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THE STUDY OF PATH-FOLLOWING ACCURACY OF ROBOTIC SINGLE-ROTOR HELICOPTER[*]

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Vyacheslav Kh. Pshikhopov, Artem E. Kulchenko, Mikhail Y. Medvedev, Vladimir A. Kostukov, Vladimir M. Chufistov

Department of Electrical Engineering and Mechatronics, South Federal University,
Taganrog, Russia

Abstract. *In this paper we study the accuracy of a single-rotor robotic small-scale helicopter flight along a complex path. The control algorithms for the autopilot are synthesized using the position-trajectory control approach. We use hardware-software complex to test the helicopter autopilot. The simulation in hardware-software complex is used to debug the autopilot software and complex study of autopilot control algorithms in early development stages without full-scale experiments. The paper shows results of the simulation of single-rotor small-scale helicopter flight.*

Key words: *control, helicopter, flight simulator, simulation, control algorithm*

1. INTRODUCTION

A single-rotor helicopter with tail rotor is the most widely used rotorcraft vehicle. As the analysis of the existing solutions shows, this type of modern small-scale helicopters can fly only along linear trajectories and/or a path composed of a set of segments without correction by the operator. In this case, the synthesis of control algorithms for such systems is done using the methods of decomposition and linearization, while more complex trajectories require the consideration of multiple nonlinear model having complex distribution of forces and moments. In a simplified model of the helicopter dynamics unaccounted physical effects are presented in the form of perturbation which leads to degradation of control precision.

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Corresponding author: Artem E. Kulchenko
Department of Electrical Engineering and Mechatronics, South Federal University, Taganrog, Russia
E-mail: rhelicto@gmail.com

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The analysis of the existing robotic helicopters control systems showed that hierarchical control systems are the most efficient algorithms, which include intelligent motion planner, multi-connected adaptive control regulator and intelligent takeoff/landing system.

This paper considers nonlinear control algorithms for a single-rotor helicopter. The paper shows the peculiarities of synthesis algorithms. The assessment of the possibilities of such a system is given by the simulation results under wind disturbances.

2. POSITION-TRAJECTORY CONTROL

2.1. Position-trajectory control algorithm

Position-trajectory control is widely used for controlling various vehicles [1]-[4]. The position-trajectory control method allows using a mathematical model of a mobile vehicle in the form of a system of nonlinear ordinary differential equations [5]. In a general form position-trajectory control algorithm has the form [6]:

$$F_u = -M(\tilde{T}\tilde{A}K_0)^{-1}(K_1\dot{Y} + K_2(t) + \tilde{A}\tilde{V} + \Psi_{tr}) + F_d + \tilde{F}_v \,, \tag{1}$$

where the desired path is described by equations of plane:

$$\begin{aligned}
\sigma &= a_{111}xg^2 + a_{122}Hg^2 + a_{133}zg^2 + a_{131}xg + a_{141}Hg + a_{151}zg + a_{161}, \\
\sigma &= a_{211}xg^2 + a_{222}Hg^2 + a_{233}zg^2 + a_{231}xg + a_{241}Hg + a_{251}zg + a_{261}, \\
\sigma &= a_{311}xg^2 + a_{322}Hg^2 + a_{333}zg^2 + a_{331}xg + a_{341}Hg + a_{351}zg + a_{361},
\end{aligned} \tag{2}$$

where a_n, i, j - coefficients, xg, Hg, zg - linear coordinates.

The components of the control algorithm are described in [6]. In (1) the control is calculated as a vector of control forces and moments in body frame coordinate system:

$$F_u = \begin{bmatrix} F_{ux} \\ F_{uy} \\ F_{uz} \\ M_{ux} \\ M_{uy} \\ M_{uz} \end{bmatrix}. \tag{3}$$

Three problems were solved to apply the generalized algorithm of position-trajectory control to the helicopter.

2.2. Control forces

The equation is made to bring the control forces to actuators control. Expressions of the equivalent rotor theory are used to derive the equations of the inverse transformation [7]. Analytical expressions for the relations between the control forces and control channels collective pitch and engine speed, cyclic and collective pitch angle of the tail rotor were obtained:

$$\begin{aligned}
&\omega = k\frac{2\mathbf{A}}{\rho\pi R(R^2)},\\
&\beta_1 = arccos(\frac{H}{\mathbf{A}}) - \beta_{01},\\
&\beta_2 = arccos(\frac{S}{\mathbf{A}}) - \beta_{02},\\
&\phi_{0TR}\omega_{TR} = k\frac{2\mathbf{A}_{TR}}{\rho\pi R_{TR}({R_{TR}}^2)},
\end{aligned} \tag{4}$$

where, β_1, β_2 are cyclic angles that are set by swashplate for pitch and roll, respectively; β_{01}, β_{02} are balancing angles on hover; H, S are projections of $\mathbf{A}$ – full aerodynamic force of the main rotor; $\mathbf{A}_{TR}$ – is full aerodynamic force of the tail rotor; ϕ_0 is collective pitch of main rotor; ϕ_{0TR} is collective pitch tail rotor; ω is angular velocity of main rotor rotation; ω_{TR} is angular velocity of tail rotor rotation; R is main rotor radius; R_{TR} is tail rotor radius.

Using (4) is difficult because of the difficulty of obtaining projections and coefficients $\mathbf{A}$ and $\mathbf{A}_{TR}$. However, the conclusions are based on experimental observations, that the lift coefficient Ct can be considered as a linear function of the collective pitch on short segments of the flight. On the basis of this, we made the assumption that $\varphi 0 = kCt$, where k is the proportionality coefficient.

Now, when the constraint equations between the control forces and control channels are obtained, they have to be supplemented by formulas of transition to analog signals of the actuators in accordance with the construction, yet in this paper are not considered.

2.3. Control constrains and control distribution

Control constraints are determined in accordance with the technical capabilities of the helicopter. Restrictions are prepared by the technical documentation for the helicopter and its actuators.

The problem of distributed control is solved, which is due to the fact that the number of control channels is fewer than the number of degrees of helicopter freedom. To solve this problem, it is proposed to use the logical expressions to specify the order of application of the control actions:

If ($\theta_{minlim} \le \theta \le \theta_{maxlim}$) and ($\gamma_{minlim} \le \gamma \le \gamma_{maxlim}$) are true, then we substitute $H = F_{ux}$, $S = F_{uy}$, and $A = F_{uz}$ in (4), else $H = \frac{1}{L}M_{uy}$ and $S = \frac{1}{L}M_{ux}$.

In both cases: $A = F_{uz}$, $A_{TR} = \frac{1}{L_{TR}}M_{uz}$.

Where, F_{ux}, F_{uy} – are longitudinal and lateral projections of control force, F_{uz}, M_{uz} – the projection of force on the vertical axis and moment on the yaw; L – length from center of mass to main rotor hub, L_{TR} – tail boom length; θ, γ – pitch and roll angles, with min/max lim indexes restrictions on the allowable angles written. These angles depend on the flight mode and balancing angles. We use $\theta = 2$, $\gamma = 3$ degrees in the vertical flight mode for small-scale single rotor helicopter and $-8 \le \theta \le 8$, $-5 \le \gamma \le 8$ in the horizontal flight mode.

Autopilots that are based on linear control algorithms with decomposition of single rotor helicopter dynamics model use special actuators control logic. This is because the multicoupling of control channels is required to be compensated. The typical actuators control logic:

$$\varphi_0\omega \to \beta_1, \beta_2 \to \varphi_{0PB}\omega_{PB}. \tag{5}$$

According the actuators control logic the regulation of $\varphi_0\omega$ lead helicopter to heading change and lateral displacement. The displacement is compensated by β_1, β_2, that are calculated in the previous step. Finally, $\varphi_{0PB}\omega_{PB}$ are used to compensate for the heading change, but this leads to altitude loss.

Using position-trajectory algorithms in autopilot allows to avoid actuators control logic, the multicoupling of control channels is automatically involved in nonlinear helicopter dynamics model.

The next step is the verification of the control algorithms.

3. HARDWARE-SOFTWARE COMPLEX AND SIMULATION

3.1. Hardware-software complex description

Hardware-software complex is designed to research the functioning of the control algorithms in the closed system. The block diagram of hardware-software complex is shown in Fig. 1.

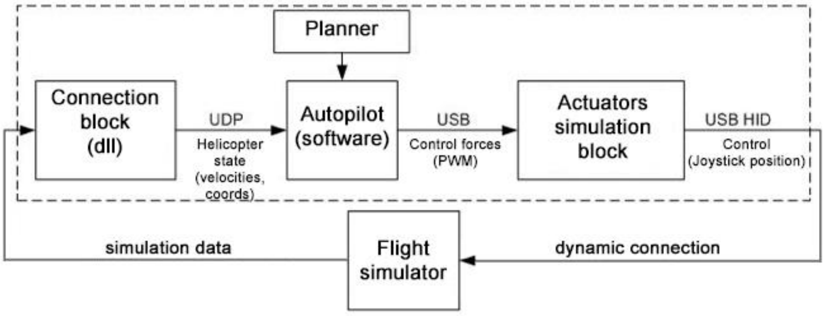

Fig. 1 The block diagram of hardware-software complex for research helicopter autopilot type

In this block diagram flight simulator, autopilot and interface unit are computer programs (Fig. 2). But actuators simulation block is a hardware device (Fig. 3).

The flight simulator is the computer program for pilot training. As a part of hardware-software complex flight simulator AerosimRC [8] is used for research and testing autopilots and navigation information filtering algorithms in the laboratory.

Autopilot and scheduler – is a computer program with a graphical user interface. It implements the control algorithms, interfaces to the connection block and actuators simulation block, as well as the function parameter registration of helicopter flight and on-board systems. It allows objective tests of the functionality of the autopilot [9].

Connection block is a dynamical linked library (software), which is used to connect to flight simulator. Connection block is used to send navigation data from flight simulator to autopilot. The user can specify frequency of navigation data.

3.2. Simulation

In this study we use simulation in hardware-software complex to test the position-trajectory control algorithm of single-rotor helicopter with tail rotor. Yamaha R-MAX is a small-scale helicopter test vehicle. It is assumed that the helicopter weight is 28 kilograms. The wind speed is about 5 m/s. The desired path has form of square ‘snake’. This type of path is selected for objective reasons. Square ‘snake’ is a complex trajectory of the polylines with length of 5 m. It would demonstrate the capabilities of the autopilot to avoid obstacles in a restricted space. For example, it could be a flight in the city. In this work we made simulation in two steps: in Matlab and in hardware-software complex. The Matlab simulation is applied for checking of control algorithms adequacy.

It should be noted that the procedure of simulation for helicopter in the hardware-software complex has distinctive features. The flight simulation in hardware-software complex is very close to a physical experiment. It consists of elements of real flight: take-off, landing, moving on the reference point of desired path.

The figures 2, 3 show the results of simulation. Table 1 includes the errors.

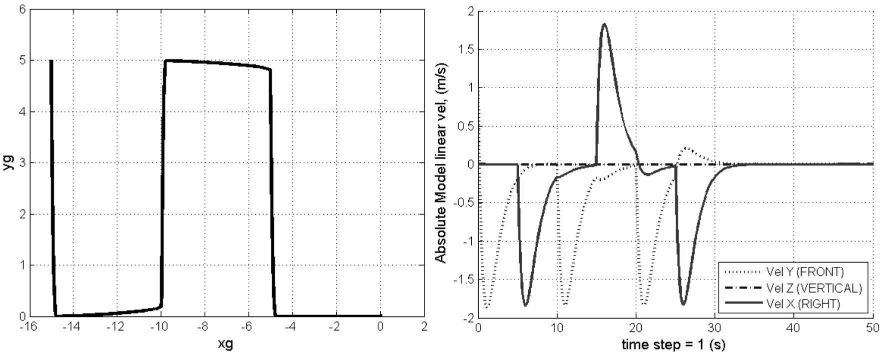

Fig. 2 Simulation in Matlab. Left: actual flight path.
Right: the velocity projections in helicopter body frame

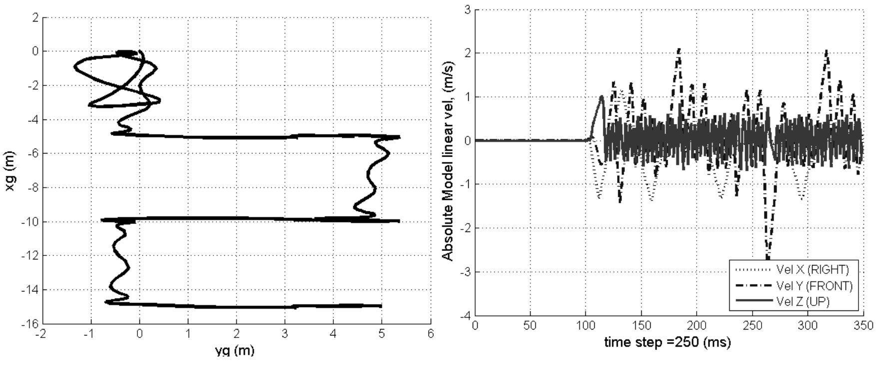

Fig. 3 Simulation in hardware- software complex. Left: actual flight path.
Right: the velocity projections in helicopter body frame

Table 1 Errors between desired and actual paths

Error type	Value (in meters)
Error in the steady state	0.57
Standart deviation	0.1202

4. CONCLUSIONS

We use simulation to make indoor validation of autopilot control algorithms synthesis procedure, to analyze its properties and define its performance in path-following accuracy with wind disturbances. The simulation results show that a small-scale single rotor helicopter with position and trajectory control algorithms provide flight along trajectories with precision that are inaccessible to the majority of the pilots and autopilot based on linear control algorithms.

Using a nonlinear helicopter dynamics model in position-trajectory control approach simplifies the control system architecture. It excludes the necessity of additional loops for multicoupling of control channels compensation. The results of simulation show the possibility of the autopilot for obstacles avoidance.

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