2nd IFAC Workshop on Research, Education and Development of Unmanned Aerial Systems
November 20-22, 2013. Compiegne, France

Rainbow Runner glider as a testbed for robust and adaptive control methods ⋆

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Abstract: In the paper the dynamics of the UAV glider *Rainbow Runner* are described and the research plan of using the glider as a testbed for robust and adaptive control methods is outlined.

Keywords: aerospace, adaptive control design, robust control, testbed, small UAV

1. INTRODUCTION

It is commonly known that importance of the experimental set-ups for testing the control algorithms in the real-world conditions can not be overestimated. Especially this concerns to application of the adaptive approach to flight control, because a lack of the designer's attention to various unmodelled plant features normally leads to non-serviceability, or, most often, to stability loss of the adaptive control system, cf. (Rohrs et al., 1985; Landau et al., 2011). Testing the adaptation algorithm is a very important stage of designing the adaptive controller.

Many researchers use intensive computer simulations and flight simulators for evaluation performance of the proposed adaptive control methods in the real-world conditions. As an example, Wise and Lavretsky (2011) presented a control design trade study related to robust and adaptive control methods for an autonomous aerial platform representative of the *Boeing/USAF X-45A Joint Unmanned Combat Air System* (J-UCAS). The benefits of the adaptive system and its performance were evaluated in the 6-DoF flight simulation environment.

Some research groups use experimental laboratory set-ups, such as the *3-DoF Quanser Helicopter Testbed* [1], as a close approximation to the real conditions for testing adaptive control laws (Chen et al., 2002; Chen and Chen, 2002; Dzul et al., 2004; Tanaka et al., 2004; Kutay et al., 2005; Andrievsky et al., 2007; Fradkov et al., 2007, 2008; Andrievsky et al., 2010; Lozano, 2010).

Myrand-Lapierre et al. (2010) demonstrated the usage of a logic-based switching supervisor, which manages the transition between modes on a real fixed-wing mini-aerial vehicle, where IMU measures the attitude and calculates and transmits orientation via cosine matrix. Bertuccelli et al. (2009); Rusnak et al. (2011) integrate in their work simulation of their algorithms with real flight tests and bring up combined results. Cox et al. (2001) claimed, that the *LoFLYTETM* program was being tested onboard an experimental waverider-shaped subsonic aircraft and would be used as a testbed for a neural network flight control system.

In the row of papers (Wise et al., 2006; Gregory et al., 2009, 2010, 2011a,b; Hovakimyan et al., 2011; Dobrokhodov et al., 2011) the examples of usage the actual experimental testbed to validate adaptive control laws are presented. The IRAC Project was created to increase the aviation safety, and to this end NASA has developed the *AirSTAR Flight Test Facility*, most significant part of which is the GMT aircraft (the full-scale model of civil aircraft). GMT is used to test control algorithms in extreme conditions, such as failure simulation. By integrating the usage of experimental GMT aircraft was solved the main problem faced in the work: the Rohr's example (Rohrs et al., 1985).

Despite the significant success of the row of research teams in experimental study of the adaptive flight control systems, it should be stressed that at present time the number of the experimental testbeds is negligibly small in compare with the number of research groups at universities and academies and can not satisfy the researchers' needs. To overcome this drawback, the experimental testbed "*Formation*" is currently under development by the Institute for Problems of Mechanical Engineering of RAS (IPME RAS), and a small UAV glider *Rainbow Runner* is intended to be one of its component.

⋆ The work was supported in part by the Russian Foundation for Basic Research (grant Nos. 11-08-01218, 12-08-0118, 13-08-00925, 13-08-01014) and Russian Federal Program "Cadres" (agreements 8846, 8855). The authors are grateful to Dr. Konstantin Amelin (*SmartFly LCC* & *SPbSU*) for his excellent consultations about the Ardupilot Mega kit.

[1] http://www.quanser.com

The paper is organized as follows. The principal structural specification of the UAV is presented in Sec. 2. The general 6-DoF model of flight dynamics in the atmosphere is presented in Sec. 3. Concluding remarks and the future work intensions are given in Sec. 6.

2. UAV GLIDER "RAINBOW RUNNER" DESCRIPTION

The *Rainbow Runner* is a radio-controlled glider, which is intended to be modified to an autopiloted drone being equipped with *Ardupilot Mega* assembly. Five-channel RC equipment is needed to achieve this goal: four channels to operate rudder, both ailerons and motor; one channel to activate the autopilot mode. There is special port in autopilot assembly for each above-listed channel.

2.1 UAV parameters

All principal *Rainbow Runner's* parameters are listed below: Wingspan: 2000 mm; Fuselage length: 880 mm; Wing area: 21 dm^2; Wing load: 24.7 g/dm^2; Take-off mass: 0.520 kg; Motor: *brushless*; Battery: 1000 mAh; 11.1 V, *Li-Pol*, 75 g; Propeller: $10X6$ *folding propeller.*

The photo of the glider is depicted in Fig. 1.

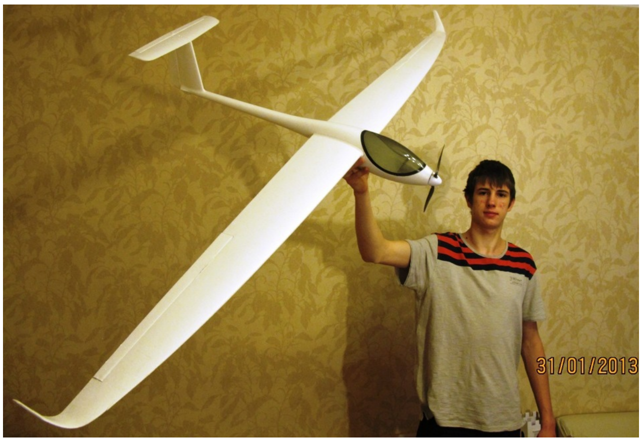

Fig. 1. "Rainbow Runner" photo.

2.2 Autopilot Ardupilot Mega 2.0

The ArduPilot Mega 2.0 is a complete open source autopilot system, with no assembly required. It allows the user to turn any fixed, rotary wing or multirotor vehicle (even cars and boats) into a fully autonomous vehicle; capable of performing programmed GPS missions with waypoints.

The ArduPilot Mega 2.0 has the following features: Includes the digital compass powered by Honeywell's HMC5883L-TR chip; Includes on-board GPS, Mediatek MT3329 module (optionally); Is an open source autopilot systems to use Invensense's 6 DoF Accelerometer/Gyro MPU-6000; Includes a barometric pressure sensor upgraded to MS5611-01BA03, from Measurement Specialties; Includes Atmel's ATMEGA2560 and ATMEGA32U-2 chips for processing and usb functions respectively.

3. UAV DYNAMICS MODEL

Before programming the controller, the mathematical model of the UAV should be designed to calculate such characteristics as the inertia moments of the UAV or the estimation of aerodynamic factors. It is also vital to precisiously calculate the traction force of the motor, which requires designing the traction measurement stand. After the installation and programming of the hardware, the main goal is to make the drone fly on its own only by transferring the GPS coordinates to it.

The following model of the UAV dynamics is used in the present work (Bukov, 1987) [2] .

3.1 Translational dynamics

$$m \begin{bmatrix} \dot{V}_k \\ V_k \dot{\theta} \\ -V_k \dot{\Psi} \cos\theta \end{bmatrix} = m D_{tr}^l \begin{bmatrix} 0 \\ -g \\ 0 \end{bmatrix} + D_{tr}^l D_l^{bf} \left(\begin{bmatrix} P \\ 0 \\ 0 \end{bmatrix} + qS \begin{bmatrix} -c_x \\ c_y \\ c_z \end{bmatrix} \right), \tag{1}$$

where V_k is the vehicle centre of mass ground speed; θ, Ψ are the path and track angles; P is the thrust; m is the mass of the vehicle; g is the gravity acceleration; q is the dynamic pressure; S is the characteristic cross-section area of the vehicle (the lifting surfaces area, or the midship area); $c_i (i = x, y, z)$ stand for the aerodynamic coefficients.

3.2 Rotational dynamics

$$\begin{bmatrix} J_x \dot{\omega}_x \\ J_y \dot{\omega}_y \\ J_z \dot{\omega}_z \end{bmatrix} + \begin{bmatrix} (J_z - J_y)\omega_y \omega_z \\ (J_x - J_z)\omega_x \omega_z \\ (J_y - J_x)\omega_x \omega_y \end{bmatrix} = qSB \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}, \tag{2}$$

where $J_i (i = x, y, z)$ are the principal moments of inertia; ω_i are the angular rates in the body axes frame; B denotes the diagonal matrix of the characteristic vehicle dimensions; m_i are the aerodynamic torques derivatives.

3.3 Translational kinematics

$$\begin{bmatrix} \dot{x} \\ \dot{h} \\ \dot{z} \end{bmatrix} = D_l^{tr} \begin{bmatrix} V_k \\ 0 \\ 0 \end{bmatrix}, \tag{3}$$

where x, h, z $(h \equiv y)$ are the coordinates of the vehicle centre of mass in the Earth reference frame.

3.4 Rotational kinematics

$$\begin{cases} \dot{\vartheta} = \omega_y \sin\gamma + \omega_z \cos\gamma, \\ \dot{\gamma} = \omega_x + \tan\vartheta(\omega_z \sin\gamma - \omega_y \cos\gamma), \\ \dot{\psi} = \dfrac{1}{\cos\vartheta} (\omega_y \cos\gamma - \omega_z \sin\gamma), \end{cases} \tag{4}$$

where ϑ, ψ, γ are the Euler angles (pitch, yaw, and roll, respectively).

[2] The Russian notation conventions of GOST 20058-80 (1981) are employed here, which differ from those of the ISO 1151-5 standard.

3.5 Supplementary relations

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = D^l_{bf} D^{tr}_l \begin{bmatrix} V_k \\ 0 \\ 0 \end{bmatrix} - D^l_{bf} \begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix},$$
$$V = \sqrt{V_x^2 + V_y^2 + V_z^2}, \tag{5}$$
$$\alpha = -\text{atan}\frac{V_y}{V_x}, \qquad \beta = \text{asin}\frac{V_z}{V},$$
$$\varrho = f_\varrho(h), \quad a = f_a(h), \quad \text{M} = \frac{V}{a}, \quad q = \frac{\varrho V^2}{2},$$

where α, β are the angle-of-attack and the sideslip angle; $W_i (i = x, y, z)$ are the components of the wind velocity vector in the Earth reference frame; $\varrho(h)$ is the atmosphere density altitude; q is the dynamic pressure. Transformation matrices D^{bf}_l, D^{tr}_l depend on the angles of axes rotation.

3.6 Linearized model

Let $u^*(t) \equiv u^*$, $x^*(t) \equiv x^*$ be a certain "reference point", the plant be time-invariant, i.e. let us assume that $\forall\, t_1, t_2 :$ $f(x^*, u^*, t_1) \equiv f(x^*, u^*, t_2) = f(x^*, u^*)$. This assumption leads to the following time-invariant linear model with a constant "bias" φ:

$$\dot{x}(t) = Ax(t) + Bu(t) + \varphi, \;\; y(t) = Cx(t) + Du(t), \tag{6}$$

where $\varphi = f(x^*, u^*) - Ax^* - Bu^*$ is a known constant, matrices A, B, C, D are found by means of Taylor approximation in the vicinity of reference point u^*, x^*, $x(t)$, $u(t)$; $y(t)$ stand for deviations from x^*, u^*, $y^* = h(x^*, u^*)$.

In this study, the following state vector $x \in \mathbb{R}^{12}$, input vector $u \in \mathbb{R}^7$ and output vector $y \in \mathbb{R}^{17}$ are taken:

$$\begin{aligned} x &= \text{col}\{V_k, \theta, \Psi, \omega_x, \omega_y, \omega_z, x, h, z, \vartheta, \gamma, \psi\}, \\ u &= \text{col}\{\delta_e, \delta_r, \delta_a, W_x, W_y, W_z, \Delta P\}, \\ y &= \text{col}\{V_k, \theta, \Psi, \omega_x, \omega_y, \omega_z, x, h, z, \vartheta, \gamma, \psi, \alpha, \beta, j_x, j_y, j_z\}. \end{aligned} \tag{7}$$

The input vector $u(t)$ includes three controlling inputs (the deflections $\delta_e, \delta_r, \delta_a$ of the controlling surfaces) and four disturbances $(W_x, W_y, W_z, \Delta P)$. ΔP stands for the uncontrollable perturbation of the thrust P. Output vector y collects the measurable variables (the set of its components can vary depending on the kit of the available sensors).

3.7 Calculation of the aerodynamic forces and torques

The *Mach Number* is calculated as $M = V/a(h)$, where $a = a(h)$ is the *acoustic velocity.* $a(h)$ is found as a function on the altitude h by linearly interpolation of the standard atmosphere data (Davies, 2003).

Aerodynamic forces X, Y, Z and torques M_x, M_y, M_z are found via the *aerodynamic coefficients*, *rudder deflections*, *attack* and *sideslip* angles. The derivative of the *lift coefficient* of the fuselage on α, $c^\alpha_{y,f}$ is taken $c^\alpha_{y,f} = 0.035$. The *lift coefficient* of the fuselage is assumed to be $c_{y,f} = 57.3\, c^\alpha_{y,f}\alpha$. The *lift force* of the fuselage $Y_f = 1.3\, q\, S\, c_{y,f}$, where $q = \varrho\frac{V^2}{2}$ is the *dynamic pressure*, S is the *midship area*; $\varrho = \varrho(h)$ is the *atmosphere density* , the following approximation is applied: $\varrho(h) = 1.225 \exp(-h/8480)$.

Then $c^\alpha_{y,w}$ may be found, the *lift coefficient* of the wing $c_{y,w}$ is calculated by the following formulas (Lebedev and Chernobrovkin, 1990):

$$a = 2.4 - 48\, c^\alpha_{y,w},$$
$$c_{y,w} = 57.3 c^\alpha_{y,w} \sin(\alpha)\cos(\alpha) + a\sin^2(\alpha)\,\text{sign}(\alpha)\, K_{aa}/k_{aa},$$

where the coefficients K_{aa}, k_{aa} are the *interference coefficients* between the wing and the fuselage. The *lift force* of the wing Y_w is calculated as follows: $Y_w = 1.17\, qS_k\, c_{y,w}$, where S_k is the wing surface area, $S_k = 0.21 m^2$.

3.8 Fore-and-aft leveling conditions

An important role of UAV control play the values of δ_e, α, m_s, that ensure fore-and-aft flight. These values are usually called *the trimming values* and are denoted as δ_{trim}, α_{trim}, $m_{s\ trim}$. They depend, first of all, on the UAV speed V and altitude h. To find the trimming values numerically, let us assume that $\dot{V}_k = 0$, $\dot{\theta} = 0$, $\dot{\omega}_z = 0$ and *rolling angle* $\gamma(t) \equiv 0$ in (5), then find δ_{trim}, α_{trim} and $m_{s\ trim}$ as the solutions of the following nonlinear equations

$$\begin{cases} -g\cos\theta^* + \frac{1}{m}\big(P\sin(\varphi^* + \alpha) - X\sin\alpha + Y\cos\alpha\big) = 0, \\ -g\sin\theta^* + \frac{1}{m}\big(P\cos(\varphi^* + \alpha) - X\cos\alpha - Y\sin\alpha\big) = 0, \\ M_z = 0. \end{cases} \tag{8}$$

Left-hand sides of (8) depend on the given *path angle* θ^* and, implicitly, on the velocity V^*_k, altitude $h*$, that are assumed to be constant (for the level flight $\theta^* \equiv 0$), and on the sought quantities δ_{trim}, α_{trim}, $m_{s\ trim}$. These dependences make possible to find the reference trajectory $\{x^*(t), u^*(t)\}$ for the linearization procedure more precisely, and also are used to find the admissible region of flight conditions (the altitude, groundspeed, trajectory inclination) and for UAV controller design. Plots of α_{trim} and δ_{trim} versus UAV speed V for altitudes $h = 0$ and $h = 2000$ m are depicted in Figure 2.

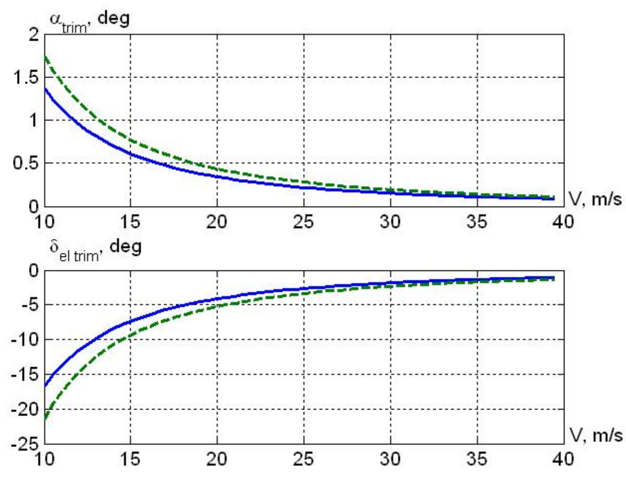

Fig. 2. Trimming angles α_{trim}, δ_{trim} vs V for $h = 0$ m (solid line) and $h = 2000$ m (dashed line).

4. ADAPTIVE AND ROBUST METHODS OF FLIGHT CONTROL FOR EXPERIMETAL EVALUATION

The mainstream of our research work on adaptive control methods lies in so-called Simple Adaptive control technique, based on the Implicit Reference Model and passification concept (Andrievsky and Fradkov, 1994; Andrievsky et al., 1996). This approach, initially proposed by Fradkov (1974), has been further developed in the series of works, see (Fradkov, 1979; Stotsky, 1994; Fradkov et al., 1999; Andrievsky and Fradkov, 2002; Andrievskii and Fradkov, 2006; Fradkov and Andrievsky, 2005; Peaucelle et al., 2006) and the references therein.

Let us briefly recall some fundamentals of this approach (Andrievsky et al., 1996).

Let the linear time invariant plant be described by the following input-output model

$$A(p)y(t) = B(p)u(t), \quad t > 0, \tag{9}$$

where $u(t) \in \mathbb{R}^1$ stands for the scalar control signal, $y(t) \in \mathbb{R}^1$ is the scalar controlled variable, measured by a sensor, the polynomials $A(p) = p^n + a_{n-1}p^{n-1} + \ldots + a_1 p + a_0$, $B(p) = b_m p^m + \ldots + b_1 p + b_0$ describes the plant dynamics, the plant relative degree $k = n - m > 0$ is a known natural number. Plant model parameters a_i, $i = 0, \ldots, n-1$, b_j, $j = 0, \ldots, m$ are unknown constants (for practice, fulfillment of the so-called *quasi-stationarity* hypothesis is usually adopted). The control goal is to ensure tracking output signal $y(t)$ to the command signal $r(t)$

$$\lim_{t\to\infty} \big(y(t) - r(t)\big) = 0. \tag{10}$$

with the prescribed dynamics. For solving this problem, the following auxiliary goal (*the adaptation goal*) is introduced, specifying the desired tracking properties:

$$\lim_{t\to\infty} \delta(t) = 0. \tag{11}$$

where $\delta(t) = G(p)y(t) - D(p)r(t)$ may be reffered to as an *adaptation error*; $G(s) = p^l + \cdots + g_1 s + g_0$, $D(s) = d_\nu p^\nu + \cdots + d_1 s + d_0$ are the given polynomials,which specify the desired closed-loop system performance. Polynomial $G(s)$ is assumed to be stable (Hurwitz) polynomial on complex argument $s \in \mathbb{C}$. Note, that since $\delta(t) = G(p)e(t)$ as $e(t) = y(t) - y_*(t)$, therefore signal $\delta(t)$ may be interpreted as an *error signal* for the equation

$$G(p)y_*(t) = D(p)r(t). \tag{12}$$

Therefore, equation (12) may be treated as the *reference equation* that describes the reference model *implicitly.*

Let the tunable control law in the main loop be taken in the following proportional form:

$$u(t) = K(t)\big[D(p)r(t)\big] + \sum_{i=0}^{l} k_i(t)\big[p^i y(t)\big] \tag{13}$$

where $K(t)$, $k_i(t)$, $i = 0, \ldots, l$ — are tunable parameters. Take the adaptation algorithm as follows:

$$\dot{k}_i(t) = -\gamma\delta(t)p^i y(t), \quad i = 0, 1, \ldots, l, \tag{14}$$
$$\dot{K}(t) = \gamma\delta(t)D(p)r(t),$$

where design parameter $\gamma > 0$ denotes *the adaptation gain.*

It can be derived (Andrievsky et al., 1996) that all the trajectories of the system (9), (10), (14) are bounded and the goals (10) and (11) are achieved if $B(s)$ is Hurwitz polynomial on $s \in \mathbb{C}$, $l = k - 1$, and the command signal $r(t)$ has vanishing derivatives: $\int_0^\infty \big[r^{(i)}(t)\big]^2 dt < \infty$, $i = 1, \ldots, s+1$.

It is worth mentioning that neither degree ν of polynomial $D(s)$ nor its coefficients appear in the above conditions. The degree of $D(s)$ is determined by the amount of the available derivatives of $r(t)$. Note also that matching condition in the form used for the Model Reference Adaptive Control (MRAC) systems is not necessary for the described implicit model reference systems. The order of reference equation (12) is equal to l and can be significantly less then the plant order n. Moreover, the true plant order need not be known for system design.

Similarly, the variable structure systems (VSS) with sliding mode controllers, may be also treated in the framework of IRM adaptive systems (Andrievsky et al., 1996). The synthesis of VSS with sliding modes is usually carried out in two stages (Utkin, 1992). At the first stage we choose sliding surface $\sigma(x) = 0$ such that the motion on this surface has the desired dynamics (compare with mentioned above implicit reference model dynamics). At the second stage, we have to ensure that the motion reaches the sliding surface in a finite time from any point in the phase space. Note that the first stage of VSS synthesis is similar to the synthesis of the adaptation algorithm. The two-stage approach to system design corresponds to supplementing the main control objective $\lim_{t\to\infty} x(t) = 0$, where $x(t)$ is the plant state vector, with the auxilliary objective $\lim_{t\to\infty} \sigma(x(t)) = 0$, where $\sigma(x)$ is the "error" vector function evaluating the deviation of the trajectory from the sliding surface. If the representing point reaches the sliding surface in the finite time t_*, then for $t \geq t_*$ the sliding mode on the surface $\sigma(x) = 0$ is realized.

Let the plant be described by the equation

$$\dot{x} = Ax + Bu, \quad y = Cx, \tag{15}$$

where $x = x(t) \in \mathbb{R}^n$ is plant state vector, $u = u(t) \in \mathbb{R}^1$ is scalar control action, $y = y(t) \in \mathbb{R}^l$ is measurable output vector. Let the control objective be given as $\lim_{t\to\infty} x(t) = 0$, and the subsidiary objective is taken as maintaining the sliding mode on plane $\sigma = Gy = 0$, where G is a $l \times n$-matrix. Choose the objective Lyapunov function in the form $V_1(x) = \frac{1}{2}x^{\mathrm{T}}Px$, where $P = P^{\mathrm{T}} > 0$ is some positive definite $n \times n$ matrix. Evaluating derivative of $V(x)$ with respect to (15) we obtain $\dot{V}(t) = x^{\mathrm{T}}P\big(Ax + Bu\big)$. Let us take control action in the form

$$u = -\gamma\,\mathrm{sign}\,\sigma, \quad \sigma = G\,y \tag{16}$$

where $\gamma > 0$ is a certain design parameter. As it shown in (Fradkov, 1979; Andrievsky et al., 1989), the above goal is achieved in system (15), (16) if there exist matrix $P = P^{\mathrm{T}} > 0$ and vector K_* such that

$$PA_* + A_*^{\mathrm{T}}P < 0, \quad PB = LC, \quad A_* = A + BK_*^{\mathrm{T}}C.$$

The mentioned condition is fulfilled if and only if the function $GW(p)$ is strictly minimal-phase (Andrievsky et al., 1989), where $W(p) = C\big(pI_n - A\big)^{-1}B$, and the sign of high frequency gain GCB is known. In that case for sufficiently large γ holds $\lim_{t\to\infty} x(t) = 0$. To eliminate dependence of system stability from initial conditions and plant parameters it was suggested to use instead of (16) the following adaptive control law (Andrievsky et al., 1989)

$$u = -K^{\mathrm{T}}(t)y(t) - \gamma \operatorname{sign} \sigma, \quad \sigma(y) = G\, y \qquad (17)$$
$$\dot{K}(t) = -\sigma(y)\Gamma y(t),$$

where $\Gamma = \Gamma^{\mathrm{T}} > 0$, $\gamma > 0$.

It should be noted that the convergence $s(t)$ to zero at the finite time t_* is essential for VSS systems. It can be shown (see, e.g., (Fradkov, 1974)) that this property is valid for any bounded region of initial conditions for the system (15), (17).

5. SIMULATION EXAMPLE

Consider the isolated lateral motion in the following flight conditions. Let groundspeed V be 15 m/s, flight path angle $\theta^* = 0$, flight altitude $h = 50$ m, pitch angle $\vartheta = 0.6$ deg (ensiring necessary trimming angle of attack α_{trim}, see Fig. 2), and the initial value of yaw angle $\psi(0) = 5$ deg. The intial conditions on other state variables are zeros.

Let us apply the signal-parametric adaptive control law (17) for yaw control. For taking into account unmodeled plant dynamics, the control action u, generated by the controller (17), is applied to the actuator, modeled by a second-order low-pass filter with time constant $\tau_\delta = 0.02$ s and damping ratio $\xi = 0.7$. Parameter γ in (17) is taken as $\gamma = 2$ deg. Signal σ in (17) is taken in the form $\sigma = \tau\omega_x + \psi$, where time constant $\tau = 0.2$ s.

Time histories of yaw angle $\psi(t)$ and rudder deflection angle $\delta_r(t)$ are pictured in Fig. 3.

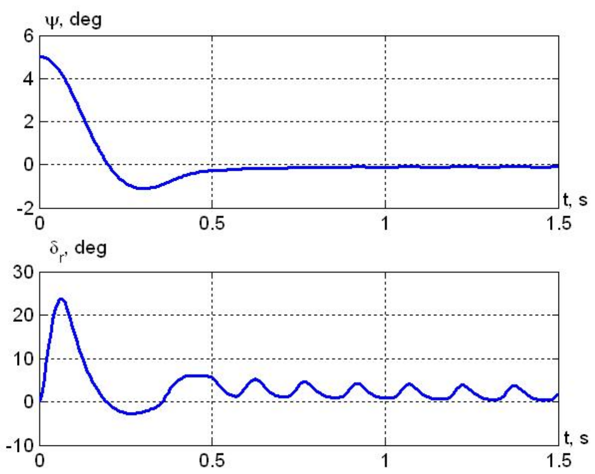

Fig. 3. Time histories of $\psi(t)$, $\delta_r(t)$ for signal-parametric controller (17).

The simulation results demonstrate good overal system performance.

6. CONCLUSION

In the paper the research plan of using the UAV glider *Rainbow Runner* as a testbed for robust and adaptive control methods is outlined. Based on the known dependencies of the aerodynamic coefficients on the UAV parameters and flight conditions (Lebedev and Chernobrovkin, 1990), the nonlinear model for the particular kind of UAV is obtained numerically. The signal-parametric adaptive attitude controller for yaw angle is designed and the overall closed-loop system performance is evaluated by means of the computer simulations. The simulation resutls demonstrate efficience of the proposed adaptive control scheme.

The future work intension is in embedding the chosen adaptive control laws to UAV autopilot for carrying out the experiments on adaptive control.

REFERENCES

Andrievskii, B. and Fradkov, A.L. (2006). Method of passification in adaptive control, estimation, and synchronization. *Autom. Remote Control*, 67(11), 1699–1731.

Andrievsky, B. and Fradkov, A.L. (2002). Combined adaptive autopilot for an UAV flight control. In *Proc. IEEE Conf. Control Applications*, 290–291. Glasgow.

Andrievsky, B., Fradkov, A.L., and Peaucelle, D. (2010). Estimation and control under information constraints for LAAS helicopter benchmark. *IEEE Trans. Contr. Syst. Technol.*, 18(5), 1180–1187.

Andrievsky, B., Peaucelle, D., and Fradkov, A.L. (2007). Adaptive control of 3DOF motion for LAAS Helicopter Benchmark: Design and experiments. In *Proc. 2007 Amer. Control Conf*, 3312–3317. New York, USA.

Andrievsky, B.R., Churilov, A., and Fradkov, A. (1996). Feedback Kalman–Yakubovich Lemma and its applications to adaptive control. In *Proc. 35th IEEE Conf. Dec. Contr.*, 4537–4542. Kobe, Japan.

Andrievsky, B.R. and Fradkov, A.L. (1994). Adaptive controllers with Implicit Reference Models based on Feedback Kalman–Yakubovich Lemma. In *Proc. 3rd IEEE Conf. on Control Applications*, 1171–1174. Glasgow, UK.

Andrievsky, B.R., Stotsky, A.A., and Fradkov, A.L. (1989). Velocity gradient algorithms in control and adaptation problems. *Autom. Remote Control*, 1533–1564.

Bertuccelli, L., Bethke, B., and How, J. (2009). Robust adaptive Markov decision processes in multi-vehicle applications. In *Proc. American Control Conf. (ACC 2009)*, 1304–1309. AACC.

Bukov, V. (1987). *Adaptive flight control with forecast.* Nauka, M. (in Russian).

Chen, D.R. and Chen, H.S. (2002). System identification of a model helicopter's yaw movement based on an operator's control. *Int. J. Nonlinear Sciences and Numerical Simulation*, 3-4, 395–398.

Chen, D.R., Chen, H.S., and Wang, J.D. (2002). Comparison between the system identification and the neural network methods in identifying a model helicopter's yaw movement. *Int. J. Nonlinear Sciences and Numerical Simulation*, 3-4, 391–394.

Cox, C., Neidhoefer, J., Saeks, R., and Lendaris, G. (2001). Neural adaptive control of LoFLYTE(R). In *Proc. American Control Conf. (ACC 2001), Arlington, VA, USA*, volume 4, 2913–2917. AACC.

Davies, M. (2003). *The Standard Handbook for Aeronautical and Astronautical Engineers.* McGraw-Hill, New York.

Dobrokhodov, V., Kaminer, I., Kitsios, I., Xargay, E., Hovakimyan, N., Cao, C., Gregory, I., and Valavani, L. (2011). Experimental validation of adaptive control: Rohrs' counterexample in flight. *AIAA J. Guidance, Control and Dynamics*, 34(5), 1311–1328.

Dzul, A., Lozano, R., and Castillo, P. (2004). Adaptive control for a radio-controlled helicopter in a vertical flying stand. *Int. J. Adapt. Control Signal Process.*, 18, 473–485.

Fradkov, A.L. (1974). Synthesis of an adaptive system for linear plant stabilization. *Autom. Remote Control*, 35(12), 1960–1966.

Fradkov, A.L. and Andrievsky, B. (2005). Combined adaptive controller for UAV guidance. *Europ. J. Contr.*, 11(1), 71–79.

Fradkov, A.L., Andrievsky, B., and Peaucelle, D. (2007). Adaptive passification-based fault-tolerant flight control. In *Prepr. 17th IFAC Symposium on Automatic Control in Aerospace (ACA'2007)*. Toulouse, France.

Fradkov, A.L., Miroshnik, I.V., and Nikiforov, V.O. (1999). *Nonlinear and Adaptive Control of Complex Systems*. Kluwer, Dordrecht.

Fradkov, A. (1979). Speed-gradient scheme and its applications in adaptive control. *Autom. Remote Control*, 40(9), 1333–1342.

Fradkov, A., Andrievsky, B., and Peaucelle, D. (2008). Adaptive control design and experiments for LAAS helicopter benchmark. *Europ. J. Control*, 14(4), 329–339.

GOST 20058-80 (1981). *Flying vehicles aerodynamics: Terms, definitions and notation. State Standard.* M. (in Russian).

Gregory, I.M., Xargay, E., Cao, C., and Hovakimyan, N. (2010). Flight test of an L_1 adaptive controller on the NASA AirSTAR flight test vehicle. In *Proc. AIAA Guidance, Navigation, and Control Conference*. AIAA, Toronto, Canada.

Gregory, I.M., Xargay, E., Cao, C., and Hovakimyan, N. (2011a). Flight test of L_1 adaptive control law: Offset landings and large flight envelope modeling work. In *Proc. AIAA Guidance, Navigation, and Control Conference*, 1–15. AIAA, Portland, OR, USA. URL `http://ntrs.nasa.gov`. (NASA Langley Research Center, Report No NF1676L-12023).

Gregory, I.M., Xargay, E., Cao, C., and Hovakimyan, N. (2011b). L_1 adaptive control law in support of large flight envelope modeling work. In *Proc. CEAS Conference on Guidance, Navigation and Control*. CEAS, Munich, Germany.

Gregory, I.M., Xargay, E., Cao, C., Hovakimyan, N., and Zou, X. (2009). L_1 adaptive control design for NASA AirSTAR flight test vehicle. In *Proc. AIAA Guidance, Navigation, and Control Conference*. AIAA, Chicago, IL, USA.

Hovakimyan, N., Cao, C., Kharisov, E., Xargay, E., and Gregory, I. (2011). L_1 Adaptive control for safety-critical systems. *IEEE Control Syst. Mag.*, 31(5), 54–104.

Kutay, A.T., Calise, A.J., Idan, M., and Hovakimyan, N. (2005). Experimental results on adaptive output feedback control using a laboratory model helicopter. *IEEE Trans. Contr. Syst. Technol.*, 13(2), 196–202.

Landau, I.D., Lozano, R., M'Saad, M., and Karimi, A. (2011). *Adaptive Control*. Springer-Verlag. Communications and Control Engineering Series.

Lebedev, A. and Chernobrovkin, L. (1990). *Unmanned vehicle aerodynamics. The textbook.* Mashinostrojenie, M. (in Russian).

Lozano, R. (2010). *Unmanned Aerial Vehicles Embedded Control*. John Wiley-ISTE Ltd.

Myrand-Lapierre, V., Desbiens, A., Gagnon, E., Wong, F., and Poulin, E. (2010). Transitions between level flight and hovering for a fixed-wing mini aerial vehicle. In *Proc. American Control Conf. (ACC 2010)*, 530–535. AACC, Baltimore, MD, USA.

Peaucelle, D., Fradkov, A.L., and Andrievsky, B. (2006). Passification-based adaptive control: Robustness issues. In *Prepr. 5th IFAC Symp. Robust Control Design (ROCOND'06)*. Toulouse, France.

Rohrs, C.E., Valavani, L.S., Athans, M., and Stein, G. (1985). Robustness of continuous-time adaptive control algorithms in presence of unmodeled dynamics. *IEEE Trans. Automat. Contr.*, 30(9), 881–889.

Rusnak, I., Weiss, H., and Barkana, I. (2011). Improving the performance of existing missile autopilot using simple adaptive control. In *Proc. 18th IFAC World Congress*, 6567–6572. IFAC, Milano, Italy. URL `http://www.ifac-papersonline.net`.

Stotsky, A.A. (1994). Combined adaptive and variable structure control. In A. Zinober (ed.), *Variable Structure and Lyapunov Control*, 313–333. Springer-Verlag, London.

Tanaka, K., Othake, H., and Wang, O. (2004). A practical design approach to stabilization of a 3-DOF RC Helicopter. *IEEE Trans. Contr. Syst. Technol.*, 12 (2), 315–325.

Utkin, V.I. (1992). *Optimization and Control using Sliding Modes*. Springer-Verlag, London.

Wise, K.A. and Lavretsky, E. (2011). Robust and adaptive control of X-45A J-UCAS: A design trade study. In *Proc. 18th IFAC World Congress*, 6555–6560. IFAC, Milano, Italy. URL `http://www.ifac-papersonline.net`.

Wise, K.A., Lavretsky, E., and Hovakimyan, N. (2006). Adaptive control of flight: Theory, applications, and open problems. In *Proc. American Control Conf. (ACC 2006)*, 5967–5971. AACC, Minneapolis, Minnesota, USA.