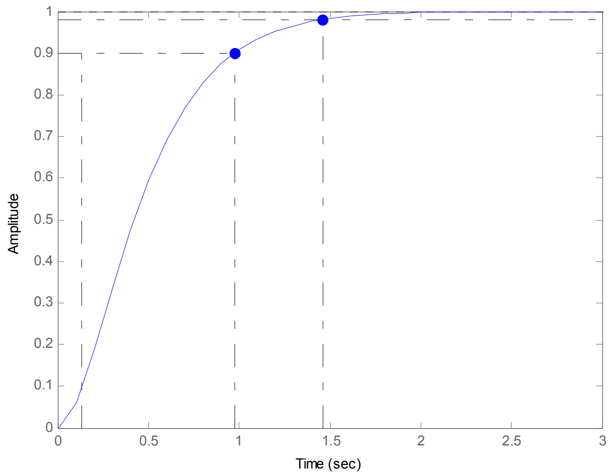

Fig. 4. Desired vertical velocity step response

This process is repeated through all the elements of the main diagonal M model. The remainder elements are set to zero.

The Wi systems are weights selected to maximize disturbance rejection, and minimize wind gusts effects and sensor noise.

$$W1 = diag\left(\frac{3^2(s+1)}{s+2\cdot 3s+3^2}, 10\frac{500s}{\frac{s}{0.001}+1}, 10\frac{500s}{\frac{s}{0.001}+1}, 5\frac{500s}{\frac{s}{0.001}+1}, \frac{7^2(s+1)}{s+2\cdot 7s+7^2}, \frac{7^2(s+1)}{s+2\cdot 7s+7^2}, 8\frac{500s}{\frac{s}{0.001}+1} \right) \qquad (7)$$

$$W2 = diag\left(0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1} \right) \qquad (8)$$

$$W_3 = I_3 \qquad (9)$$

$$W_4 = I_7 \qquad (10)$$

The general criteria used to select Wi weights, can be encountered in [8].

6 Controller synthesis

The H∞ method purpose is to minimize the deviation to desired output and the control

effort. The minimization results are achieved with the *hinf* MATLAB command.
Fig. 5 shows the singular values [9] of the sensitivity function [9].

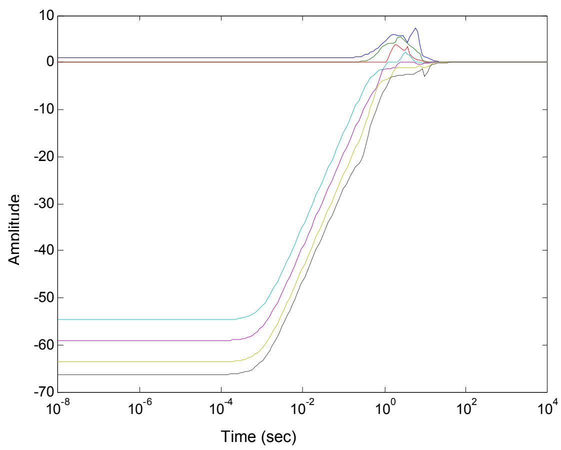

Fig. 5. Singular values of the sensitivity function

Fig. 6 shows the singular values of the complementary sensitivity function.

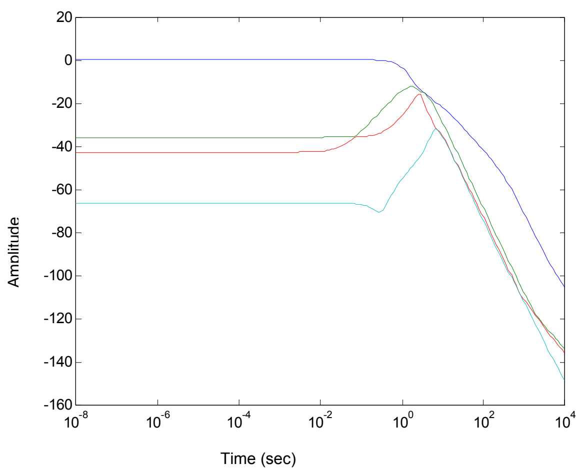

Fig. 6. Singular values of the complementary sensitivity function

The Fig. 7 shows the actual vertical velocity step response versus the desired one. The real behaviour is very similar to the looked-for and presents an oscillatory behaviour. This figure illustrates the specifications fulfilment. The actual vertical velocity rise time is over 0.8 seconds, the settling time is minor than 3 seconds, and the overshoot is zero.

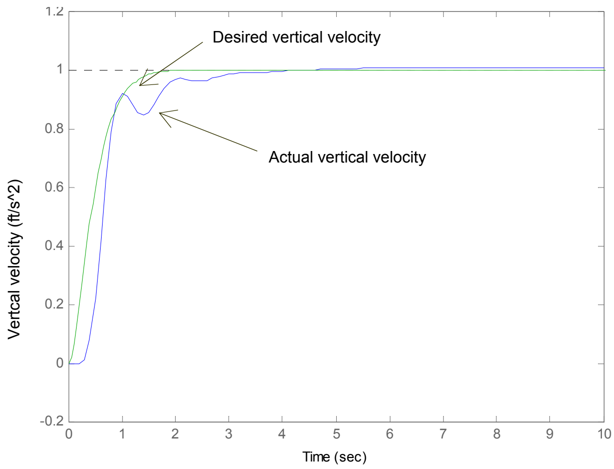

Fig. 7. Desired vertical velocity behaviour versus actual

7 Inner loop simulation results

The next step consists on the closed loop behavior validation. This objective is reached using simulation. Now the flight path angle specifications fulfillment is proved. The simulation results shown in the Fig. 8 and Fig. 9 correspond to a -10 feet per second vertical velocity step. Fig. 8 shows the vertical velocity behavior, and Fig. 9 the flight path angle behavior. Fig. 9 shows the validity of the approximation described in the equation (5).

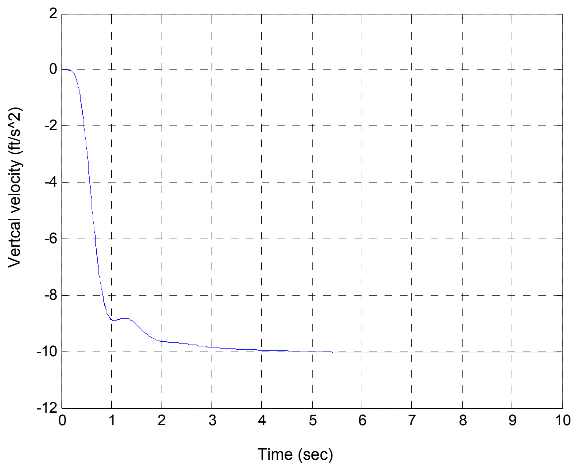

Fig. 8. Vertical velocity step response

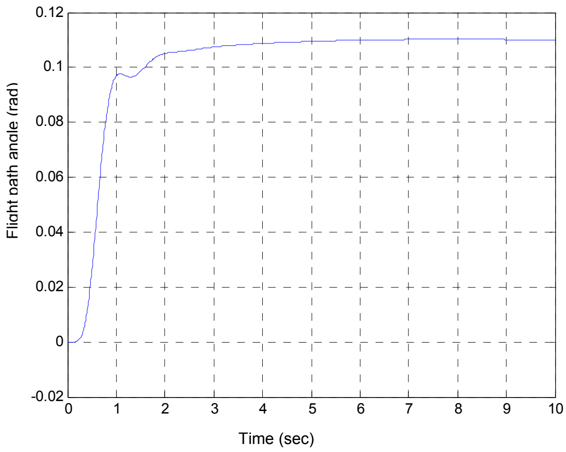

Fig. 9. Flight path angle behavior during vertical velocity step

8 Outer loop

The height, heading and lateral deviation specifications are reached by means of an outer loop. The synthesis of the height tracking reference controller is performed using the H∞ Loop Shaping technique [8]. This controller architecture is shown in Fig. 10.

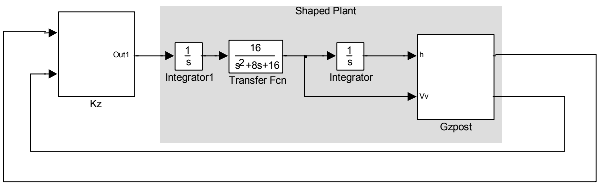

Fig. 10. Outer loop height controller

The plant used in the synthesis of the height tracking reference controller is the desired vertical velocity model who defines the first element of the M model. The complete model including inner loop controller could be use as plant. However, a high order controller would be obtained.

9 Design validation

In this section the controlled aircraft robustness is verified by mean of simulations. These simulations have been performed using the six degrees of freedom nonlinear aircraft model. Both, inner and outer controllers, are connected.

First of all, the height tracking reference in case of nominal conditions is shown in Fig. 11. The input used is a 100 feet altitude step. The actual altitude rise time is 3 seconds and the settling time is 7 seconds. This design fulfills the specifications at nominal conditions.

The aircraft center of gravity can vary between 15% and 31% of mean aerodynamic chord (m. a. c.) and the mass between 18 and 31 Kg. Now several simulations have been performed to check the controlled aircraft performances and robustness in case of parameter variations.

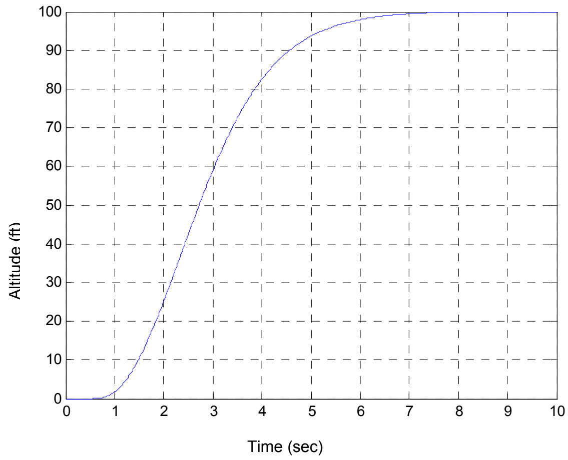

Fig. 11. Height step response: mass 20kg and center of gravity position 25%

Fig. 12 shows the 100 feet magnitude step response in case of 31Kg mass and 25% m. a. c. center of gravity position. The response presents a little overshoot of approximately 2 feet (2%), the rise time is less than 3 seconds and the settling time is around 10 seconds. This figure illustrates a more swinging behavior than at nominal conditions.

Fig. 13 shows the step response in case of 31Kg mass and 31% m. a. c. It represents the worse flight configuration. In this case the overshoot is 5% approximately and the rise time and settling time are 3.5 seconds and 18 seconds respectively.

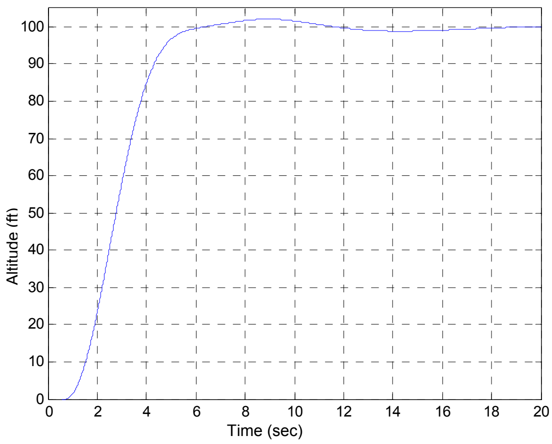

Fig. 12. Height step response: mass 31kg and center of gravity position 25% m. a. c.

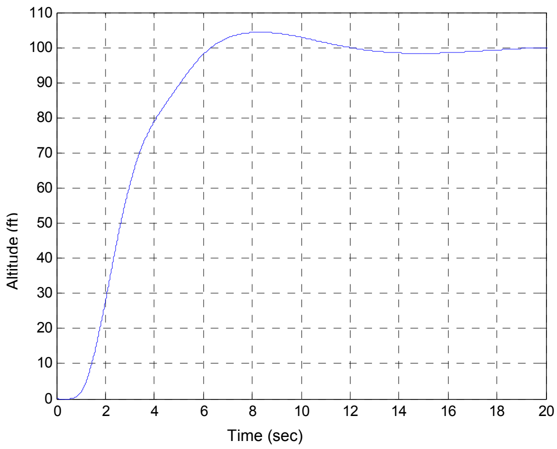

Fig. 13. Height step response: mass 31kg and center of gravity position 31% m. a. c.

These simulations show that controlled aircraft fulfil the specifications.

9 Conclusions

This paper outlines a real controller synthesis applied to an UAV that fulfills a complete specifications set.

The architecture selected is formed by an inner and an outer loop. The inner loop provides the stability and robustness characteristics and the outer loop the tracking reference performances.

The reference vector used, formed by vertical velocity, true airspeed and heading angle, suggest a non traditional way to pilot the aircraft that is based on command the desired reference vector and lets the controller to select throttle position and surfaces deflections. This kind of pilot-machine interaction appears to be a more intuitive approximation.

The desired behaviour is introduced using a matching model (M). This architecture allows modifying the desired performances without varying the controller architecture.

The outer loop controller provides a very good behavior in case of step responses, ramp responses and combinations of these two input types. It's important to note that the outer loop shows a signal derivative at the input and this should be avoided. This signal derivative is not part of the real implementation. In this case the inputs of the outer loop are provided directly by the GPS (height and vertical velocity).

The specifications and robustness performances have been validated by mean of simulation.

It's relevant to take into account that the simulations showed are not enough to validate the design. The controlled aircraft performances should be verified by means of full test cases along the whole flight envelope, varying the parameters and assuming manoeuvres that affect the lateral-directional and longitudinal dynamics. These test cases have been completed obtaining very good performance.

10 Acknowledgements

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