COMBINED ADAPTIVE CONTROLLER FOR UAV GUIDANCE

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Abstract

Combined adaptive control law for an autopilot of the unmanned aerial vehicle (UAV) homing guidance system is proposed. The adaptation algorithm provides prescribed attitude motion dynamics for different flight conditions. Simulation results verify efficiency of the combined adaptive controller in the case of significant uncertainty of the UAV parameters and time dependence of the guidance loop.

1 Introduction

The demands on modern guided systems are becoming more stringent than in the past. The unmanned aerial vehicle (UAV) autopilots have to be able to produce a response that is accurate and fast despite severe variations in speed and altitude of the airframe. Hence the challenge for autopilot design is to produce closed loop airframe responses that are much faster than the nature weathercock frequency of the airframe, and to produce accurate and fast response in the face of large parametric uncertainty [12]. The promising way to fulfill these requirements is application of the *adaptive control technique*. Chosen method of adaptation has to meet the conflicting requirements on the tuning rate and performance quality under the conditions of lack of the UAV state measurements. The *variable-structure* control technique, utilizing forced *sliding motions* ensures high adaptability in the some region of UAV parameters [11], but in the general case can not provide the optimal closed-loop system performance. The adaptation methods based on the *parameter identification* make the optimality easier to secure, but have relatively long period of tuning.

The *combined* adaptive controller [1–4, 8] uses both variable-structure and identification approaches and is able to meet the claims indicated above.

The so-called *persistent excitation condition* is well known condition of convergence of the parameter estimates to their true values [7, 10]. Fulfillment of this requirement is an open question for the considered system, because the UAV controlling input (the rudder deflection) is produced by the autopilot as a function on current UAV position and the command (reference) signal. This signal is produced for the autopilot by the guidance system and also depends on the UAV state variables. Besides, for practical applicability of the proposed scheme more realistic plant model (in comparison with [1, 5, 9]) has to be taken. First of all, it is necessary to take into account nonlinearities of the UAV model, atmospheric disturbances and sluggishness of the steering gears.

The considered homing guidance system is inherently *nonlinear* (due to nonlinearities in the adaptation/identification algorithms) and *time-dependent* (due to kinematics of approaching the target). Examination of the overall system is provided by means of the computer simulation.

2 Combined adaptive controller

The adaptation algorithm includes the bang-bang controller with forced sliding motion, parametric identification algorithm and the parallel feedforward compensator (or *shunt* [1, 5, 9]). The adaptation control law is an internal part of the *subordinate control system*. The main loop of the considered system is time-dependent. The control action in this loop can be considered as the reference signal for the internal adaptive controller. The adaptation algorithm provides the prescribed dynamic properties of the internal system when the plant parameters are changed in the wide range.

By means of the shunt [1] the UAV attitude angular velocities are not used in the control law.

The main loop of the considered system is used for approaching the target. The kinematic relations effect time-dependence of this system.

Let us consider the general equations of the LTI SISO continuous-time plant:

$$\dot{x}_p(t) = A_p x_p(t) + B_p u(t),\ y_p(t) = C_p x_p(t), \qquad (1)$$

where $x_p(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}$, $y_p(t) \in \mathbb{R}$. The plant transfer function can be written as:

$$\mathrm{W}_p(s) = C_p\,(sI_n - A_p)^{-1}\,B_p = \frac{\mathrm{B}(s)}{\mathrm{A}(s)} \qquad (2)$$

where $s \in \mathbb{C}$ stands for the argument; $\deg \mathrm{A}(s) = n$, $\deg \mathrm{B}(s) = m, k = n - m$ is the *plant relative degree*. In the considered case of the UAV lateral motion, the model (1) can be written in the following form:

$$\left\{\begin{array}{l}\dot\beta(t) = \omega_y(t) + a_z^\beta \beta(t) - a_z^{\delta_r}\delta_r(t),\\ \dot{\omega_y}(t) = -a_{m_y}^\beta \beta(t) - a_{m_y}^{\omega_y}\omega_y(t) - a_{m_y}^{\delta_r}\delta_r(t),\\ \dot\psi(t) = \omega_y(t)\ ,\end{array}\right. \tag{3}$$

where $\psi(t)$, $\omega_y(t)$ stand for the yawing angle and its velocity; $\beta(t)$ is an angle of slide; $\delta_r(t)$ is an angle of the rudder deflection; a_z^β, $a_{m_y}^\beta$, $a_{m_y}^{\omega_y}$, a_β^δ and $a_{m_y}^{\delta_r}$ are the UAV model parameters. Their values depend on the flight conditions and assumed to be *a priory* unknown. Let us also neglect the time lag of autopilot servo and consider the rudder deflection $\delta_r(t)$ as a *control action*. The yaw angle $\psi(t)$ only (without the yawing rate ω_y) is assumed to be measurable by means of the UAV onboard sensors. Note, that Eq. (3) corresponds to the transfer function (2), where $\deg A(s) = 3$, $\deg B(s) = 1$ the relative degree $k = 2$ and the matrices A, B, C are as follows:

$$A = \begin{bmatrix} a_z^\beta & 1 & 0\\ -a_{m_y}^\beta & -a_{m_y}^{\omega_y} & 0\\ 0 & 1 & 0\end{bmatrix}, \quad B = \begin{bmatrix} -a_z^{\delta_r}\\ -a_{m_y}^{\delta_r}\\ 0\end{bmatrix},$$

$C = [0, 0, 1]$.

2.1 The identification algorithm

To obtain the identification algorithm, let us rewrite the plant model (2) in the following form:

$$\begin{array}{l} y^{(n)}(t) + a_1 y^{(n-1)}(t) + \cdots + a_n y(t)\\ = b_0 u^m(t) + \cdots + b_m u(t).\end{array} \tag{4}$$

For the considered UAV model (3) it is valid: $a_1 = a_{m_y}^{\omega_y} - a_z^\beta$, $a_2 = a_{m_y}^\beta - a_z^\beta a_{m_y}^{\omega_y}$, $a_3 = 0$. $b_0 = -a_{m_y}^{\delta_r}$, $b_1 = a_{m_y}^\beta a_z^{\delta_r} + a_{m_y}^{\delta_r} a_z^\beta$, Equation (4) can be rewrtitten as follows:

$$y^{(n)} = \varphi(t)^T \theta^*, \tag{5}$$

where the *regressor* $\varphi(t) = \left[-y^{(n-1)},\ \ldots, -y, u^{(m)},\ \ldots, u\right]^T$ and the vector of parameters $\theta^* \in \mathbb{R}^{n+m+1}$. Note, that for the considered system, because $a_3 = 0$, the number of unknown plant parameters can be reduced and θ^* can be taken as $\theta^* = [a_1, a_2, b_0, b_1]^T \in \mathbb{R}^4$. Introducing the signals $\tilde y^{(n)}(t)$, $\tilde\varphi(t)$ as

$$D(p)\tilde y^{(n)}(t) = y(n)(t), \quad D(p)\tilde u(t) = u(t),$$

where $p = d/dt$; $D(s) = s^n + d_1 s^{n-1} + \cdots + d_n$ is some Hurwitz polynomial, one gets the following equations:

$$\tilde y^{(n)} = \tilde\varphi(t)^T \theta^*, \tag{6}$$

The signals $\tilde y(t)$, $\tilde\varphi(t)$ can be produced by means of the filters:

$$\begin{array}{l}\dot\xi(t) = A_d \xi(t) + b_d y(t),\\ \dot\psi(t) = A_d \psi(t) + b_d u(t),\end{array} \tag{7}$$

where $\xi(t)$, $\psi(t) \in \mathbb{R}^n$; A_d, b_d have the phase space canonical form, $\det(s\mathbf{I} - A_d) = D(s)$. In the present study it is taken: $d_1 = 2\omega_f$, $d_2 = 2\omega_f^2$, $d_3 = \omega_f^3$, where parameter $\omega_f > 0$ is chosen bandwidth of the filters (7).

Let us consider now the fictitious system $\dot\theta^*(t) = w(t)$, $\tilde y(t) = \tilde\varphi(t)^T\theta^*(t) + v(t)$ with the state space vector θ^*, output signal $\tilde y$, white noise disturbances $w(t)$, $v(t)$, zero *system matrix* and the *output matrix* $\tilde\varphi(t)^T$. Applying the *Kalman filtering* technique to this system one gets the identification algorithm as follows:

$$\begin{array}{l}\dot\theta(t) = -\Gamma(t)\phi(t)\sigma(t),\\ \dot\Gamma(t) = -\Gamma(t)\phi(t)\phi(t)^T\Gamma(t) + \alpha\Gamma(t),\end{array} \tag{8}$$

where $\theta(t) \in \mathbb{R}^4$ stands for the vector of the UAV model parameter estimates, $\theta = \left[\hat a_1, \hat a_2, \hat b_0, \hat b_1\right]^T$; $\phi(t) = \left[-\tilde y^{(2)}\ , -\tilde y^{(1)}, \tilde u^{(1)}, \tilde u\right] \in \mathbb{R}^4$ is the regressor; $\alpha > 0$ is the algorithm parameter.

2.2 The sliding-mode controller

The sliding-mode control law is used to ensure an ideal tracking of the UAV yawing angle $\psi(t)$ after the *reference signal* $r(t)$ and has a following form:

$$\delta_r(t) = -k_s\sigma(t) - \gamma \mathrm{sign}\sigma(t), \tag{9}$$

where k_s, γ are the controller parameters, the *tracking error* $\sigma(t)$ is founded as $\sigma(t) = \bar\psi(t) - r(t)$. The signal $\bar\psi(t)$ is a sum of UAV yawing angle $\psi(t)$ and the *shunt* (*parallel feedforward*) output $y_s(t)$, i.e. $\bar\psi(t) = \psi(t) + y_s(t)$. The shunt transfer function [1] $W_c(s) = \dfrac{\kappa\varepsilon\left(\varepsilon s + 1\right)^{k-2}}{\left(s + \lambda\right)^{k-1}}$ for the considered example turns into the function of the first-order inertial unit.

The reference signal $r(t)$ is produced by means of the *tunable pre-filter* to provide the prescribed dynamics of the inner closed-loop UAV attitude control system [1]. Pre-filter adjustment is produced on basis of parameter estimates $\theta(t)$. The input command signal of the pre-filter $\psi^*(t)$ is generated by means of the *guidance system*.

2.3 The guidance law

The *proportional navigation* guidance law is widely used for homing guidance systems [12]. In spite of this fact, in the present paper a pure *pursuit method* and a *direct pointing* method are used, because the focal point of the present study is examination of the efficiency of the combined adaptation law in the closed-loop guidance system. The guidance reference signal $\psi^*(t)$ for an adaptive autopilot has one of the following forms:

$$\psi^* = -k_g\left(\psi - \Psi_t\right), \tag{10}$$

$$\psi^* = -k_g\left(\Psi - \Psi_t\right), \tag{11}$$

where k_g is the guidance gain; $\Psi(t) = \psi(t) - \beta(t)$ is the UAV *track angle*; Ψ_t is the azimuth angle of line-of-sight to a target (one can notice that $\psi - \Psi_t$ means the *sighting angle* to a target in the UAV body-frame axes). To describe the guidance

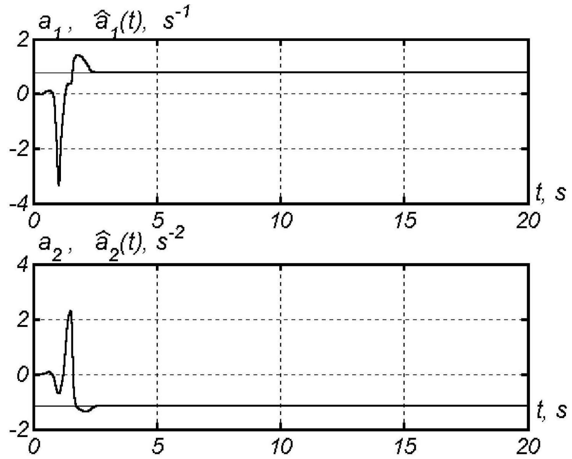

Figure 1: Time histories of the parameters a_1, a_2 estimates $\hat{a}_1(t)$, $\hat{a}_2(t)$ (Ex. #1).

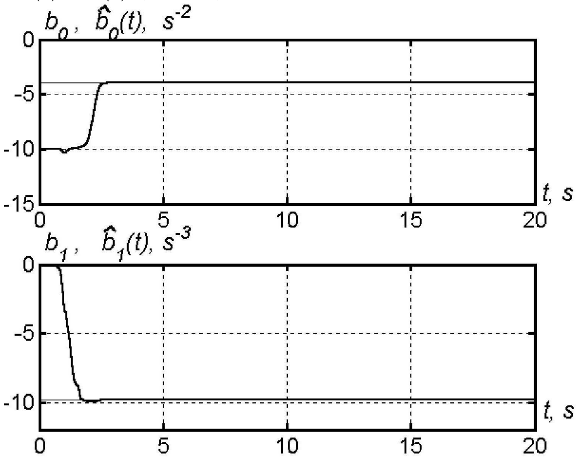

Figure 2: Time histories of the parameters b_0, b_1 estimates $\hat{b}_0(t)$, $\hat{b}_1(t)$ (Ex. #1).

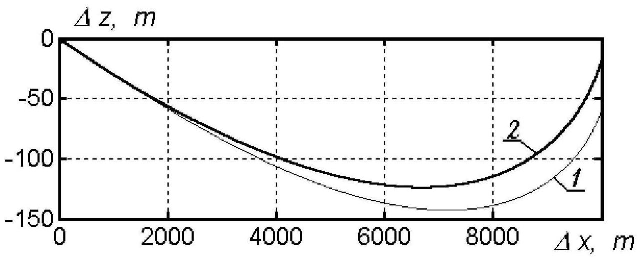

Figure 3: Flight path: *1* – guidance law (10); *2* – guidance law (11), (Ex. #1).

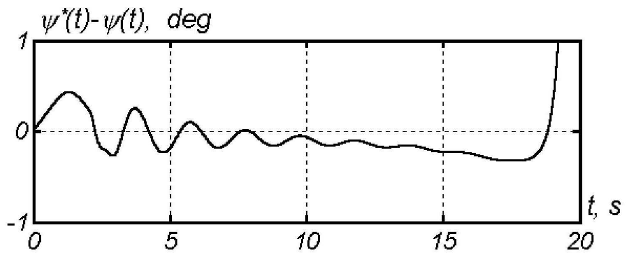

Figure 4: Tracking error $\Delta\psi(t) = \psi^*(t) - \psi(t)$ time history (Ex. #1).

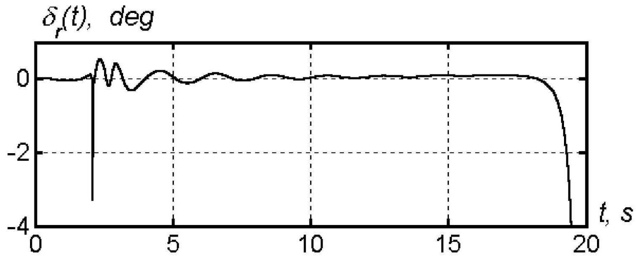

Figure 5: Rudder angle $\delta_r(t)$ time history (Ex. #1).

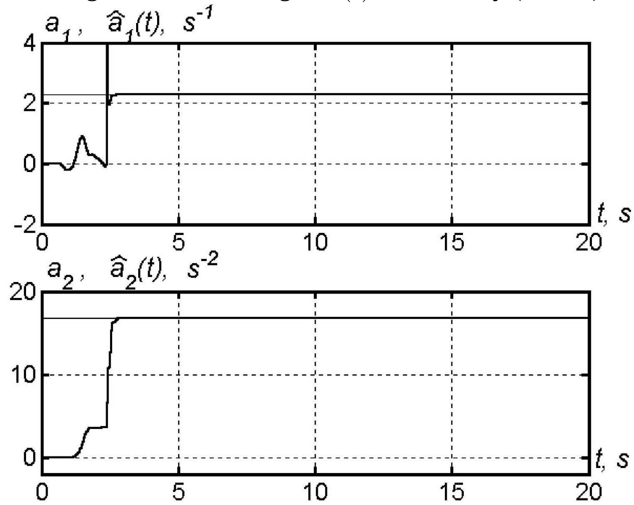

Figure 6: Time histories of the parameters a_1, a_2 estimates $\hat{a}_1(t)$, $\hat{a}_2(t)$ (Ex. #2).

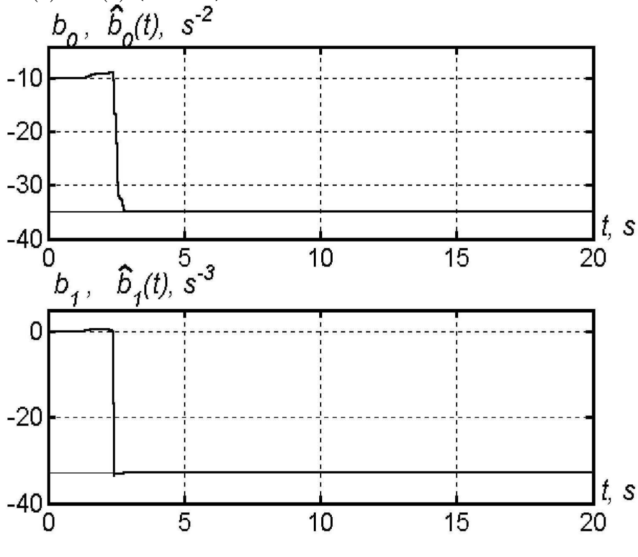

Figure 7: Time histories of the parameters b_0, b_1 estimates $\hat{b}_0(t)$, $\hat{b}_1(t)$ (Ex. #2).

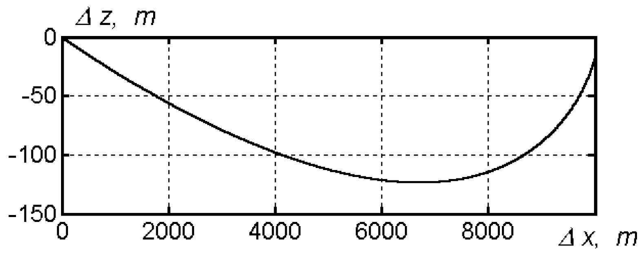

Figure 8: Flight path; the guidance law (11), (Ex. #2).

process, the following kinematic model is used:

$$\begin{aligned}
&x = Vt, \\
&x_t = D_0 + V_{x_t} t, \quad z_t = z_{t0} + V_{z_t} t, \\
&\Delta x = x_t - x, \quad \Delta z = z_t - z, \\
&D = \sqrt{\Delta x^2 + \Delta z^2}, \\
&\dot{z} = -V\Psi, \\
&\Psi_t = -\arctan(\Delta z/\Delta x),
\end{aligned} \tag{12}$$

where V_{x_t} and V_{z_t} are the components of the target velocity vector, so that $V_{x_t} = V_t \cos q_t$, $V_{z_t} = -V_t \sin q_t$; q_t is the target azimuth (in some Earth frame); $x(t)$, $z(t)$, $x_t(t)$, $z_t(t)$ are, correspondingly, the UAV and target lateral coordinates; V stands for the UAV ground speed.

3 Numerical examples

In this section some numerical examples and simulation results are presented.

Example 1. For this example the following parameters of the hypothetical UAV model have been taken: $a^{\beta}_{m_y} = -1.3\ s^{-2}$, $a^{\beta}_{z} = -0.4\,s^{-1}$, $a^{\delta_r}_{m_y} = 9.85\,s^{-2}$, $a^{\delta_r}_{z} = 2.6\cdot 10^{-3}\ s^{-1}$ $a^{\omega_y}_{m_y} = 0.37\ s^{-1}$ (one can notice that the unstable UAV model ith the set of eigenvalues $\{0, 0.75, -1.53\}$ is presented). UAV ground speed $V = 500\ m/s$, $V_t = 20\ m/s$, $q_t = 90\ deg$. Desired closed-loop attitude control system eigenvalues are picked up as follows: $s = \{-10, -2.1\ \pm 2.14i,\ -0.8\}$. Initial distance between UAV and target is taken equal to 10 *km*.

The time histories of the UAV parameter estimates $\hat{a}_1(t)$, $\hat{a}_2(t)$, $\hat{b}_0(t)$, $\hat{b}_1(t)$ are shown in Figs. 1, 2. It can be seen, that the transient time of estimation processes is approximately 2.5 *s*, and, therefore, the estimation rate is close to that one of the UAV attitude dynamics. In Fig. 3 the flight paths in the relative coordinates $(\Delta x, \Delta z)$ for two variants of the guidance law (10) and (11) are demonstrated. This results show that the law (11) for the case of the moving target is preferable. Figure 4 demonstrates the tracking error time history. It gives an idea of dynamic properties of the inner control loop. The rudder angle time history is shown in Fig. 5.

Example 2. Now let us consider the other flight conditions with the following parameter values of the UAV model: $a^{\beta}_{m_y} = 15.5\ s^{-2}$, $a^{\beta}_{z} = -1.1\ s^{-1}$, $a^{\delta_r}_{m_y} = 33\ s^{-2}$, $a^{\delta_r}_{z} = 0.09\ s^{-1}$ $a^{\omega_y}_{m_y} = 1.2\ s^{-1}$ This model parameters correspond to stable UAV attitude dynamics with the eigenvalues $\{0, -1.15 \pm 3.94i\}$. The rest parameters of the UAV model, of the target motion, and of the control law are taken identical those ones in the previous example.

The simulation results for this example are shown in Figs. 6–10. These results demonstrate that the parameter estimates are obtained during the same time interval as for Ex. #1. The flight path for this case is shown in Fig. 8. Obviously that it has neglible differences with that of Ex. #1.

4 Conclusions

The combined adaptive control law for an autopilot of the UAV homing guidance system is proposed. The adaptive algorithm for UAV attitude control includes the variable-structure controller with forced sliding motion, parametric identification algorithm and the parallel feedforward compensator. The adaptation algorithm provides the prescribed dynamic properties of the attitude control system for various flight conditions of the UAV. Simulation results verify efficiency of the combined adaptive controller in the case of significant uncertainty of the UAV parameters and time-dependence of the main loop.

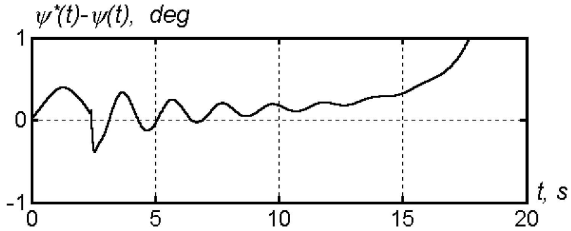

Figure 9: Tracking error $\Delta\psi(t) = \psi^*(t) - \psi(t)$ time history (Ex. #2).

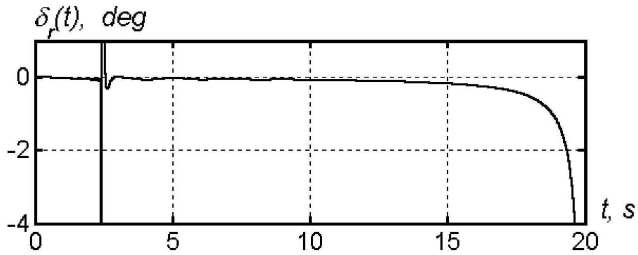

Figure 10: Rudder angle $\delta_r(t)$ time history (Ex. #2).

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