UDC 629.735.051

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An Hinf BASED ROBUST ALTITUDE HOLD FLIGHT CONTROL SYSTEM FOR A TACTICAL UAV

1. Introduction

One of the main aspect in designing an efficient controller for unmanned aerial vehicle (UAV) is to provide accommodation for change in vehicle's dynamics and presence of uncertainties in the vehicle model. If a vehicle operates in severe atmospheric conditions, i.e. flies in a turbulent air, wind gusts presence, ect, control problem becomes even more challenging. Overview of the recent studies, which are referred to UAV control problem, shows that different control strategies can be applied. Thus, [1] introduces flight control system which is based on PID controller and uses gain scheduling algorithm based on the airspeed to improve performance of the controller. In [2] strategies for an autolanding controller for a fixed wing UAV are described, which are based on PID controllers and use model inversion in their algorithms. In [3] a fuzzy logic based control system for autonomous UAV system is developed. Design of a robust flight control system for a mini-UAV using coupled stability derivatives is highlighted in [4]. Robust nonlinear controller design is employed in [5].

This paper focuses on developing an altitude hold control system for a tactical UAV. H_∞ robust controllers are designed and implemented to control fast dynamics of the vehicle, while altitude and velocity controllers are introduced as PID controllers. For simulation purposes a model of the UAV is developed, and simulations are performed for various atmospheric disturbances, such as tailwind, headwind and turbulence.

2. Mathematical Model

A tactical UAV was taken as the development platform for the control system design. The UAV possesses elevator, ailerons, rudder and flaps actuators. The UAV is driven by a 21 HP piston engine, which is controlled through the throttle, and a pusher propeller. A picture of the METU TUAV is included in Figure 1. Basic specifications of the UAV are given in Table 1.

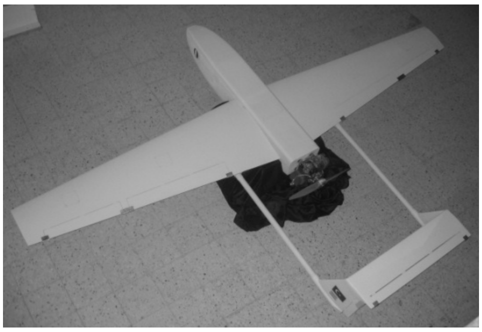

Fig. 1. Tactical UAV

Table 1.

Specifications of the Tactical UAV System

Wing Span:	4.3 m
Length:	3 m
Width of Fuselage:	0.3 m
Maximum Take-off Weight:	120 kg
Maximum Speed:	83 m/s
Stall Speed:	18 m/s
Cruise Speed:	35-40 m/s
Range:	600 km
Maximum Endurance:	5 hr
Operation Altitude:	3000 m
Payload:	FLIR Camera
Propulsion:	21HP Two Cylinder Gasoline Engine

The nonlinear model of the TUAV contains the following components: 6-DOF aircraft equations of motion, actuator models, aerodynamic and engine models, atmosphere and gravity force models, model of turbulence and wind gusts. The aerodynamic model is created using the wind tunnel tests results provided by [6]. Characteristics of the engine, which include specific fuel consumption (SFC), power and RPM relationships, are obtained from [16]. Turbulence model is represented by the Dryden wind turbulence model that implements the mathematical representation of MIL-F-8785C [7]. The actuators are assumed to be the first order servos with rate and angular limits as follows: ±200deg/s for elevator and ailerons, ±30deg for elevator, ±25deg for ailerons.

3. Trimming, Validation and Linearization

Once the model had been trimmed an open-loop simulation was performed for validation that the model exhibits classic fixed wing aircraft trim characteristics. The nonlinear model of the TUAV had been linearized around a certain trim condition, and the characteristics of the longitudinal and lateral modes are given in Tables 2-4.

Table 2.

Longitudinal Modes Characteristics

Mode Name	Root Location	Natural Frequency ω_n (rad/s)	Period (s)	Damping ratio ξ	Time to Half Amplitude t_{half} (s)
Short Period	-2.7317 $\pm 9.4696i$	9.855	0.637	0.288	0.252

Phugoid	-0.02 ±0.2615i	0.262	23.981	0.076	34.65

Table 3.

Dutch-roll Mode Characteristics

Mode Name	Root Location	Natural Frequency ω_n (rad/s)	Period (s)	Damping ratio ξ	Time to Half Amplitude t_{half} (s)
Dutch-roll	-0.2441 ±3.2075i	3.216	1.953	0.076	2.826

Table 4.

Roll and Spiral Mode Characteristics

Mode Name	Root Location	Time Constant (s)	Time to Half Amplitude t_{half} (s)
Roll	-6.0467	0.165	0.114
Spiral	-0.0092	108.695	75.0

4. Altitude Hold Controller Design

The altitude hold controller is implemented using the dual feedback loop architecture. The aircraft's altitude and velocity are controlled by outer feedback loop. The inner feedback loop is used to control the pitch angle of the aircraft through the actuation of the elevator. Additionally, a roll controller is implemented to the system to compensate disturbances in the lateral channel.

4.1. Longitudinal Channel

The longitudinal controller consists of the inner and outer control loops. The block diagram of the controller is shown in Fig. 2. The aircraft's altitude error is minimized by the outer feedback loop by demanding an appropriate pitch attitude from the inner feedback loop. PID controller is used to control height of the aircraft and its structure is illustrated in Fig. 3.

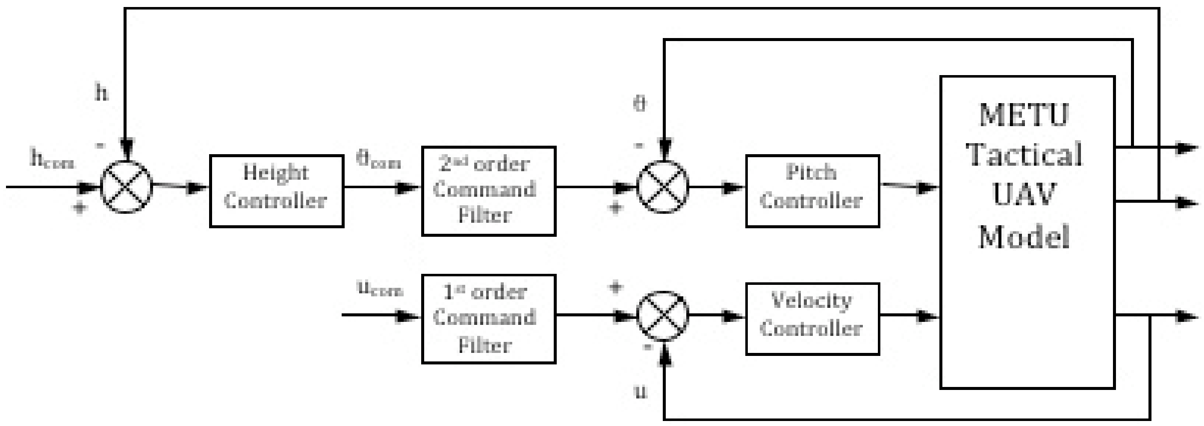

Fig. 2. Longitudinal Controller

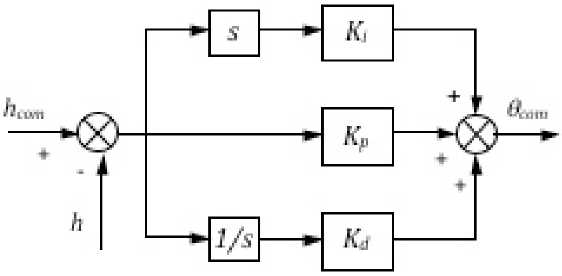

Fig. 3. PID Altitude Controller

For controlling aircraft's velocity closed-loop feedback system uses inertial velocity (x-body component) to determine the appropriate throttle response. The velocity control system, which is represented by a PID controller, compares the commanded velocity to the measured velocity, and when the velocity error is not zero, the control system inputs a corrective command to the throttle to increase or decrease the measured velocity in order to achieve a zero velocity error. In order to shape the input velocity command, a 1^{st} order filter is used; its time constant is chosen to be equal to 0.15 rad/s.

4.1.1. Pitch Controller Design

The inner loop in longitudinal channel of the altitude hold controller, which implements the pitch attitude control system, is developed by H_{inf} controller design technique. The main purpose of the pitch control system is to track the command pitch angle, which is demanded by the altitude hold controller. Hence pitch dynamics of the aircraft is faster

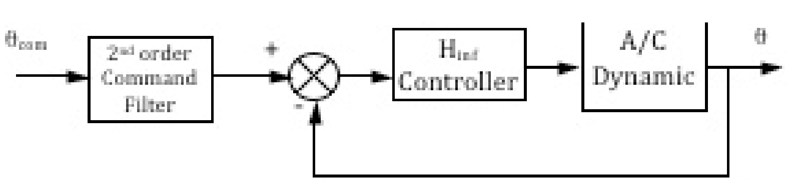

Fig. 4. Pitch Channel Control System Configuration

comparing to the altitude change, it is important to follow pitch commands fairly well. Block diagram of the pitch control loop is given in Fig. 4.

Typical classical controllers provide a good performance to operate in calm atmosphere. However, if the aircraft flies in a turbulent air, or there is a wind gust, there is no guarantee that classical controller will satisfy the desired performance and stability requirements. Another problem comes when the plant model deviates from its nominal design condition due impossibility to obtain an accurate data, using simplifications in the modelling process (i.e. linearization of nonlinear dynamics), or when plant's parameters deviate in time.

Robust control theory provides methods for designing controllers that would produce accurate and fast response in the face of uncertainties or disturbances. H_∞ design allows solving the control problem and guarantee the design requirements in the presence of uncertainties in the vehicle model and disturbances acting upon the aircraft. The main aim of robust design is to find a controller for the system, such that the closed-loop system is robust. [8], [9] gives definition of optimal and suboptimal H_∞ problem, and also provides solution to general H_∞ control problem. Modeling uncertainties and weighting functions, H_∞ norm concepts are precisely described in [10, 11].

Procedure of designing the H_∞ controller is more involved compared to classic controller design, it includes partitioning and interconnecting plant depending on the number of control inputs, measured outputs, disturbances and errors. Basic control system configuration, which is used for robust controller design, is given in Fig. 5. Generalized plant P consists of the nominal vehicle model and weighting functions. Signal w represents all the inputs: references, disturbances, sensor noises, and etc. The components of z are all the signals that must be controlled: tracking errors between reference signals and plant outputs, actuator signals whose values are limited, etc. The vector y includes sensors measurements. Finally, u contains all controlled inputs to the generalized plant. The signals w, z, y, and u are, in general, vector-valued functions of time.

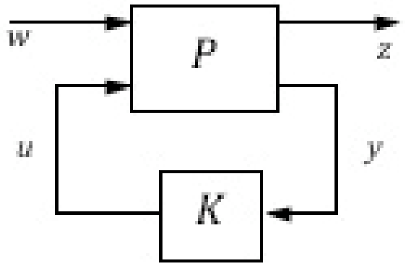

Fig. 5. General Configuration

Vehicle's dynamics is defined as the transfer function from the system's input (elevator deflection) to the system's output (pitch angle) obtained from the linearized longitudinal dynamics of the METU TUAV. Weighting functions represent the effect of disturbances, sensor noise, plant's parameters variations, and tracking error. It is assumed that multiplicative uncertainty appeares due to is change in the vehicle's aerodynamics. For longitudinal motion the most important aerodynamic derivatives that effect stability are static longitudinal stability derivative $C_{m\alpha}$ and pitch-damping derivative C_{mq}. Turbulence is represented by the Dryden turbulence model, which is created by passing a band-limited white noise through appropriate forming filter. Assumed the presence of the sensor noise with a frequency of 100 Hz and standart deviation of 0.5% of the output nominal value.

MATLAB Robust Control Toolbox is used for designing the H_∞ controller for the METU TUAV. It performes partitioning and interconnection of the generalized plant and computation of a stabilizing H_∞ controller. The performance of a nominally-stable uncertain system model is measured by the input/output gain, which, in general, degrades (increases) for some values of its uncertain elements. Robust performance of the designed pitch control system is analysed using MATLAB/ Robust Control Toolbox. "Robustperf" command gives the measure of the level of the input/output gain degradation. It calculates upper and lower bound on robust performance margin. The value of the input/output gain (H_∞ norm) of the uncertain system can be found as a reciprocal to the robust performance margin.

As a result of implementing H_∞ controller synthesis procedure in MATLAB, a pitch controller had been obtained, and its performance characteristics are the following: upper and lower bound on robust performance margin 0.9481, critical frequency: 1.3057, performance margin 1.05. Response of the pitch controller is illustrated in Fig. 6.

4.2. Lateral Channel

Lateral channel of the altitude hold system is represented by the roll conroller, which is designed by means of H_∞ control technique. The function of the roll autopilot is to bring the airplane to a desired roll orientation and stabilize the roll attitude if aircraft is subjected to disurbances. Ailerons are used as a control surfaces. The algorithm for designing a roll controller duplicates the design procedure, which was used for a pitch angle controller, described above. Here, plant is represented by the fransfer function from ailerons deflection to the roll angle. The weighting function that reflects system's multiplicative uncertainty is defined assuming variations in aerodynamic parameters. In lateral motion airplane effective dihedral $C_{l\beta}$ and roll-damping C_{lp} are of the primary importance for airplane's stability.

Using MATLAB Robust Control Toolbox, the H_∞ roll controller had been abtained with the following performance characteristics: upper and lower bound on robust performance margin 0.9299, critical frequency: 2.9213, performance margin 1.08. Response of the control system to the given input is shown in Fig. 6.

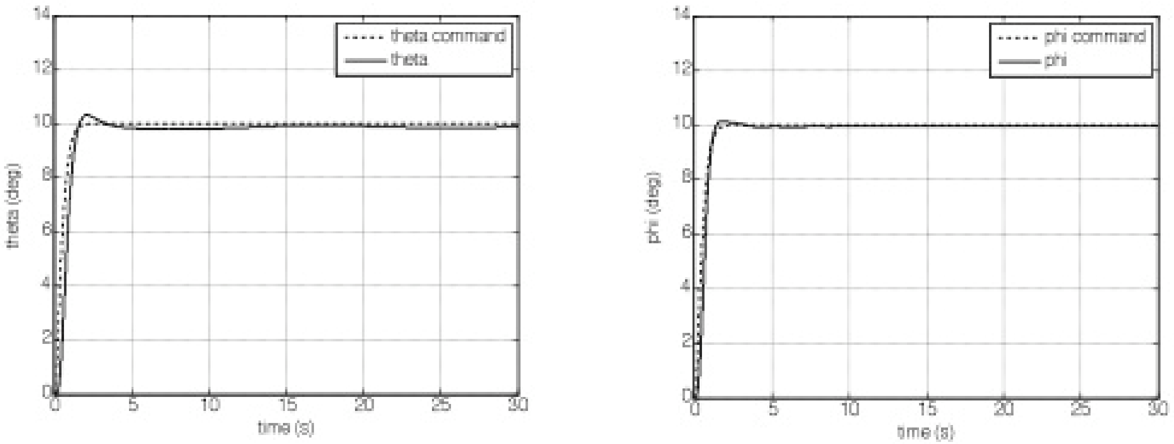

Fig. 6. Pitch and roll responses

5. Simulation Results

Verification of the designed altitude hold controller’s performance is held by simulation in MATLAB/Simulink environment. Different wind/turbulence conditions are investigated. Simulations are performed for a constant velocity command, and zero roll angle command.

5.1. Case 1: No Wind, No Turbulence

Simulation results show that the UAV follow the desired altitude command very closely. The maximum error occures at the initial time of the input command and decays to the minimum value in 10 seconds (Fig. 7). Responses of the pitch angle response and angle of attack are given in Fig. 8, 9. Corresponding elevator position and the velocity response are illustrated in Fig. 8 and 9, respectively.

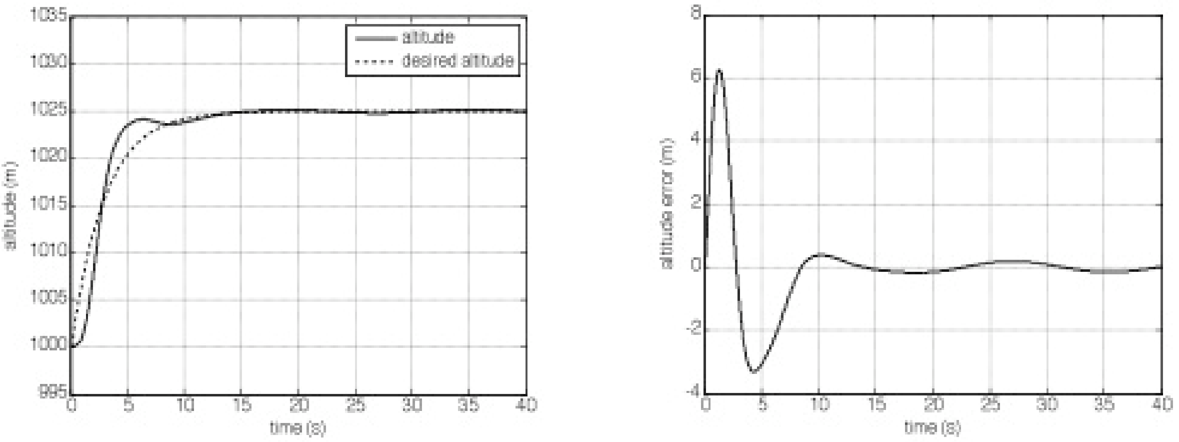

Fig. 7. Attitude and altitude error

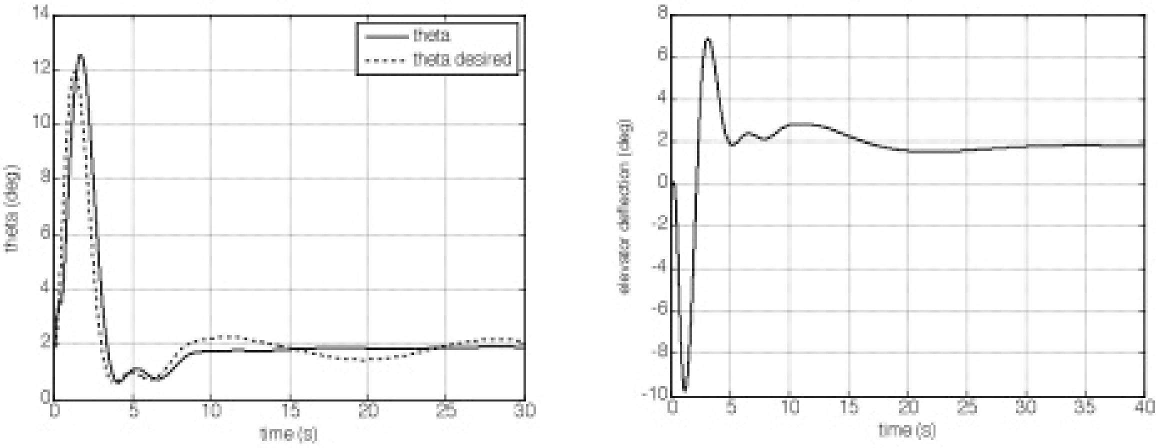

Fig. 8. Pitch angle and elevator position

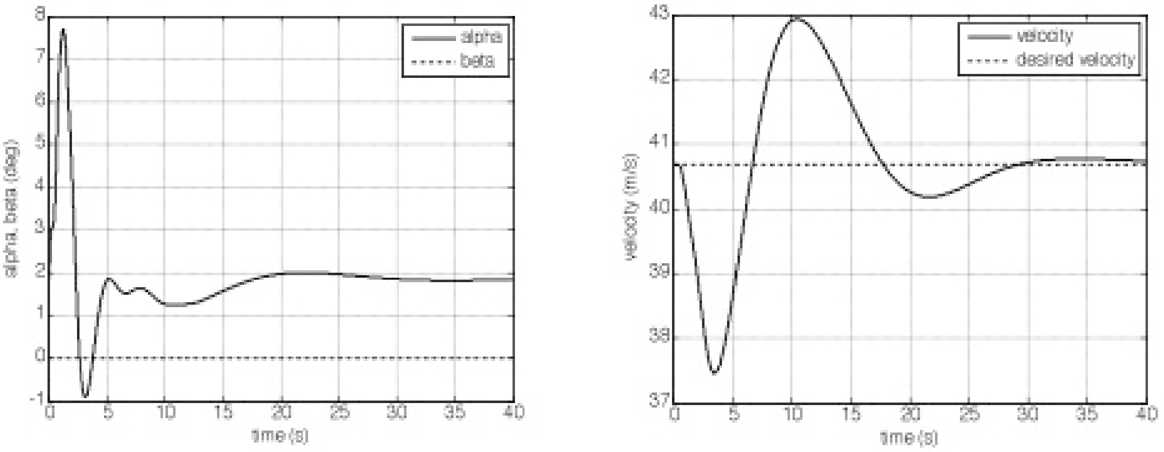

Fig. 9. Angle of attack, sideslip and velocity of the UAV

5.2. Case 2: 2.5 m/s Tailwind + Turbulence

Simulation is performed with a presence of the tail wind of 2,5 m/s and turbulence. Fig. 10 illustrates wind and turbulence profile.

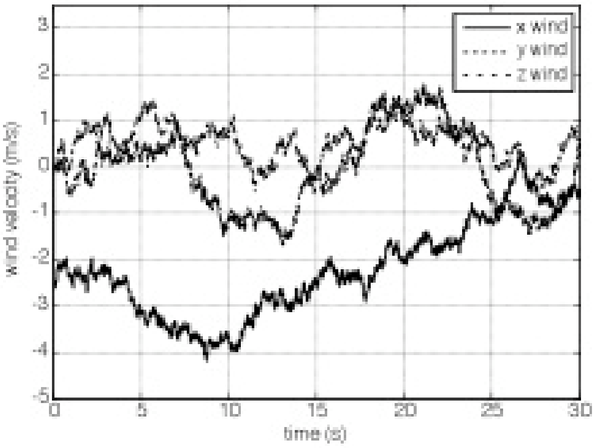

Fig. 10.Wind level

The altitude response and its error are given in Fig. 11. It is seen, that the altitude hold controller performs with no significant error in altitude. Roll control system is involved for stabilizing the roll angle, which is disturbed by the lateral component of the turbulence wind. Responses of pitch and roll channels are shown in Fig. 12, and corresponding deflections of control surfaces are illustrated in Fig. 13. Changes in angle of attack, sideslip angle can be seen in Fig. 14, which also shows the velocity response of the UAV.

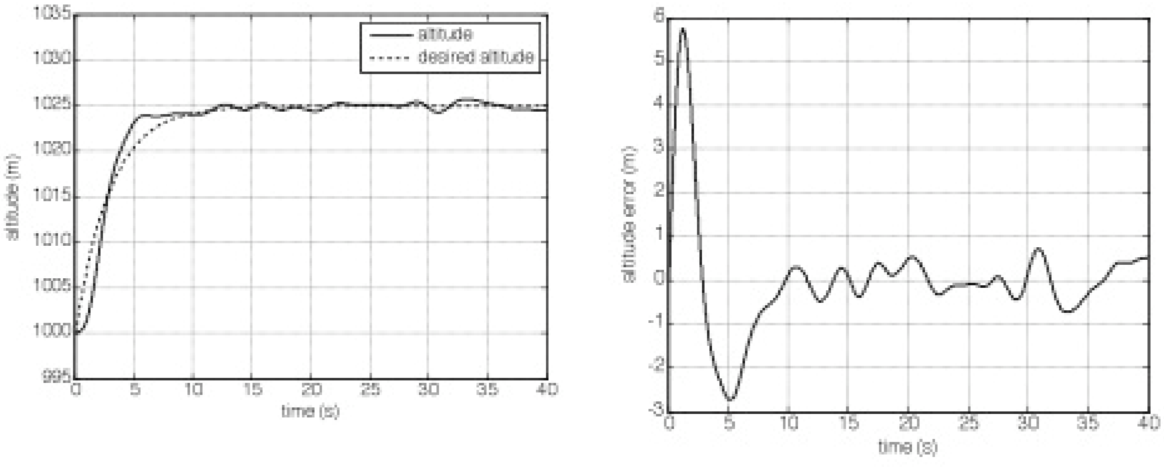

Fig. 11. Attitude and altitude error

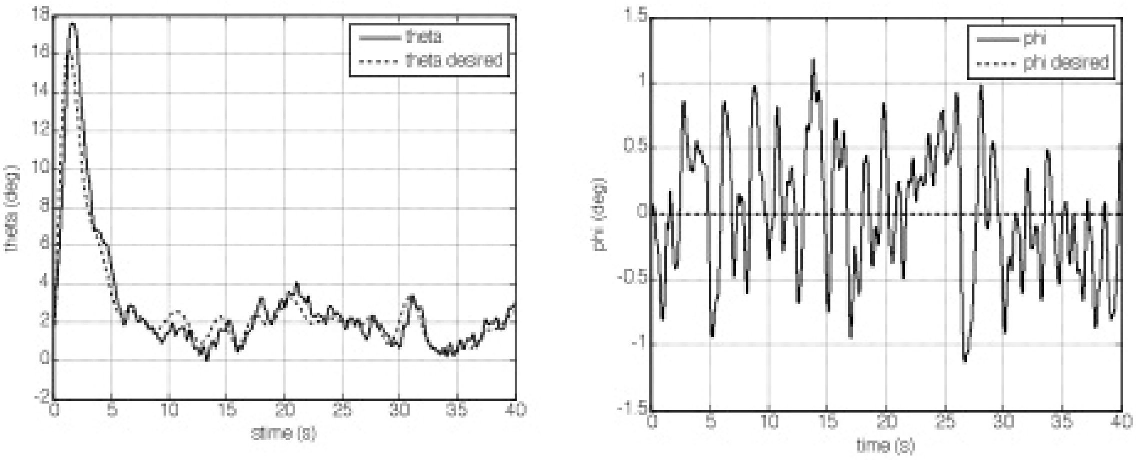

Fig. 12. Pitch and roll angle responses

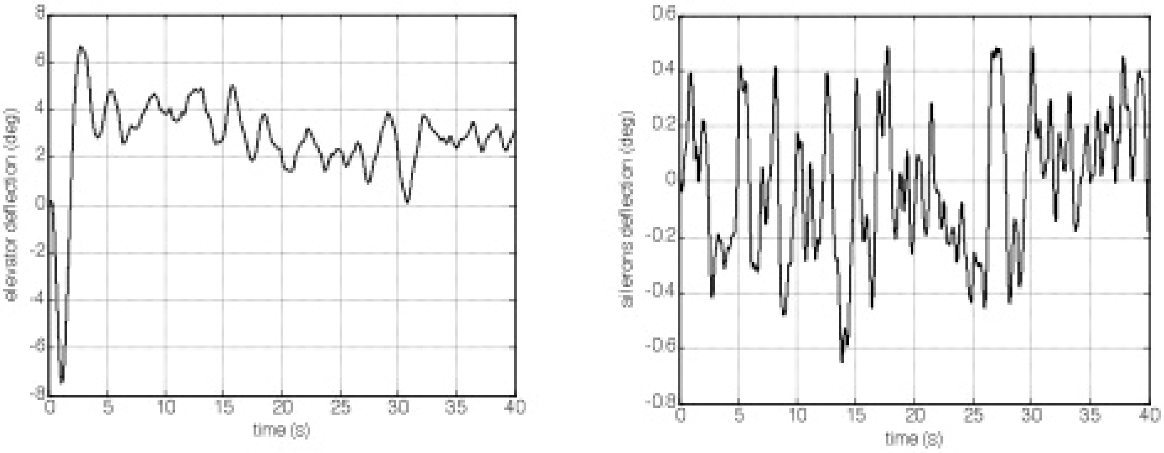

Fig. 13. Elevator and ailerons positions

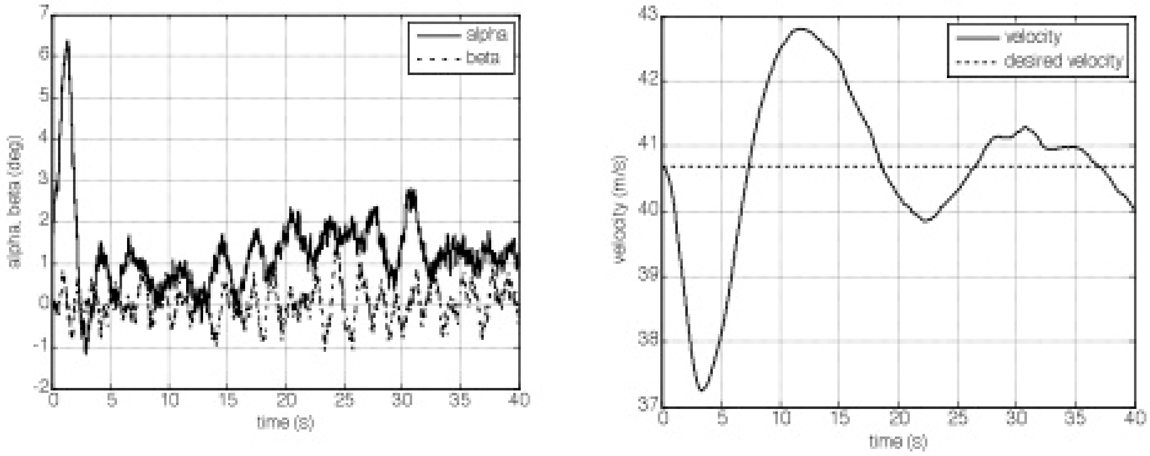

Fig. 14. Angle of attack, sideslip and velocity

5.3. Case 3: 5 m/s Headwind + Turbulence

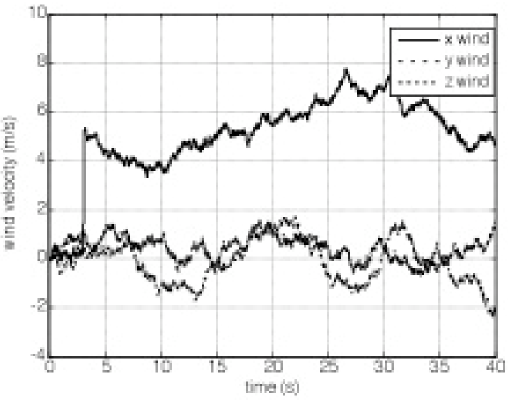

Fig. 15. Wind level

Consider the case when in addition to the turbulence, a head wind gust appeares at the 3rd second of the simulation. Simulation results for the wind profile given in Fig. 15, show that controller exhibits a sufficient performance with acceptable errors in altitude tracking (Fig. 16, 17). Headwind gust, appearing at the initial moment of simulation tends to increase the pitch angle, which can be observed from Fig. 18. Deviations in roll attitude, caused by turbulence, are stabilized by the roll control system. Deflections of elevator and ailerons are given in Fig. 18, and Fig. 19 represents response of the angle of attack and velocity.

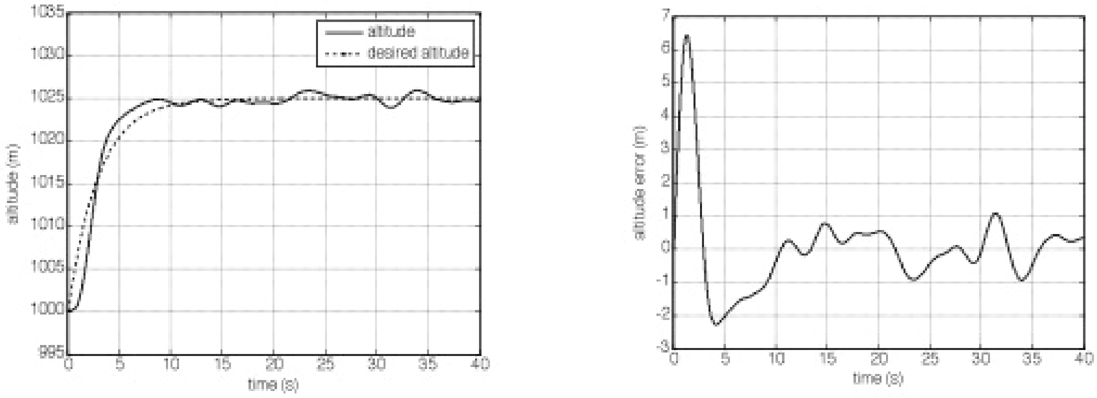

Fig. 16. Attitude and altitude error

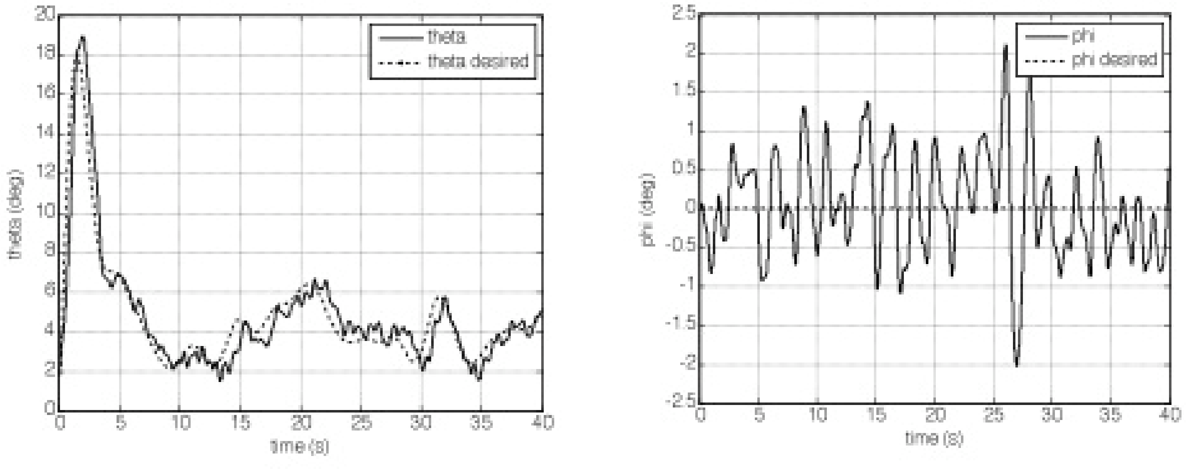

Fig. 17. Pitch and roll angle responses

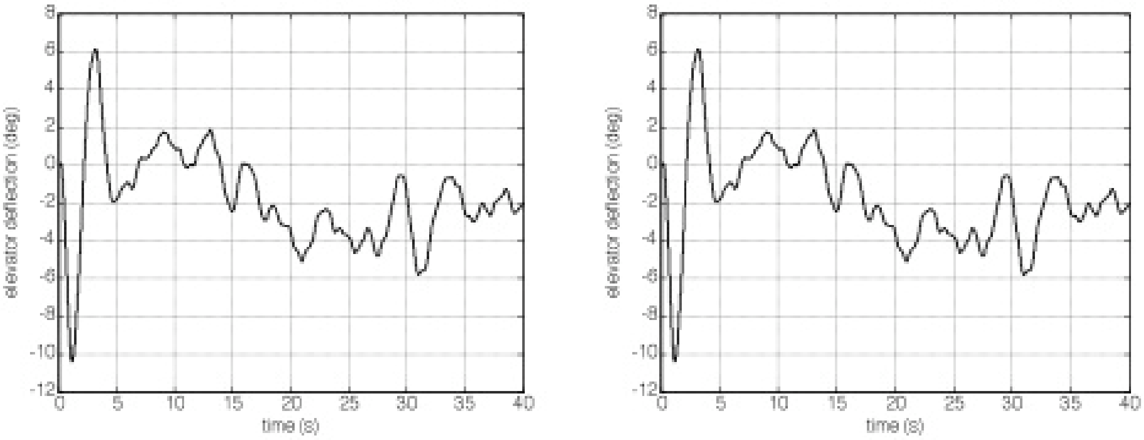

Fig. 18. Elevator and ailerons positions

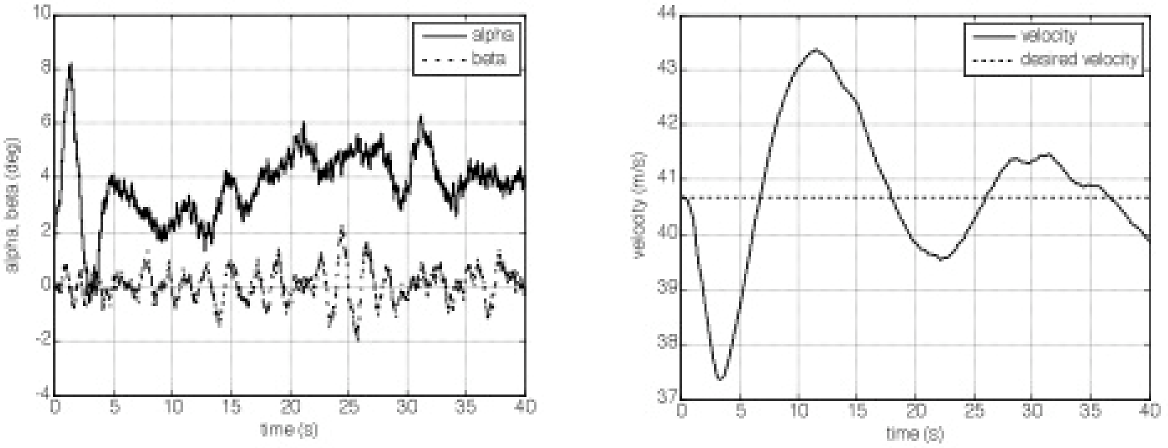

Fig. 19. Angle of attack, sideslip and velocity

6. Conclusions

Altitude hold control system is designed for a tactical UAV. A nonlinear model of the UAV is developed. The control system combines both classical and robust controllers, which are implemented to the different levels. The outer loops aim to track the given altitude and velocity commands, and they are designed my means of classical control theory. The inner loops intend to stabilize aircraft's angular positions, and involve H_∞ robust controllers. The H_∞ robust controller design algorithm consideres the uncertainties of the model's parameters and the disturbances, which act upon the system, and therefore provides robust performance in the face of plant uncertainty and disturbances. MATLAB Robust Control Toolbox is used for designing the H_∞ robust controller and obtaining its performance characteristics. Command filters are implemented to the control system to match dynamics of the aircraft. Number of simulations is performed to illustrate the controller's performance, to assure that it tolerates presence of various atmospheric disturbances (tail wind, head wind and turbulence).

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