Pomiary Automatyka Robotyka, ISSN 1427-9126, R. 24, Nr 3/2020, 29–35, DOI: 10.14313/PAR_237/29

Development of Adaptive Control for an Asymmetric Quadcopter

Ryszard Beniak, Oleksandr Gudzenko
Opole University of Technology, Faculty of Electrical Engineering, Automatic Controland Computer Science, ul. Prószkowska 76, 45-758 Opole, Poland

Abstract: The paper presents an adaptive control algorithm for an asymmetric quadcopter. For determining the control algorithm, the identification was made, and an identification algorithm is presented in the form of a recursive method. The control method is realized using inverse dynamics, full state feedback and finally adaptive control method. The algorithms for the off-line and on-line identification of quadcopter model parameters are also presented. The paper shows the effectiveness of the selected algorithm on the example of the movement along a given trajectory. Finally, recommendations of the application of these different methods are made.

Keywords: quadcopter, adaptive control, inverse dynamics, full state feedback, wind

1. Introduction

During the last 20 years, the interest in unmanned aerial vehicles has been growing because of their availability and simplicity of control. One variety of unmanned aerial vehicles is a quadcopter. A quadcopter is an aircraft with four rotors. They are widespread, as evidenced by a large number of publications [1–17]. With such devices, one can produce photo and video recording, deliver small loads and perform other tasks for monitoring the Earth's surface. To effectively perform these tasks, one needs to control the quadcopter precisely.

PD or PID – controllers [3, 5, 8–13], linear-quadratic controller [1, 2], the model predictive control [3, 7], Backstepping Control [5, 6], Sliding Mode Control [5] and Inverse Control [2, 5, 14], using neural networks [24] are the most popular controllers used for quadcopter control. There are also some adaptive algorithms for controlling a quadcopter [15–17].

The main disadvantage of most control algorithms is the lack of precise knowledge about quadcopter parameters such as weight quadcopter, inertia tensor, motors' traction coefficient, aerodynamic coefficient, the distance from the quadcopter's centre of mass to motors' centres. In case of the real objects, such parameters may vary, when, e.g. propellers are replaced, or new equipment is added to the quadcopter. Also, for each quadcopter one needs to carry out the identification of parameters separately, which is a costly process. Therefore, in most cases, these parameters are determined with low accuracy. For this reason, during flight, it is necessary to apply the methods of adaptive control.

The purpose of this paper is to provide an universal algorithm for quadcopter adaptive control along a given trajectory and to assess its effectiveness. This paper is a continuation of the work presented in [18–19]. Article [19] shows the degree of effective control's dependence on the scope of accurate knowledge on the model parameters. The conclusion was that there was a need to develop such algorithms. This paper uses a more comprehensive mathematical model of an asymmetric quadcopter.

The paper consists of six sections. In the first section, the problem and the goal of its solution were formulated, and the advantages of the adaptive method are shown. The second section presents the mathematical model of an asymmetric quadcopterand the scheme of the control algorithm. The third section presents the wind model. The fourth section focuses on the adaptive control algorithm, in particular the method of identifying the model parameters. In the next section, presents the conditions in which the modeling was conducted, and the simulation results were obtained. In the last section, are presented the conclusions about the efficiency of the algorithm, and make recommendations for its use.

2. Development of the Mathematical Model

The problem of motion control of a quadcopter along with a given trajectory has been solved according to the schema (Fig. 1).

A detailed description of the mathematical model of an asymmetric quadcopter (1) is presented in [18]. The equations in the form (2) relate angle speed of motor rotation with the driving force and moments. In Fig. 1 $\mathbf{U}_{ref} = (U_{r1}, U_{r2}, U_{r3}, U_{r0})^{\mathrm{T}}$ is a control obtained with control algorithms.

Autor korespondujący:
Ryszard Beniak, r.beniak@po.edu.pl

Artykuł recenzowany
nadesłany 28.01.2020 r., przyjęty do druku 15.08.2020 r.

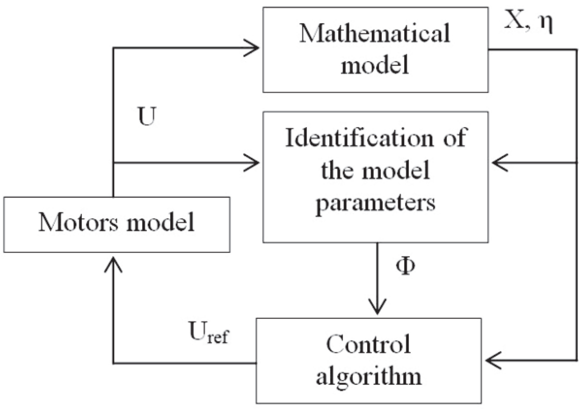

Fig. 1. Block diagram of the simulated quadcopter
Rys. 1. Schemat blokowy symulowanego quadrocoptera

$$\begin{cases} \mathbf{I}\dot{\Omega} + \Omega \times \mathbf{I}\Omega + \Omega \times \begin{bmatrix} 0 \\ 0 \\ I_m \cdot \sum_{i=1}^{4} \omega_i \end{bmatrix} = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} \\ M\ddot{\mathbf{X}} = \mathbf{G}(\eta) U_0 - \begin{bmatrix} 0 \\ 0 \\ Mg \end{bmatrix} - \mathbf{F}_{res} \\ \dot{\eta} = \Lambda(\eta)^{-1}\Omega \end{cases} \tag{1}$$

$$\begin{cases} U_1 = k_2 \sum_{i=1}^{4} \omega_i^2 \cdot y_{i,c} \\ U_2 = -k_2 \sum_{i=1}^{4} \omega_i^2 \cdot x_{i,c} \\ U_3 = k_1\left(-\omega_1^2 - \omega_2^2 + \omega_3^2 + \omega_4^2\right) \\ U_0 = k_2 \sum_{i=1}^{4} \omega_i^2 \end{cases} \tag{2}$$

where $\mathbf{I}$ is inertia tensor, $\mathbf{\Omega}$ is angular velocity vector, I_m is motors' moment of inertia, ω_i is i-th motor's angular velocity of rotation, $\mathbf{U} = (U_1, U_2, U_3, U_0)^{\mathrm{T}}$ is control, M is quadcopter's mass, $\mathbf{X} = (x, y, z)^{\mathrm{T}}$ is quadcopter's centre of mass, $\boldsymbol{\eta} = (\varphi, \theta, \psi)^{\mathrm{T}}$ are Euler angles, $\mathbf{F}_{res} = (F_{res,x}, F_{res,y}, F_{res,z})^{\mathrm{T}}$ is resistance force vector, $\mathbf{G}(\boldsymbol{\eta})$ is matrix transformation between inertial and related coordinate systems, which has the form (3), $\Lambda(\boldsymbol{\eta})$ is transition matrix for the angular velocity, which has the form (4), k_1 and k_2 are constant coefficients, $x_{i,c}$ and $y_{i,c}$ are distances from the centre of the i-th motor to the quadcopter's gravity centre for axes $0x$ and $0y$, respectively.

$$\mathbf{G}(\eta) = \begin{bmatrix} \cos(\varphi)\sin(\theta)\cos(\psi) + \sin(\varphi)\sin(\psi) \\ \cos(\varphi)\sin(\theta)\sin(\psi) - \sin(\varphi)\cos(\psi) \\ \cos(\varphi)\cos(\theta) \end{bmatrix} \tag{3}$$

$$\Lambda(\eta) = \begin{bmatrix} 1 & 0 & -\sin(\theta) \\ 0 & \cos(\varphi) & \sin(\varphi)\cos(\theta) \\ 0 & -\sin(\varphi) & \cos(\varphi)\cos(\theta) \end{bmatrix} \tag{4}$$

3. Wind Model

Movement of the quadcopter is strongly influenced by the wind, which is always present in the atmosphere. Usually, a quadcopter flies at altitudes up to 100 m. According to [21, 23], the wind speed $\mathbf{V}_{wind}$ at such heights can be represented as(5):

$$\mathbf{V}_{wind} = \mathbf{V}_{const} + \mathbf{V}_{rand}, \tag{5}$$

where $\mathbf{V}_{const}$ and $\mathbf{V}_{rand}$ are deterministic and stochastic components of wind velocity, respectively:

$$\mathbf{V}_{const} = (V_{const,x}, V_{const,y}, V_{const,z})^{\mathrm{T}} \text{ and } \mathbf{V}_{rand} = (V_{rand,x}, V_{rand,y}, V_{rand,z})^{\mathrm{T}}.$$

Deterministic and stochastic components can be represented as (6) and (7), respectively. The stochastic component is modelled using Dryden differential equations. The choice and detailed description of the wind model is presented in [21, 23].

$$\mathbf{V}_{const} = \frac{V_0}{k_{karman}} \ln\left(\frac{z + z_0}{z_0}\right), \tag{6}$$

where $\mathbf{V}_{const}$ is wind velocity at altitude z, $\mathbf{V}_0$ is "friction velocity", k_{karman} is Karman constant, $k_{karman} = 0.38$, z_0 is layer thickness of surface roughness.

$$\begin{aligned} &\dot{V}_{rand,x} + \frac{V_a}{L_x} V_{rand,x} = \sigma_x \sqrt{\frac{2V_a}{L_x}} W_x \\ &\ddot{V}_{rand,y} + \frac{2V_a}{L_y}\dot{V}_{rand,y} + \left(\frac{V_a}{L_y}\right)^2 V_{rand,y} = \sigma_y \sqrt{\frac{3V_a}{L_y}}\left(\dot{W}_y + \frac{V_a}{\sqrt{3}L_y} W_y\right) \\ &\ddot{V}_{rand,z} + \frac{2V_a}{L_z}\dot{V}_{rand,z} + \left(\frac{V_a}{L_z}\right)^2 V_{rand,z} = \sigma_z \sqrt{\frac{3V_a}{L_z}}\left(\dot{W}_z + \frac{V_a}{\sqrt{3}L_z} W_z\right) \end{aligned} \tag{7}$$

where x, y, z are unit vectors in the coordinate system associated with the quadcopter, σ is the intensity of turbulence, $\sigma = (\sigma_x, \sigma_y, \sigma_z)^{\mathrm{T}}$, $\mathbf{L}$ is spatial wavelengths, $\mathbf{L} = (L_x, L_y, L_z)^{\mathrm{T}}$, V_a is quadcopter velocity, $\mathbf{W}$ is white noise, $\mathbf{W} = (W_x, W_y, W_z)^{\mathrm{T}}$. Parameters for the Dryden model of wind gusts are defined in MIL-F-8785C [22].

The resulting resistance force can be represented as (8):

$$\mathbf{F}_{res} = \mathbf{k}_{res} \cdot \widetilde{V}_a^2 \cdot sign\left(\widetilde{V}_a\right), \tag{8}$$

where $\widetilde{V}_a$ is the velocity of the quadcopter relative to air mass, $\mathbf{k}_{res}$ is the coefficient of resistance.

4. Identification and Control Algorithms

The choice of the control algorithm is an essential step in creating an autonomous control system. The analysis of control algorithms in [19, 20] showed that the control algorithms depend on the exact knowledge of the model parameters. Than the more complex the control algorithm and the mathematical model used that the more significant this effect is. It turns out that if the error value in the parameters is more than 15%; the most effective is the full state feedback method. Therefore, it is necessary to develop a control system that does not reduce control effectiveness when changing model parameters and adapts to their changes.

In this paper, inverse dynamic, full state feedback method sand adaptive control were chosen. Using the chosen methods as an example, the efficiency of using the algorithm for the identification of model parameters in quadcopter control is shown. For all presented methods, the first step of the identification is the identification of mechanical motor parameters.

4.1. Identification of Motor Parameters

The presented algorithm of adaptive control can refine the parameters of the quadcopter model. However, in the literature, little attention is paid to identifying the parameters of quadcopters' motors. These parameters depend on both the mechanical characteristics of the engine and the shape and size of the blades. They directly affect the accuracy of the quadcopter control. Therefore, it is necessary to develop an algorithm for identifying the parameters of the motors.

Complete identification of the quadcopter parameters in the regular mode in the form (1) and (2) cannot be performed with the help of the adaptive algorithm. This is because the inverse matrixin (16) degenerates and, as a consequence, the matrix $\mathbf{P}_k$ does not converge.

There are several ways to solve the problem of identifying the motor parameters.

The first way is at the start of the quadcopter realizes special manoeuvres. This approach is better to use when specifying the motor parameters; otherwise, the quadcopter can become uncontrollable. However, this approach will allow increasing the efficiency of control at each launch or in the process of flight.

The second method requires the creation of additional equipment for the motor calibration be for emounting on the quadcopter. This method can more accurately calibrate and determine the flaws of each motor.

Pressure sensors FSR-402, which depend on the connected resistance were used. In Fig. 3 are graphs of the dependence of the force applied to the sensors on its measurements.

Figure 4 shows a plot of the signal supplied to the motor from the traction force of the motor measured by the calibration device. As can be seen from Fig. 4, this characteristic is almost linear. Reducing the force at high engine speeds is caused by air flow turbulence and motor vibrations. This problem requires further investigation and isolation of the sensors. The proposed algorithm, along with the calibration device, identifies with high accuracy the traction force of the motor.

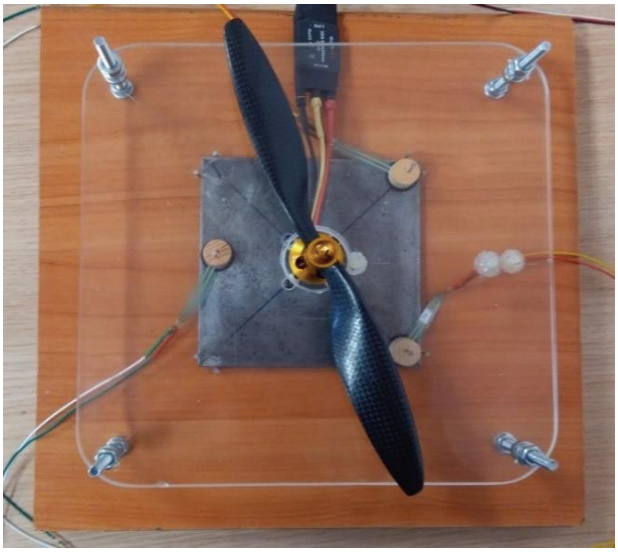

Fig. 2. Equipment for calibrating of motors
Rys. 2. Osprzęt do kalibracji silników

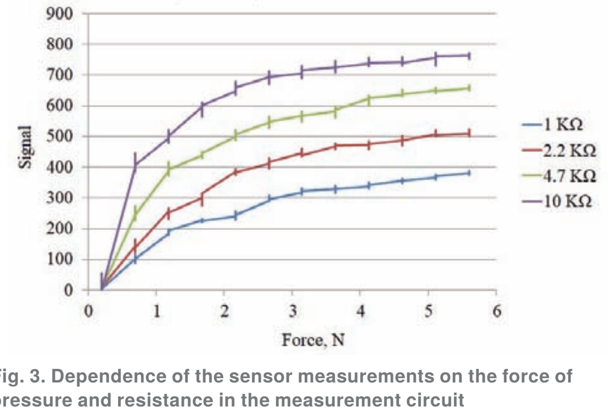

Fig. 3. Dependence of the sensor measurements on the force of pressure and resistance in the measurement circuit
Rys. 3. Zależność pomiarów wartości z czujnika od nacisku na czujniki i rezystancji w obwodzie pomiarowym

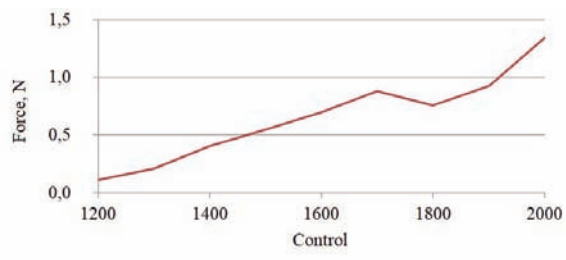

Fig. 4. Dependence of the supplied signal on the motor traction, values from 1200 to 2000 describe the controls
Rys. 4. Zależność dostarczonego sygnału od trakcji silnika, wartości od 1200 do 2000 opisują sterowanie

4.2. Inverse Dynamics

This method is presented in detail in [18, 19, 23]. Let us describe only the implementation features for the chosen model of a quadcopter.

The method of inverse dynamics is based on finding the desired values of the forces and moments of motors based on a given the trajectory of motion and a known mathematical model of the object. In this case, the trajectory of motion was set by the centre of mass of the quadcopter X_c^{tr} and one orientation angle ψ^{tr}.

On the given trajectory of motion, the desired linear and circular accelerations of the quadcopter are determined as (9, 11). Additional members are necessary to give the control algorithm stability and continuity. And full state vector can be determined from the accelerations and the trajectory, like (10, 11)

$$\ddot{X}^* = \ddot{X}^{tr} - C_1(X - X^{tr}) - C_2(\dot{X} - \dot{X}^{tr}), \tag{9}$$

$$\begin{aligned} \tilde{\theta} &= \operatorname{arctg}\left[\frac{\left(M\ddot{x}^* + F_{res,x}\right)c_\psi + \left(M\ddot{y}^* + F_{res,y}\right)s_\psi}{M\ddot{z} + Mg + F_{res}(\dot{z})}\right] \\ \tilde{\varphi} &= \operatorname{arctg}\left[\frac{\left(M\ddot{x}^* + F_{res,x}\right)s_\psi + \left(M\ddot{y}^* + F_{res,y}\right)c_\psi}{M\ddot{z} + Mg + F_{res}(\dot{z})}c_{\tilde{\theta}}\right] \end{aligned} \tag{10}$$

$$\begin{aligned} \ddot{\varphi}^* &= \ddot{\varphi}^{tr} - C_3\left(\varphi - \tilde{\varphi}\right) - C_4\left(\dot{\varphi} - \dot{\varphi}^{tr}\right) \\ \ddot{\theta}^* &= \ddot{\theta}^{tr} - C_3\left(\theta - \tilde{\theta}\right) - C_4\left(\dot{\theta} - \dot{\theta}^{tr}\right) \\ \ddot{\psi}^* &= \ddot{\psi}^{tr} - C_3\left(\psi - \psi^{tr}\right) - C_4\left(\dot{\psi} - \dot{\psi}^{tr}\right) \end{aligned} \tag{11}$$

where C_1, C_2 are matrixes of known feedback coefficients; C_3, C_4 are known feedback coefficients, F_{res} is resistance force, $c_{\bullet} = \cos(\cdot)$, $s_{\bullet} = \sin(\cdot)$.

Knowing the desired state vector of a quadcopter at any time on the chosen trajectory, the control vector was determined as (12–13).

$$U_0 = \frac{M\ddot{z}^* + Mg + F_{res,z}}{c_\theta c_\varphi} \tag{12}$$

$$U = I\Lambda\ddot{\eta}^* + I\dot{\Lambda}\dot{\eta}^{tr} + \Lambda\dot{\eta}^{tr} \times I\Lambda\dot{\eta}^{tr} \tag{13}$$

where $\ddot{\eta}^* = \left(\ddot{\varphi}^*, \ddot{\theta}^*, \ddot{\psi}^*\right)^{\mathrm{T}}$, $\ddot{\eta}^{tr} = \left(\ddot{\varphi}^{tr}, \ddot{\theta}^{tr}, \ddot{\psi}^{tr}\right)^{\mathrm{T}}$.

4.3. Full State Feedback

The full state feedback method is described in detail and is presented in [18, 19, 23]. Its hould be noted that this method is applied to the linear model, which can be obtained from (2) by full linearisation. Such models are presented in [18, 19]. The control algorithm for this method can be written as (14).

$$\begin{aligned} U_1 &= -p_{1,1}\left(y - y^{tr}\right) - p_{2,1}\left(\dot{y} - \dot{y}^{tr}\right) - p_{3,1}\left(\varphi - \varphi^{tr}\right) - p_{4,1}\left(\dot{\varphi} - \dot{\varphi}^{tr}\right) \\ U_2 &= -p_{1,2}\left(x - x^{tr}\right) - p_{2,2}\left(\dot{x} - \dot{x}^{tr}\right) - p_{3,2}\left(\theta - \theta^{tr}\right) - p_{4,2}\left(\dot{\theta} - \dot{\theta}^{tr}\right) \\ U_3 &= -p_{1,3}\left(\psi - \psi^{tr}\right) - p_{2,3}\left(\dot{\psi} - \dot{\psi}^{tr}\right) \\ U_0 &= Mg - p_{1,0}\left(z - z^{tr}\right) - p_{2,0}\left(\dot{z} - \dot{z}^{tr}\right) \end{aligned} \tag{14}$$

where $p_{i,j}$, $\forall i, j$: $i = 1, .., 4$; $j = 0, .., 3$ are feedback coefficients.

4.4. Adaptive Control

The control algorithm based on the inverse dynamics is essentially not linear from the state vector and the parameters of the quadcopter model. A full state feedback method is linear from the state vector and the model parameters. Therefore, for significant errors in measuring the state vector or the values of the model parameters, the efficiency of the inverse dynamics method is significantly impaired in comparison with the full state feedback method. To solve this problem, it is necessary to develop an adaptive control algorithm for the quadcopter.

The following assumptions have been made. The model parameters are not changing over time. They can only be changed between runs and taken into account that it is necessary to analyse a large amount of information received to identify the model. Therefore, a recursive method to identify the model parameters has been selected [20].

Definable parameters are the inertia tensor and the quadcopter's mass $\Phi = (I_x, I_{xy}, I_{xz}, I_y, I_{yz}, I_z, M)^{\mathrm{T}}$. The general form of the equation (1) can be written as (15).The identification algorithmis presented in the form of (16–18) with the initial conditions as in (19).

$$\mathbf{U}_k = \mathbf{\Gamma}_k \cdot \mathbf{\Phi}, \tag{15}$$

$$\mathbf{L}_{k-1} = \frac{\mathbf{P}_{k-1} \cdot \mathbf{\Gamma}_{k-1}^{\mathrm{T}}}{\lambda \cdot \mathbf{E} + \mathbf{\Gamma}_{k-1} \cdot \mathbf{P}_{k-1} \cdot \mathbf{\Gamma}_{k-1}^{\mathrm{T}}} \tag{16}$$

$$\mathbf{P}_k = \frac{\mathbf{P}_{k-1} - \mathbf{L}_{k-1} \cdot \mathbf{\Gamma}_{k-1}^{\mathrm{T}} \cdot \mathbf{P}_{k-1}}{\lambda} \tag{17}$$

$$\mathbf{\Phi}_k = \mathbf{\Phi}_{k-1} + \mathbf{L}_{k-1}(\mathbf{U}_{k-1} - \mathbf{\Gamma}_{k-1} \cdot \mathbf{\Phi}_{k-1}) \tag{18}$$

$$\mathbf{P}_0 = 10^5 \cdot \mathbf{E}, \ \mathbf{\Phi}_0 = 0 \cdot \mathbf{E} \tag{19}$$

where $\mathbf{U}_k$ is control, $\mathbf{\Gamma}_k$ is a matrix of the model's identification a system, $\mathbf{L}_k$ is a matrix of identification coefficients, $\mathbf{P}_k$ is a matrix of algorithm convergence estimates, $\mathbf{\Phi}_k$ is an estimation of model parameters, λ is an adaptation parameter, $\lambda = 0.95$, $\mathbf{E}$ is the identity matrix and k stands for individual iterations.

5. Simulation

To effectively identify the model parameters for a quadcopter, described in the previous chapter, it is necessary to perform such manoeuvres that would reveal all parameters. For this reason, a quite aggressive "eight-shape" manoeuvre was chosen. Figure 5 shows an example of the quadcopter's movement along the trajectory. The trajectory consisted of two parts. In the first part, during the 0.1 s the quadcopter did not move and remained at a given point. In the second part, the quadcopter performed manoeuvres.

The simulation results are presented in Figs. 6–11. The angular rotation speed of the i-th motor was limited to $150 < \omega_i < 500$, $i = 1, \ldots, 4$. The model parameters are:

$$M = 0.7 \ [\mathrm{kg}] \quad I_m = 10^{-3} \, [\mathrm{kg} \cdot \mathrm{m}^2] \quad g = 9.8 \ [\mathrm{m/s}^2]$$

$$k_1 = 7.426 \cdot 10^{-5} \, [\mathrm{kg} \cdot \mathrm{m}^2] \quad k_2 = 1.485 \cdot 10^{-5} \, [\mathrm{kg} \cdot \mathrm{m}]$$

$$\mathbf{I} = \begin{pmatrix} 0.0123 & -0.0012 & -0.0001 \\ -0.0012 & 0.0135 & -0.0002 \\ -0.0001 & -0.0002 & 0.0227 \end{pmatrix} [\mathrm{kg} \cdot \mathrm{m}^2]$$

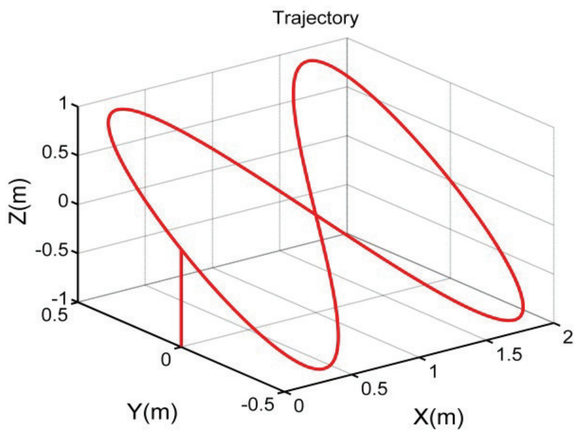

Fig. 5. The motion path of the quadcopter
Rys. 5. Trajektoria ruchu quadrocoptera

The identification of quadcopter's parameters for asymmetry of the construction is made when the robot is take-off. The hardest ones to identify are the deviation moments of inertia. This because the absolute value of these elements is several orders lower than the principal moments of inertia and their impact becomes insignificant in the quadcopter's movement. The maximum identification error of the mass and principal moments of inertia is less than 1%, and the modulus of the inertia metric is less than 5% (Figs. 6, 7).

Fig. 6. The error identification of the moment of inertia for z axis
Rys. 6. Identyfikacja błędu dla momentu bezwładności dla osi z

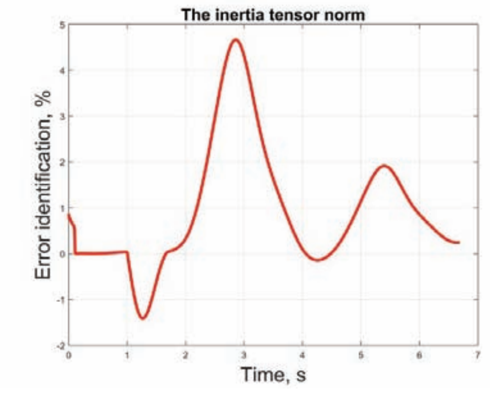

Fig. 7. The identification error of the moment of inertia tensor norm
Rys. 7. Identyfikacja błędu momentu bezwładności dla tensora momentu bezwładności

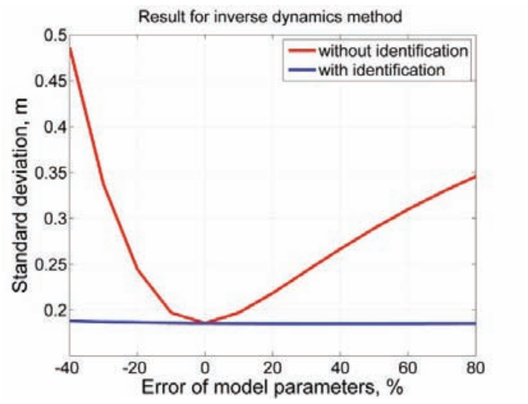

Fig. 8. The standard deviations of the error of the model parameters for the inverse dynamics method
Rys. 8. Odchylenia standardowe błędu parametrów modelu dla metody dynamiki odwrotnej

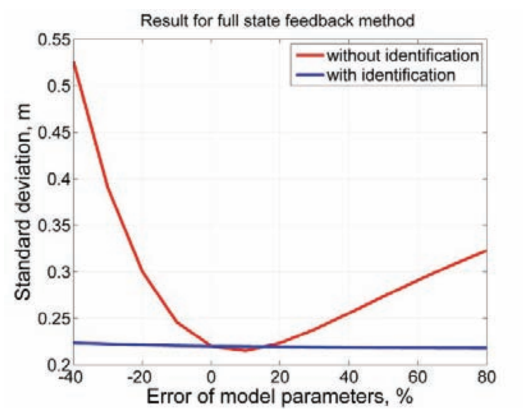

Fig. 9. The standard deviations of the error of the model parameters for a full state feedback method
Rys. 9. Standardowe odchylenia błędu parametrów modelu dla metody przesuwania biegunów

Simulations were performed to verify the effectiveness of the chosen control method. Figures 8 and 9 show the dependence of the model parameters' error on the standard deviation of the quadcopter's centre of mass along a given trajectory of movement. The results have been obtained for the inverse dynamics method. For the full state feedback method, the results are similar. Figures 8 and 9 show that the adaptive control method works effectively even for the range of the model parameters' errors between –40% and 80% without using additional special manoeuvres at the start.

Figures 10 and 11 show the dependence between the diagonal and the not diagonal elements of the convergence matrix **P**, respectively. Results are presented in absolute values of alogarithmic scale. For the remaining elements of the matrix **P** relationship is similar. Figures 10 and 11 confirm the reliability and performance of the identification algorithm.

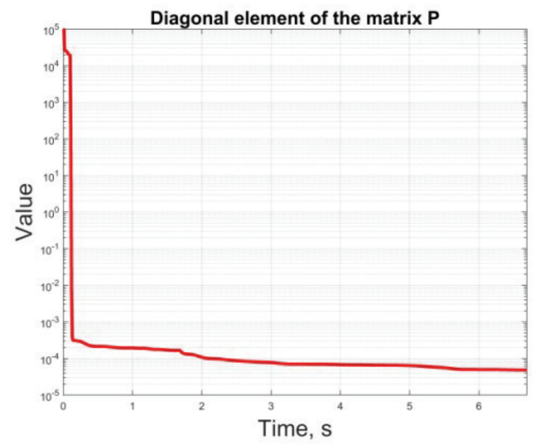

Fig. 10. The convergence of the identification algorithm for the diagonal element of the P matrix
Rys. 10. Zbieżność algorytmu identyfikacji dla elementu diagonalnego macierzy P

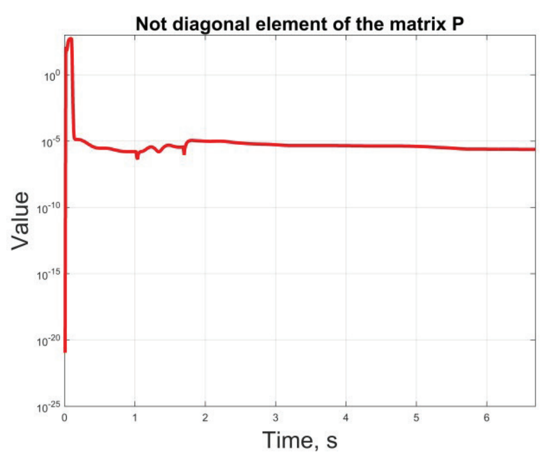

Fig. 11. The convergence of the identification algorithm for the non-diagonal element of the P matrix
Rys. 11. Zbieżność algorytmu identyfikacji dla elementu niediagonalnego macierzy P

6. Conclusions

In the paper, the problem of adaptive control quadcopter movement along the predetermined path was solved. For testing the control algorithm, an asymmetric quadcopter model was used. Recurrent adaptation method had been selected based on the inverse dynamics and full state feedback method. Both approaches have demonstrated their effectiveness and have approximately the same results. However, the inverse dynamics method performs best for aggressive manoeuvres. A full state feedback method, in turn, performs best at the initial stage of adaptation, when the parameters of the model are known with low accuracy or some parameter is unknown.

As simulation results show, an adaptive algorithm can significantly improve the quality of control and the standard deviation from the desired path. In the future, authors are planning the analyse of the impact of sensor errors on control efficiency.

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Opracowanie sterowania adaptacyjnego dla quadrocoptera asymetrycznego

Streszczenie: W pracy przedstawiono algorytm sterowania adaptacyjnego dla asymetrycznego quadrocoptera. W celu określenia sterowania zrealizowano identyfikację parametrów i przedstawiono algorytm identyfikacji w formie metody rekurencyjnej. Metoda sterowania realizowana jest z wykorzystaniem dynamiki odwrotnej, przesuwania biegunów oraz sterowania adaptacyjnego. Zaprezentowano algorytmy identyfikacji parametrów modelu quadrocoptera w trybie off-line i on-line. W artykule przedstawiono skuteczność wybranych algorytmów na przykładzie ruchu wzdłuż podanej trajektorii. Na zakończenie artykułu przedstawiono zalecenia dotyczące stosowania różnych metod sterowania.

Słowa kluczowe: quadrocopter, sterowanie adaptacyjne, odwrotna dynamika, przesuwanie biegunów, wiatr

Ryszard Beniak, DSc, PhD
r.beniak@po.edu.pl
ORCID: 0000-0002-9554-489X

Received the MSc. degree from the Opole University of Technology, Poland, and the PhD degree from Silesian University of Technology, Gliwice, Poland, in 1986 and 1993 respectively. In 2014 he became an associate professor at the Opole University of Technology. Professional interests concern: modelling and simulations of converter drives, identification methods, modelling and control of mobile robotic systems and modern methods for integration of ordinary differential equations.

Oleksandr Gudzenko, MSc
shurman_g@mail.ru
ORCID: 0000-0002-3914-9094

Received the MSc. degree in Applied Mathematics from National Technical University "Kharkiv Polytechnic Institute", Ukraine in 2010. He writes a octorate in Opole University of Technology, Polish. His research interests include nonlinear control, adaptive control, and system identification of unmanned aerial vehicles.