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Marta M. Komnatska, Post-graduate student

LINEAR MATRIX INEQUALITY BASED DESIGN OF FLIGHT CONTROL SYSTEM COMBINED WITH FUZZY TUNING

National Aviation University
E-mail: martakomnatska@gmail.com

This paper is dedicated to the synthesis of combined control structure. The architecture of the controller is divided into two loops. The inner loop controller is based on robust static output feedback design under linear matrix inequality approach with H-infinity method in order to attenuate the external disturbances at pre-determined level. The outer loop controller is designed using fuzzy Takagi-Sugeno inference system. The efficiency of the proposed approach is demonstrated on example of lateral channel control of small Unmanned Aerial Vehicle.

Розглянуто синтез багатовимірної системи управління польотом з двома контурами управління. Для внутрішнього контуру управління методом лінійних матричних нерівностей синтезовано робастний статичний регулятор за виходом, який забезпечує пригнічення зовнішніх атмосферних збурень. Зовнішній контур управління розроблено на основі нечіткої моделі логічного виводу типу Такагі – Сугено нульового порядку. Дослідження проведено на прикладі управління бічним рухом безпілотного літального апарата.

Рассмотрен синтез многомерной системы управления полетом с двумя контурами управления. Для внутреннего контура управления методом линейных матричных неравенств синтезирован робастный статический регулятор по выходу, обеспечивающий гашение внешних атмосферных возмущений. Внешний контур управления разработан на основе нечеткой модели типа Такаги–Сугено нулевого порядка. Исследование проведено на примере управления боковым движением беспилотного летательного аппарата.

Statement of purpose

Recently, the usage of unmanned aerial vehicles (UAVs) has gained a great attention from the control system society, since these vehicles are able to perform different tasks starting from civil missions as agriculture, ecological and metrological, to military operations. Mostly, the UAVs are used in dangerous and inaccessible region in order to avoid physical injuries in case of manned vehicles utilization. Therefore, the remaining challenge in this area is to design a control system with law cost and less power consumption without compromising the flight mission.

To satisfy the aforementioned requirements, the robust control theory could be applied. The designer of such control law needs to take into account several objectives to meet the desired performance and robustness of the closed loop system. The UAVs are subjected to various disturbances within the flight envelope. These perturbations could be internal and/or external as well as structured and/or unstructured.

Moreover, to reduce the weight of the UAV the components of the state space vector are not all measured.

The solution to this problem various methods of flight control system are proposed in the literature. Among them, it is possible to mark out the works related to the robust PD controller design proposed in [1]. Another attractive approach is proposed in [2; 3], where the state observer in combination with linear quadratic regulator is used. In these references, to preserve the required level of performance without loosing the robustness of the flight control system (FCS) H_2/H_∞ – robust optimization procedure is used. To increase the robustness of the closed loop system in [4; 5] another structure of control law is synthesized. It comprises a combination of fuzzy and crisp control theories. The usage of fuzzy control gives an opportunity to supply the FCS with artificial intelligence and in such a way improve the desired flight requirements.

This paper is devoted to the static output-feedback (SOF) design combined with fuzzy control.

The structure of the control law is divided into two loops, namely inner and outer. The inner controller is designed using the SOF and the outer loop controller is based on fuzzy Takagi-Sugeno (TS). Notice, that the static output – feedback control design is obvious and simple be to implemented since it requires only available signals for measurement. Regardless the simplicity of this method, it remains one of the most researched and open problem in control theory and application. The aim of static OPFB is to design a controller with desired order. A survey devoted to this problem is presented in [6].

In [7] the solution to the problem is based on Linear Matrix Inequalities (LMI) approach using powerful software, namely Matlab LMI Toolbox.

In [8] the existence of OPFB control law is given in terms of solvability of two coupled Lyapunov inequalities. Many theoretical conditions have been offered for the existence of OPFB, nevertheless there are few good solution algorithms. Most existing algorithms require the determination of an initial stabilizing gain, which can be extremely difficult.

The method used in this paper is based on H-infinity approach, which allows to attenuate the external disturbances with pre-determined level γ. It is well known, that H-infinity design provide a better response in the presence of parametric disturbance than H_2 optimal techniques. Therefore, numerous works are devoted to the H-infinity design for the static OPFB. Among them it is possible to cite the following work [8–13].

In addition to the aforesaid, it is necessary to point out that control systems with combined structure have received a wide application in the area of UAVs in the last years [4; 5; 14]. It is explained by the fact, that such combined schemes give an opportunity to equip the system with necessary flexibility, enhance performance and robustness, decrease the cost design of FCS. That is why, in this paper the combined control structure is considered.

The outer loop of this scheme is devoted to the TS fuzzy controller design of zero type. This method permits to stabilize the heading angle with a simple fuzzy controller. Furthermore, the parameters of the fuzzy controller membership functions are adjusted to remove the error between the reference signal and the actual output of the UAV applying the gradient descent method. The combined control structure is given on fig. 1.

In order, to prove the efficiency of the proposed technique, the lateral channel of UAV in coordinate turn is used as a case study.

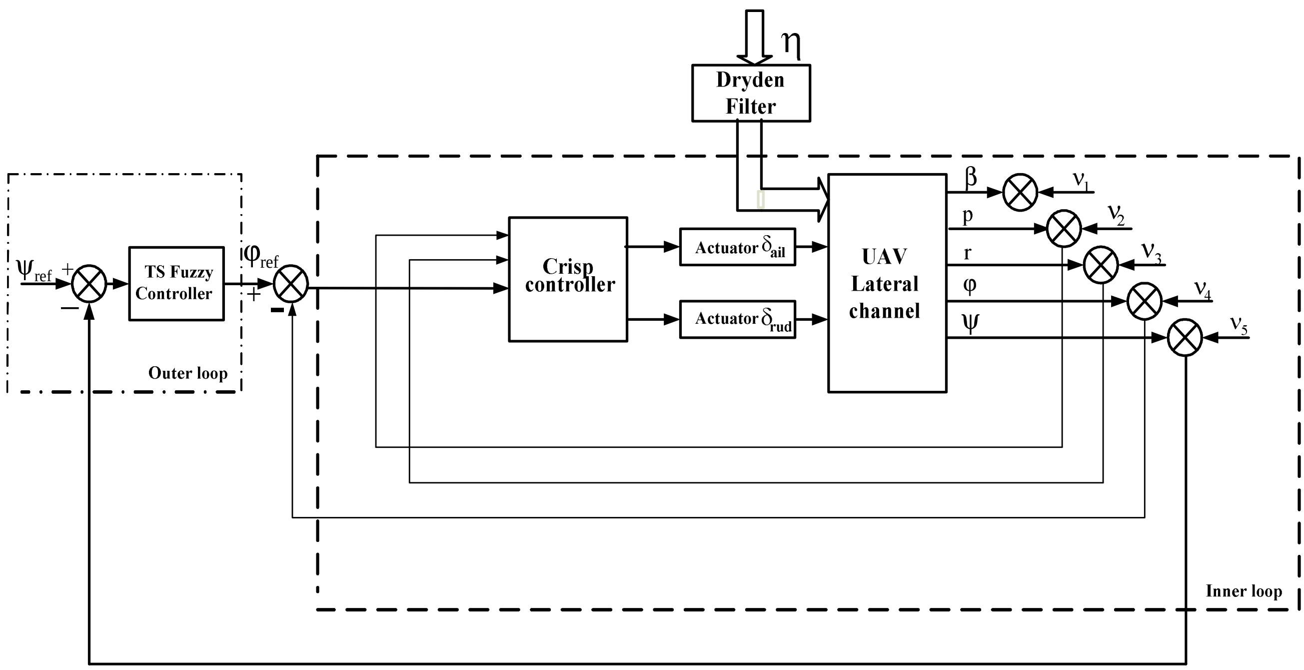


Fig. 1. Block diagram of the overall closed loop system

H-infinity static output feedback design approach

This section presents the H_∞ SOF controller design with disturbance attenuation. The controller design is formulated in the context of the convex analysis via LMI [11]. The LMI approach permits to obtain a constant OPFB gain K for a set of linear models received by the linearization of the nonlinear model for different operating conditions.

System description

The model of the controlled plant could be represented as follows:

$$\begin{cases} \dot{x} = Ax + B_u u + B_d d; \\ y = Cx, \end{cases} \quad (1)$$

where $x \in R^n$ is the state space vector;

$u \in R^m$ is the control vector;

$y \in R^p$ is the output vector and $d \in R^n$ is a disturbance vector.

Besides that, the state space matrices of the controlled plant have the following dimension

$$A \in R^{n \times n}, B \in R^{m \times n}, C \in R^{p \times n}.$$

It could be seen, that number of measuring variables p is less than number of all phase coordinate n. Hence, our control law is designed taking into account only variables that are available for measurement.

The control law is given by:

$$u(t) = -Ky(t) = -KCx, \quad (2)$$

where K is a constant output feedback gain, that minimizes performance index:

$$J = \int_0^\infty \|z(t)\|^2 = \int_0^\infty \left(x^T Q x + u^T R u\right) dt,$$

where $Q \ge 0$ and $R > 0$ are diagonal matrices, weighting each state and control variables, respectively.

Output signal $z(t)$ used for performance evaluation is defined as follows:

$$z = \begin{bmatrix} \sqrt{Q} & 0 \\ 0 & \sqrt{R} \end{bmatrix} \begin{bmatrix} x \\ u \end{bmatrix}.$$

Bounded L_2 gain design problem

The system L_2 gain is said to be bounded or attenuated by γ if [11 –13]:

$$\frac{\int_0^\infty \|z(t)\|^2 dt}{\int_0^\infty \|d(t)\|^2 dt} = \frac{\int_0^\infty \left(x^T Q x + u^T R u\right) dt}{\int_0^\infty \left(d^T d\right) dt} \le \gamma^2.$$

Therefore, it is necessary to find constant output feedback gain matrix K that stabilizes the control plant such that the infinity norm of the transfer function referring exogenous input to performance output $z(t)$ approaches minimum. The minimum gain is denoted by γ^*.

In order to find constant output feedback gain K the following theorem is needed.

Theorem: Necessary and Sufficient Conditions for H_∞ Static OPFB Control Design

Assume that $Q \ge 0$ and $(A, \sqrt{Q})$ is detectable. Then the system defined by equations (1) is output-feedback stabilizable with L_2 gain bounded by γ, if and only if (A, B) is stabilizable and (A, C) is detectable. Therefore, such matrices K^* and L exist that

$$K^* C = R^{-1}\left(B^T P + L\right) \quad (3)$$

where $P > 0, P^T = P$ is a solution of the following equality:

$$PA + A^T P + Q + \frac{1}{\gamma^2} P B_d B_d^T P - P B R^{-1} B^T P + $$
$$+ L^T R^{-1} L = 0. \quad (4)$$

The Proof see in the reference [12; 15].

Notice that according to the above stated definition the pair (A,B) is said to be stabilizable if there exists a real matrix K such that $(A - BK)$ is (asymptotically) stable. The pair (A,C) is said to be detectable if there exists a real matrix L such that $(A - LC)$ is stable. The system (2) is said to be OPFB stabilizable if there exists a real matrix K such that $A - BKC$ is stable.

Our goal is to find SOF controller that simultaneously stabilizes a set of autonomous system. The LMI technique permits to solve this problem [11]. Thus, it is possible to transform the equality (4) into the LMI form. On the next stage, we have used the following change of variable $X = P^{-1}$. Pre-multiplying and post-multiplying right and left sides of the equality (4) by X, taking into account it's transformed form, and basin on Schur's complement, we obtain:

$$\begin{bmatrix} A_i X + X A_i^T - B_i R^{-1} B_i^T & B_{di} & X Q^{1/2} & X L^T \\ B_{di}^T & -\gamma^2 I & 0 & 0 \\ Q^{1/2} X & 0 & -I & 0 \\ LX & 0 & 0 & -R \end{bmatrix} \le 0 \quad (5)$$

where $i = 1, \ldots, N$ in (5) denotes a set of models associated with certain operating conditions within the flight envelope.

SOF Design Algorithm

In the following the steps of SOF design are given. This is the algorithm of H_∞ SOF design, which uses the solution of Riccati equation in contrast to Lyapunov equation, at each step to solve the H_∞ problem for a specified admissible disturbance attenuation.

1. Initialization: set $n = 0$, $L_0 = 0$, specify γ, Q, R.
2. Solve for P_n the following inequality:

$$\begin{bmatrix} P_n A_i + A_i^T P_n + Q & P_n B_i & P_n B_{di} & L_n^T \\ B_i^T P_n & -R & 0 & 0 \\ B_{di}^T P_n & 0 & -\gamma^2 I & 0 \\ L_n & 0 & 0 & -R \end{bmatrix} \le 0$$

Update K

$$K_{n+1} = R^{-1}\left(B^T P_n + L_n\right) C^T \left(C C^T\right)^{-1}.$$

Update L

$$L_{n+1} = R K_{n+1} C - B^T P_n .$$

3. Check convergence: if $\|K_n - K_{n+1}\| \le \varepsilon$, namely if K_{n+1} and K_n are close enough to each other, go to 4, otherwise set $n = n+1$ and go to step 2.
4. Terminate: set $K = K_{n+1}$.

The following Lemma 1 states the convergence of the proposed algorithm: If the algorithm described in the above section convergences, then it provides the solution to equations (3), (4).

For the Proof of Lemma see [13].

Outer Loop Controller Design basing on Takagi - Sugeno fuzzy inference system

The efficiency of fuzzy control theory has gained a great attention in the area of automatic control, especially for unmanned aerial vehicle. Fuzzy control approach attempts to represent a human way of thinking understandable for computers in a set of 'IF-THEN' rules. The fuzzy control approach to unmanned aerial vehicle control facilitate the procedure of controller design. The addition of fuzzy controller in the control loop together with traditional controller allows to increase the robustness of the closed loop system and meet the required flight performance [4–5]. This section is devoted to Takagi-Sugeno fuzzy controller (TSFC) design for outer loop.

The TSFC considered in this paper is of type zero, where the rule base is embedded in following form:

IF e is X^j THEN u is b_i

where X^j is the linguistic values of the rule antecedent;

b_i is the output membership function.

We use the Gaussian membership functions that are specified with the centers c^i and spreads σ^i for the premise part of control rules, the output is considered as singleton membership function. The expression of the Gaussian membership function is given by:

$$\mu_i\left(e(t), c^i, \sigma^i\right) = \exp\left(-\frac{1}{2}\left(\frac{e(t) - c^i}{\sigma^i}\right)^2\right).$$

Using product for the premise, implication and center-average defuzzification, the overall output of the TSFC is computed as [16]:

$$\varphi_{ref}\left(e(t)\mid\theta_k\right)=\frac{\sum_{i=1}^{R} b_i \prod_{j=1}^{n} \exp\left(-\frac{1}{2}\left(\frac{e(t)-c^j}{\sigma^j}\right)^2\right)}{\sum_{i=1}^{R} \prod_{j=1}^{n} \exp\left(-\frac{1}{2}\left(\frac{e(t)-c^j}{\sigma^j}\right)^2\right)}$$

where $k=n+R$;

$j=1,\ldots,n$;

$i=1,\ldots,R$.

The input to the TSFC is the error $e(t)$ between the reference yaw angle signal and the actual output of the UAV:

$$e(t)=\psi_{ref}(t)-\psi(t). \quad (6)$$

The output of the outer loop controller corresponds to the reference signal $\varphi_{ref}(t)$ for the inner loop. In order to adjust the shape of the membership functions we have used approach described in [14]. According to [14] the parameters of the fuzzy controller are adjusted by applying gradient descent method. Thus, tuning of the input and output membership function parameters of the TSFC is realized under gradient descent method, which uses the partial derivatives of the error with respect to the input and output membership functions parameters. Solving this optimization problem gives the following equations for adjusting parameters of the TSFC:

$$b_{i,k+1}=b_{i,k}-\lambda_1 \left.\frac{\partial E_t}{\partial b_i}\right|_k ; \quad (7)$$

$$c_{k+1}^j=c_k^j-\lambda_2 \left.\frac{\partial E_t}{\partial c^j}\right|_k ; \quad (8)$$

$$\sigma_{k+1}^j=\sigma_k^j-\lambda_3 \left.\frac{\partial E_t}{\partial \sigma^j}\right|_k ; \quad (9)$$

In (7), (8) and (9) λ_l, $l=1,2,3$ is a step size of the gradient descent algorithm.

The block diagram of the overall closed loop system is given above on fig. 1.

On fig. 2 the procedure of adjusting membership functions parameters is depicted ($\bar{p}$ is a vector of adjustable parameters of the fuzzy controller).

It is necessary to point out, that reference model generates the desired performance of the overall system. In general, the reference model may be any type of dynamical system.

The performance of the overall system is evaluated with respect to its output ψ by generating an error signal between the reference signal and actual UAV output (6).

In our case, the reference model is approximated with the second order model with settling time in 30 s and without overshoot.

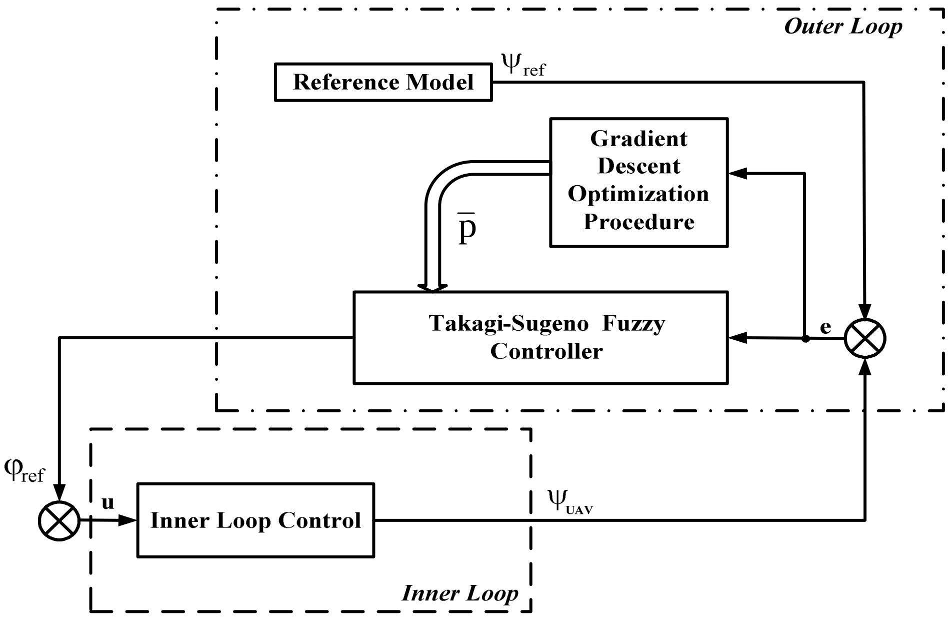


Fig. 2. Procedure of adjusting membership functions parameters

Case study

To demonstrate the efficiency of the proposed approach a lateral channel of the Unmanned Aerial Vehicle (Aerosonde UAV) is used as a case study. The state space vector of the lateral channel is $X=[v, \ p, \ r, \ \varphi, \ \psi]$, where v is the lateral velocity component, r is the yaw rate, p is the roll rate, φ is the bank angle and ψ is the heading angle. The control input vector $U=[\delta_a \ \ \delta_r]$ is represented by ailerons and rudder deflections, respectively.

The nonlinear model of the Aerosonde model is linearized for three operating conditions to form a nominal model at true airspeed of 26 m/s and two parametrically perturbed models at 23 and 30 m/s.

The linearized state space models are represented by matrices A, B, C. Disturbance d is affecting the lateral speed component v, the yaw rate r and the roll rate p, so that $d=[v \ \ p \ \ r]^T$:

$$A_n=\begin{bmatrix} -0.72 & 1.07 & -25.98 & 9.81 & 0 \\ -4.73 & -23.31 & 11.22 & 0 & 0 \\ 0.77 & -3.02 & -1.17 & 0 & 0 \\ 0 & 1 & 0.04 & 0 & 0 \\ 0 & 0 & 1.0009 & 0 & 0 \end{bmatrix};$$

$$B_n=\begin{bmatrix} -1.59 & 4.08 \\ -140.33 & 2.52 \\ -5.53 & -25.78 \\ 0 & 0 \\ 0 & 0 \end{bmatrix};$$

$$B_{dn}=\begin{bmatrix} 0.72 & -1.07 & 25.98 \\ 4.73 & 23.31 & -11.22 \\ -0.77 & 3.02 & 1.17 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix};$$

$$A_{p1}=\begin{bmatrix} -0.64 & 1.51 & -22.95 & 9.79 & 0 \\ -4.19 & -20.63 & 9.93 & 0 & 0 \\ 0.68 & -2.68 & -1.04 & 0 & 0 \\ 0 & 1 & 0.066 & 0 & 0 \\ 0 & 0 & 1.002 & 0 & 0 \end{bmatrix};$$

$$B_{p1}=\begin{bmatrix} -1.25 & 3.19 \\ -109.84 & 1.98 \\ -4.33 & -20.18 \\ 0 & 0 \\ 0 & 0 \end{bmatrix};$$

$$B_{dp1}=\begin{bmatrix} 0.64 & -1.51 & 22.95 \\ 4.19 & 20.63 & -9.93 \\ -0.68 & 2.68 & 1.04 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix};$$

$$A_{p2}=\begin{bmatrix} -0.83 & 0.57 & -29.99 & 9.78 & 0 \\ -5.48 & -26.98 & 12.98 & 0 & 0 \\ 0.89 & -3.50 & -1.36 & 0 & 0 \\ 0 & 1 & 0.019 & 0 & 0 \\ 0 & 0 & 1.0002 & 0 & 0 \end{bmatrix};$$

$$B_{p2}=\begin{bmatrix} -2.13 & 5.45 \\ -187.35 & 3.37 \\ -7.39 & -34.41 \\ 0 & 0 \\ 0 & 0 \end{bmatrix};$$

$$B_{dp2}=\begin{bmatrix} 0.83 & -0.57 & 29.99 \\ 5.48 & 26.98 & -12.98 \\ -0.89 & 3.5 & 1.36 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

The measured variables for the inner loop are $\overline{X}=[p, \ \ r, \ \ \varphi]$, hence the observation matrix is given as follows:

$$C=\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The atmospheric turbulence used in the simulation is represented by the Dryden filter. Its state space description is given as follows [17]:

$$A_{dr} = \begin{bmatrix} -\frac{1}{\tau_p} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -\frac{1}{\tau_v^2} & -\frac{2}{\tau_v} & 0 \\ 0 & \frac{k_v}{\tau_v} & \frac{k_v \lambda_v}{\tau_r} & -\frac{1}{\tau_r} \end{bmatrix};$$

$$B_{dr} = \begin{bmatrix} \frac{k_p}{\tau_p} & 0 \\ 0 & 0 \\ 0 & \frac{1}{\tau_p} \\ 0 & 0 \end{bmatrix};$$

$$C_{dr} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & k_v & k_v \lambda_v & 0 \\ 0 & \frac{k_v}{\tau_r} & \frac{k_v \lambda_v}{\tau_r} & \frac{-k_r}{\tau_r} \end{bmatrix},$$

where

$\tau_p = 4b/\pi V$;

$k_p = \left(\sigma_w \sqrt{0.8/V}\,(\pi/4b)^{1/6}\right)/L_w^{\ 1/3}$;

$\tau_v = L_v/V$;

$\lambda_v = \sqrt{3}/V$,

$k_v = \sigma_v \sqrt{L_v/\pi V}$;

$k_r = 1/V$;

$\tau_r = L_v/V$;

L_w and L_v represent the turbulence scale lengths;

σ_w, σ_v are the r.m.s values of turbulent wind lateral and vertical velocities.

The computation of these values depends on the altitude at which the aircraft is flying.

The inputs to the Dryden Filter are white noises corresponding to the lateral wind gust component and vertical one; the outputs are the lateral turbulent speed component v_g, the turbulent yaw rate r_g and turbulent roll rate p_g.

The attenuation level γ for the H_∞ problem for the inner loop is found to be equal to 0,5629. The obtained inner loop gain matrix is defined as follows:

$$K = \begin{bmatrix} 0.0494 & -0.1150 & 0.488 \\ -0.0161 & 0.1465 & 0.0193 \end{bmatrix}.$$

Table reflects standard deviations of the UAV outputs in a stochastic case of nominal and parametrically perturbed models.

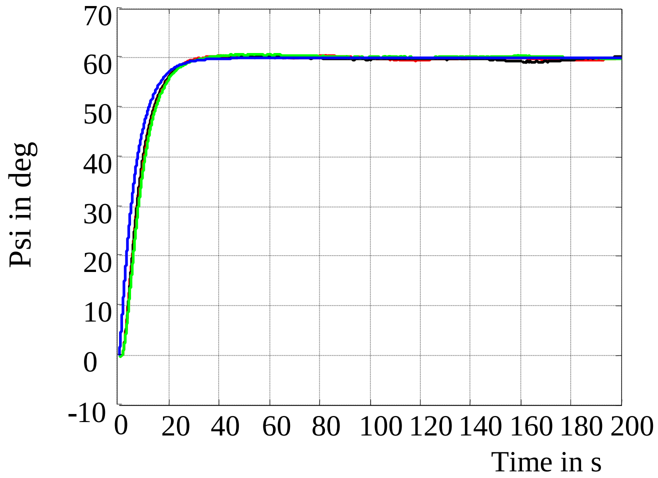
As stated above, the outer loop controller is designed using TSFC for yaw angle hold mode at the reference signal. The error between the reference signal and actual position of the UAV is removed through fuzzy controller by adjusting parameters using gradient descent algorithm. TSFC comprises one input and one output. Three Gaussian shaped membership functions are utilized to represent the "crisp" value on the universe of discourse and singletons for output. The initial position of the Gaussian shaped membership functions are chosen to be uniformly distributed; with the centers c^i and spreads σ^i, where the centers have been located at: [-8,2 0 8,2] and the spreads have been chosen equal to $\sigma^i = 3{,}68$, respectively.

The total number of control rule is 3.

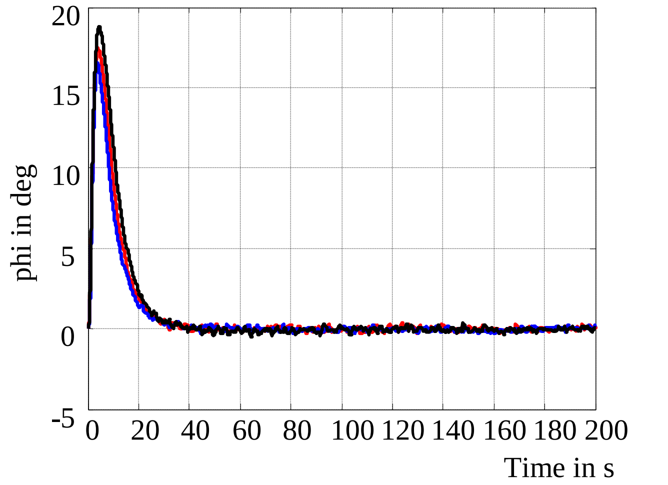
The following figures show the simulation results with the yaw angle reference signals (see fig. 3).

Standard deviations of the UAV outputs in a stochastic case

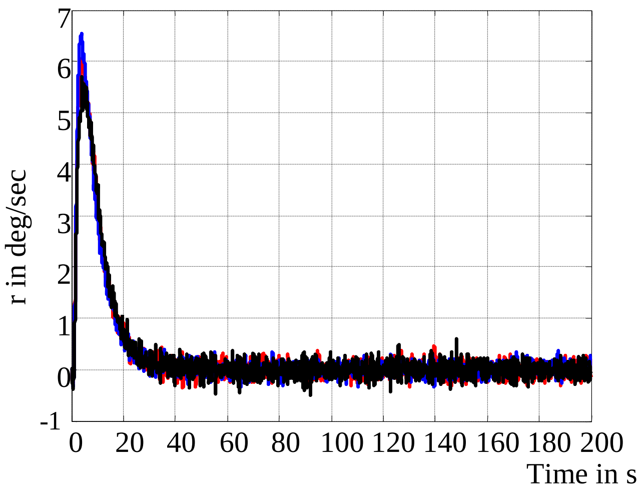
Plant	Standard deviation						
	σ_v, °	σ_p, deg/s	σ_r, deg/s	σ_φ, °	σ_ψ, °	σ_{ail}, °	σ_{rud}, °
Nominal	0.0503	0.3483	0.1266	0.1170	0.2031	0.1547	0.0164
Perturbed 1	0.0671	0.3199	0.1144	0.1334	0.2640	0.2063	0.0173
Perturbed 2	0.0305	0.3953	0.1334	0.1300	0.1235	0.0974	0.0155



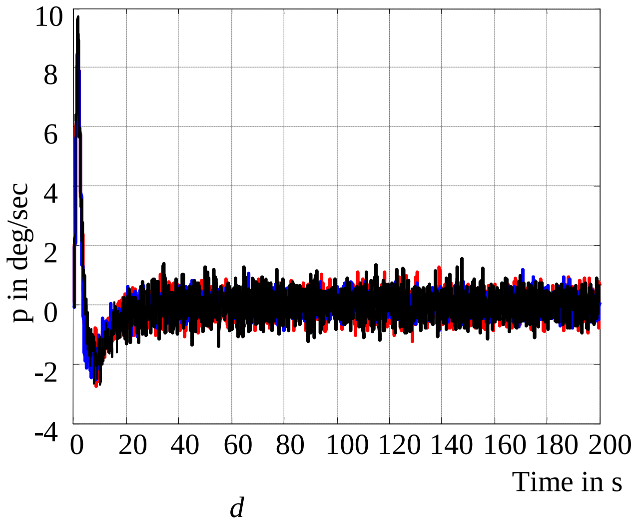
a



b



c



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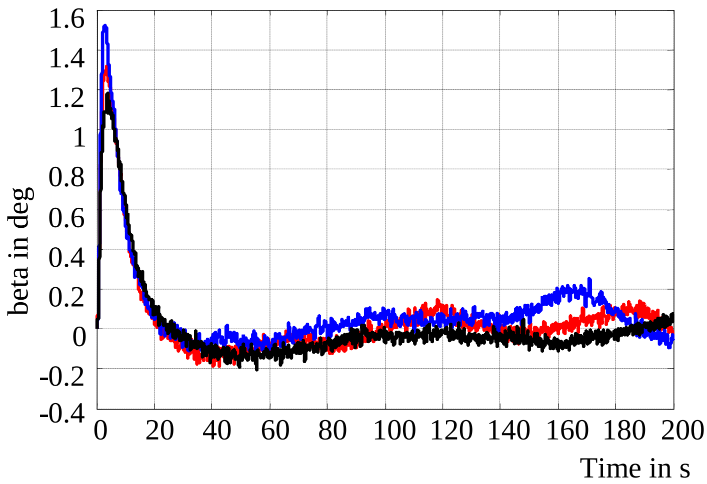

e

Fig. 3. Simulation results of motion nominal and perturbed models in the presence of turbulence:
a – heading angle;
b –bank angle;
c – yaw rate;
d – roll rate;
e – sideslip angle

Conclusion

The simulation results of the lateral channel of the UAV prove the effectiveness of the proposed control method. The required flight performances are respected as well as the robustness of the closed loop system. It can be seen that the handling quality of the nominal and the perturbed models are satisfied. The heading of the UAV is held at the reference signal the other angle deflections for such UAV are also respected.

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