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An H-infinite robust tracker controller for an UAV under realistic simulated environmental effects

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Abstract: In this paper a robust multivariable H-infinite controller for an UAV to track all types of manoeuvres in the presence of noisy environment is addressed. The results demonstrate the ability of the proposed control scheme to maintain the desired trajectory despite the presence of noise and uncertainties. Tests with realistically large control inputs are used to validate the design.

1. INTRODUCTION

There is a considerable and great interest in using unmanned vehicles to perform a multitude of tasks (Office of the Secretary of Defense 2001 and Ward *et al*. 2003). UAVs already provide clear opportunity to reduce the risk of life threatening missions that might otherwise be performed by human-piloted craft.

Nevertheless, the design of control systems for UAVs is clearly a complex task. The aircraft's response to control inputs depends heavily on the parameter uncertainties of the plant. For instance, the variations in the center of gravity or the time varying dependence of the mass affect the control response. Hence, it is necessary the use of robust design methods with satisfactory performance over a specified range of plant parameter variations (Stevens and Lewis, 1992).

The objective of this work is to design a robust controller for tracking all type of input commands in a noisy environment. The controller is designed as a compromise of robustness and performance in order to fulfill the specifications.

The robust design is divided in two loops, an outer-loop for tracking reference performance and an inner-loop to achieve stability and robustness to expected parameter uncertainty.

Advantages, properties and benefits of the design are analyzed.

In Section 2 of this paper the modeling and identification assumptions are outlined. Section 3 presents the controller design. Section 4 details the reduction order problem. Validation is presented in Section 5. Finally some concluding remarks are made.

2. MODELING AND IDENTIFICATION

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 square meters.

--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.

Aircraft dynamics are described by a set of nonlinear differential equations (Stevens and Lewis, 1992). The resulting model is described by a thirteen state order model (Lambrechts *et al*., 1997). The main parameters of the aircraft are determined by a complete identification flight set through

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the full envelope. See (Gómez *et al*., 2006) and (López *et al*., 2006) for details.

In order to design an altitude command tracker using linear design methods, it is necessary to obtain a state space linear model of the form:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \tag{1}$$

where the state, output and control vectors are respectively:

$$x = [V_T \;\; \alpha \;\; \beta \;\; \phi \;\; \theta \;\; \psi \;\; P \;\; Q \;\; R \;\; p_N \;\; p_E \;\; h \;\; pow]^T$$
$$y = \left[a_x \;\; a_y \;\; a_z \;\; P \;\; Q \;\; R \;\; lon \;\; lat \;\; h \;\; \dot{p}_N \;\; \dot{p}_E \;\; \dot{h}\right]^T$$
$$u = [\delta_{tl} \;\; \delta_e \;\; \delta_a \;\; \delta_r]^T \tag{2}$$

The state vector components are: true airspeed (V_T), angle of attack (α), sideslip angle (β), roll angle (ϕ), pitch angle (θ), yaw angle (ψ), roll rate (P), pitch rate (Q), yaw rate (R), north position (p_N), east position (P_E), altitude (h) and power (pow).

The output vector is formed by: x-component of acceleration (a_x), y-component of acceleration (a_y), z-component of acceleration (a_z), roll rate (P), pitch rate (Q), yaw rate (R), longitude (lon), latitude (lat), altitude (h), north position derivative ($\dot{p}_N$), east position derivative ($\dot{p}_E$) and altitude derivative ($\dot{h}$).

The control vector is defined by: throttle (δ_{tl}) , elevator (δ_e), aileron (δ_a) and rudder (δ_r).

The dynamics are linearized about a representative flight condition. This nominal condition is: $V_T = 30\, m/s$, centre of gravity position=25% of mean aerodynamic chord, ϕ=0 rad, $\psi = 0$ rad, $R = 0$ rad, $P = 0$ rad, $\theta = 0$ rad, rate of climb = 0 rad and lateral acceleration = 0 rad.

3. CONTROLLER DESIGN

The objective of this work is to design a robust controller capable of tracking all type of input commands in a noisy environment, taken into account other realistic characteristics such as delays. The controller has to be designed as a compromise of robustness and performance in order to fulfills the specifications.

3.1. Control scheme

The control architecture is based in that proposed by Tucker and Walker (Tucker and Walker, 1997). As Fig. 2 shows basically it consists of two parts: an inner-loop controller to achieve stability and robustness to expected parameter uncertainty; and an outer-loop for tracking reference performances.

Two different controllers conforms the outer-loop: the altitude controller and the heading angle-lateral deviation controller. Both controllers are synthesized using the H infinity Loop Shaping technique see (López and Dormido, 2005), (McFarlane *et al*., 1992) and (Skogestad *et al*,. 1996). In (López *et al*., 2007) QFT techniques are also presented for this problem.

Fig. 3 shows the inner loop architecture. Its main goal is to minimize both the deviation to desired output and the control effort. The reference inputs are vertical speed, airspeed and roll angle. The feedback variables are the vertical velocity, airspeed, the roll angle, the pitch rate, the yaw rate, the roll rate and the sideslip. In the scheme ri represents the references vector while zi represents the performance vector and u represents the vector of commands generated by the controller.

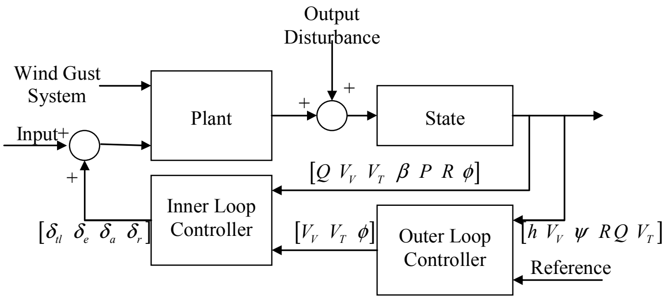

Fig. 2. Control architecture

The plant Gtotal is formed by the plant G (the linearized UAV model), the actuators model and the corresponding delays. These delays are modelized using the first order Pade approximations. They are used to represent plant uncertainties in the high frequency range such as modelling errors, neglected actuator dynamics, etc. Four delays of 100 ms are included in the plant model one in each input including the throttle.

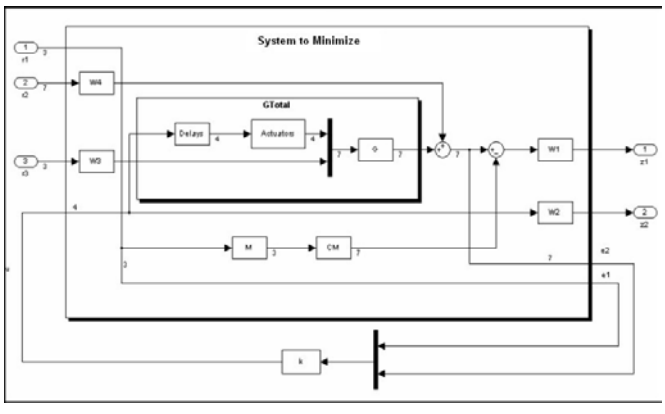

Fig. 3. Inner Loop architecture

The actuator model for δ_e, δ_a and δ_r is given by the following first order linear approximation:

$$\frac{10}{s+10} \tag{3}$$

The engine model is represented by

$$\frac{2}{s+2} \tag{4}$$

Although aileron, rudder, elevator and throttle have limits in their deflections and rates they have not been taken into account in the model in order to don't augment the order of the system. Later during the controller synthesis a trade off between actuator and engine model limits and controller performances is accomplished.

The sensor noise is represented like white noise. The standard deviations of the sensor noise corresponding to the output vector are 0.1 m/s^2 for accelerations, 0.005 rad/s for angular velocity, 5 m for position, 0.5 m/s for velocity.

3.2. The inner loop: synthesis procedure

The controller's synthesis is accomplished using an iterative procedure. First, the weights are selected, then the controller K is synthesized and finally the resulting system performances are analysed.

The controller designed guarantees the stability and follows an ideal model, the so called matching model (M).

The design is focused on maintain the vertical velocity deviation and airspeed deviation near to zero. The controller must guarantees stability and follows an ideal model, the so called matching model (M).

The matching model M, which defines the behaviour of the vertical speed, the true speed and the heading angle consists of the following three second order systems:

$$M = \begin{bmatrix} \frac{4^2}{s^2+2\cdot 4s+4^2} & 0 & 0 \\ 0 & \frac{1.5^2}{s^2+2\cdot 1.5s+1.5^2} & 0 \\ 0 & 0 & \frac{2.25^2}{s^2+2\cdot 2.25s+2.25^2} \end{bmatrix} \quad (5)$$

The weights matrixes Wi are selected to take into account frequency dependent specifications on performance and robustness. They are added to maximize disturbances rejection and to minimize wind gusts effect Label1 s and sensor noises.

W1 is related with the tracking of the reference. So, its elements are selected as low pass filters. Only the yaw rate and roll rate are selected as pass band filters.

W2 is devoted to minimize the control effort. This is why it is selected as high pass filters.

W3 and W4 are unity matrix, they weight turbulences and output disturbances respectively.

After an iterative process, the weights selected are the following:

$$W1 = diag\left(\frac{3^2(s+1)}{s+2\cdot 3s+3^2}, 10\frac{500s}{\frac{s}{0.001}+1}, 10\frac{500s}{\frac{s}{0.001}+1}, 5\frac{500s}{\frac{s}{0.001}+1}, \frac{7^2(s+1)}{s+2\cdot 7s+7^2}, \frac{7^2(s+1)}{s+2\cdot 7s+7^2}, 8\frac{500s}{\frac{s}{0.001}+1} \right) \quad (6)$$

$$W2 = diag\left(0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1}, 0.5\frac{\frac{s}{0.1}+1}{\frac{s}{0.008}+1} \right) \quad (7)$$

$$W_3 = I_3 \quad (8)$$

$$W_4 = I_7 \quad (9)$$

After some iterations, a stabilizing controller $K(s)$ is determined. This controller minimizes the variables z1 y z2 (see Fig. 3.) which corresponds to deviation between the desired output, provided by the matching model, and the real aircraft output and control effort. The resulting sub-optimal robust stability margin is $\gamma = 4.98$.

3.3. Singular value analysis

In order to validate the controller designed it must be analyzed if specifications are met. Performace specification means to minimize the sensitivity function as much as possible for low frequencies. At the same time, control effort should be small in the high frequency range.

The singular values of the sensitivity function and the control effort are shown in Fig.4 and Fig. 5 respectively.

Fig. 4. shows the different behavior between low and high frequency range. The singular values of the sensitivity function in the low frequency range enables good tracking reference characteristics. In the high frequency range the singular values are near to one to obtain the noise reduction and robustness goal.

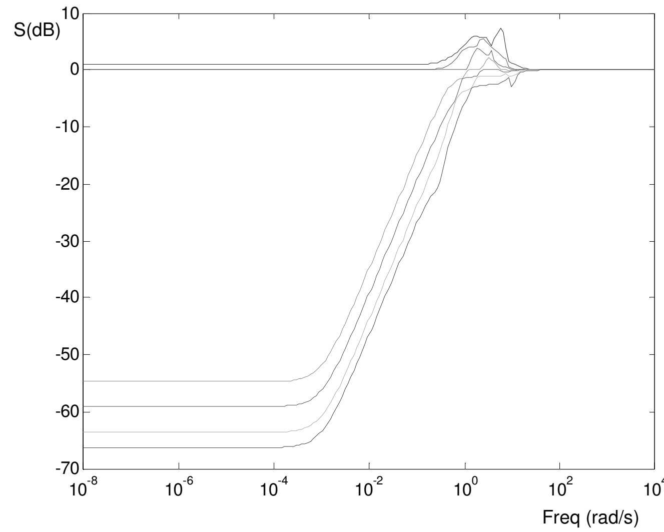

Fig. 4. Singular values of the sensitivity function

Fig. 5. shows the control effort behavior which is lower in the high frequency range, as it was expected.

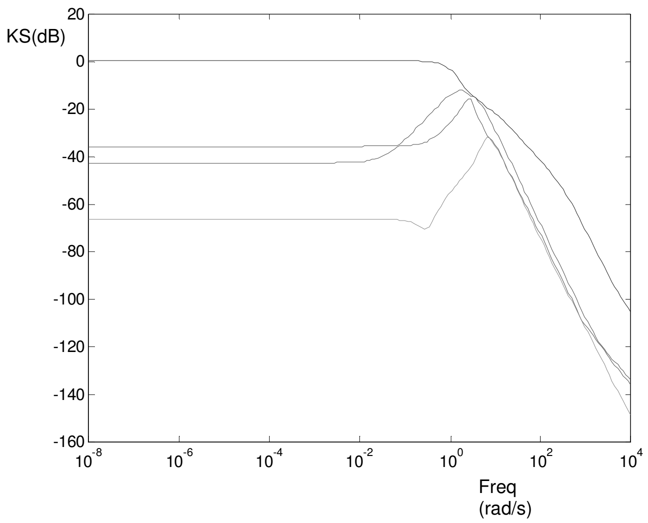

Fig. 5. Singular values of the control effort

4. ORDER REDUCTION

Since the H-infinite controller designed has a size 46 state space realization, it is necessary to apply controller reduction techniques. A final state realization for the controller of dimension 27 was achieved using Hankel Minimum Degree Approximation (MDA) without balancing reduction method (Balas et al. 2001).

This method has been applied iteratively checking the frequency and time responses every step to evaluate the performance of the proposed UAV control scheme. One example of the time response in one step of this iterative process is shown in Fig. 6. and in Fig. 7.

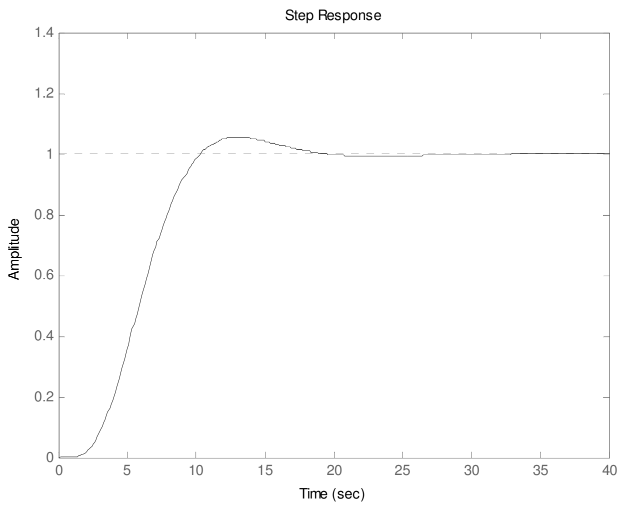

Fig. 6. Lateral deviation step response (correct order reduction)

Fig. 7. shows the effect of an incorrect order reduction. This performance is obtained when an order reduction is forced and the reduced controller is not able to maintain the desired specifications.

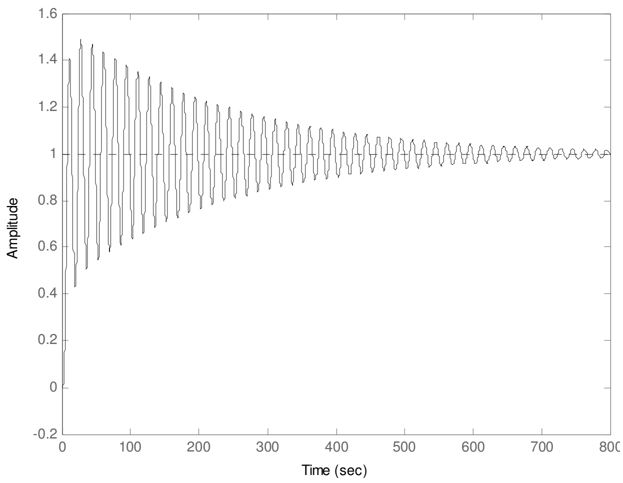

Fig. 7. Lateral deviation step response (incorrect order reduction)

5. CONTROLLER TESTING

In order to validate the controller designed, a set of test cases have been developed. Below, an experience corresponding to 45 degrees heading angle step response is shown. The results allow to check the performance of the aircraft in a noisy environment along this type of maneuver.

The airplane desired reference is illustrated in Fig. 8. The dashed line is the desired trajectory.

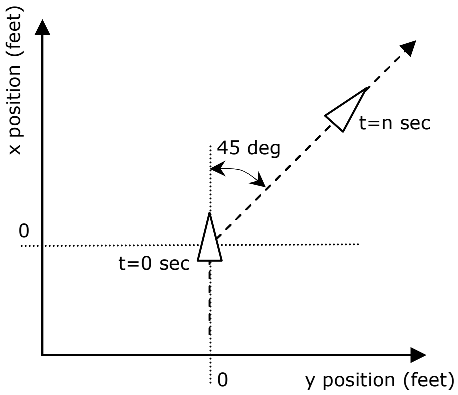

Fig. 8. Airplane desired trajectory

Fig. 9. shows the airplane real trajectory tracked. The dashed line is the desired trajectory and the continuous line is the real one.

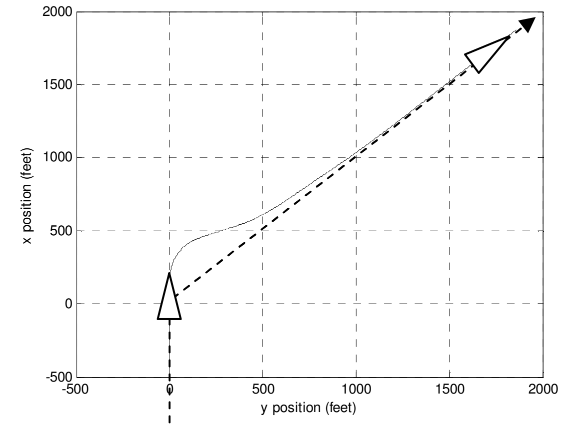

Fig. 9. Airplane real trajectory

Fig. 10. KUAV during test cases

Fig. 11. shows the noisy accelerations output provided by the inertial sensors to the controller.

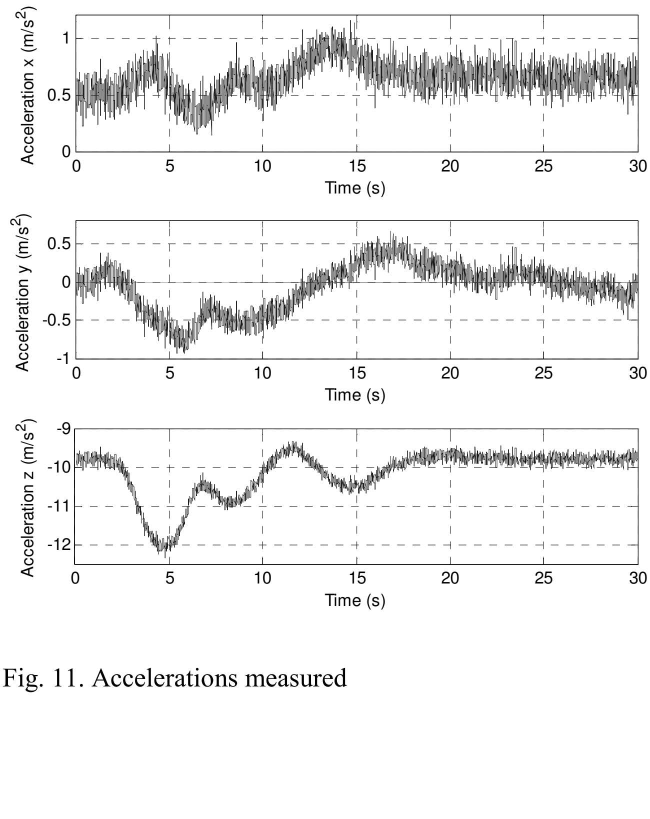

Fig. 11. Accelerations measured

The controller is able to manage adequately the noisy output and calculate the control vector. Control variables evolution are shown in Fig. 12. The throttle varies about 2% of its maximum value and elevator, ailerons and rudder present and smooth behaviour. The aileron and rudder are deflected by the controller to order the 45 degrees change of direction. Immediately a sustentation loose typical in this type of maneuvers is suffered by the aircraft. To compensate this trend the elevator acts to raise the nose of the aircraft and slightly increase the throttle to maintain the velocity.

Fig. 12 confirms that the control variables remain far from its saturation values. The power demand is less than 40% and the elevator, aileron and rudder demanded deflections are less than 5 degrees.

In this case, if the altitude holder is not connected, in 5 seconds the airplane suffers an altitude lost of 3 m and rapidly, after waiting about 5 seconds, it recovers the desired altitude.

The UAV quickly corrects its heading angle turning to reduce the error. In about 4.5 seconds the error is null, however, the airplane continues turning. This is produced because of the lateral deviation. If the airplane stops its turning movement in 4.5 seconds, it would continue straight ahead along a parallel line to the desired trajectory. To reduce the lateral deviation it must continue turning and augmenting, in a first stage, the heading angle error. Following this strategy, the controller gains its tracking heading angle and its lateral deviation reduction goal.

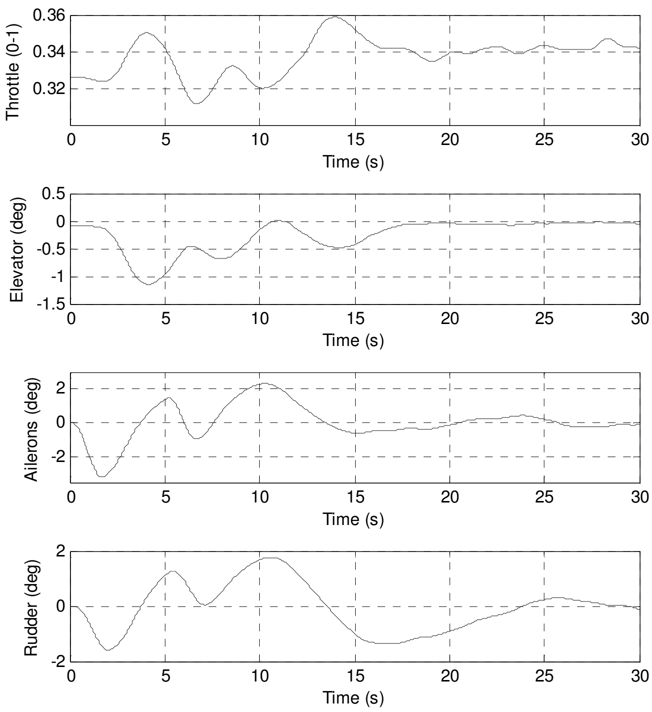

Fig. 12. Control variables evolution during the 45 feet heading angle response

Fig. 13 shows the onboard equipment mounted on the UAV.

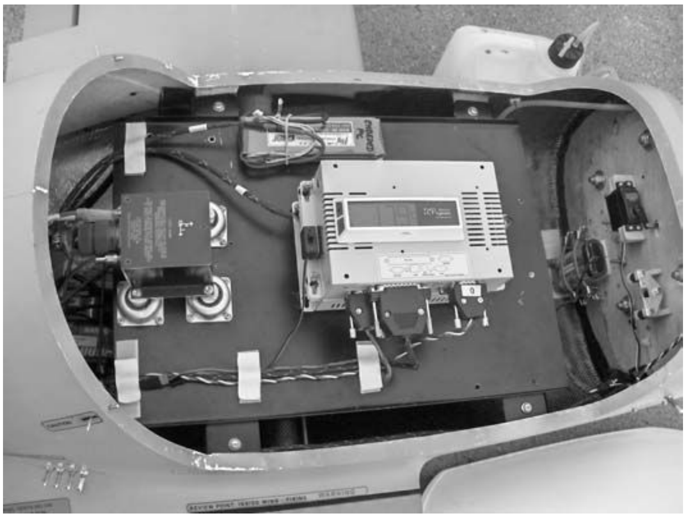

Fig. 13. On-board HW equipment

6. CONCLUSIONS

An H-infinite controller is implemented in an UAV to track all types of manoeuvres in the presence of noisy environment. It is shown that the controller guarantee good performance, attenuating high frequency noise due to sensors supplying suitable control signals. Future work is to compare this design with other robust control system design methods, such as QFT.

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