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V. P. SEVERIN, E. N. NIKULINA, V. S. BURIKOVSKIY

## DEVELOPMENT OF THE CONTROLLER FOR THE QUADCOPTER FINKEN IN SIMULATION ENVIRONMENT VREP

Задача керування квадрокоптером Finken, розробленого на кафедрі інтелектуальних систем університету Отто фон Геріке м. Магдебург, представлена. Описана та реалізована математична модель квадрокоптера у середовищі моделювання VRep. Розглянуті та проаналізовані принципи роботи ПІД регулятора. Описані та імплементовані моделі руху квадрокоптера. Створена модель ПІД регулятора для керування квадрокоптером у середовищі моделювання VRep. Забезпечено стійкий рух квадрокоптера під час польоту. Представлені перспективи використання розробленої моделі керування рухом квадрокоптера.

**Ключові слова:** квадрокоптер, регулятор, математична модель, керування рухом, стійкість, середа VRep.

Представлена задача управління квадрокоптером Finken, созданного на кафедре интеллектуальных систем университета Отто фон Герике г. Магдебург. Описана и реализована математическая модель квадрокоптера в среде моделирования VRep. Рассмотрены и проанализированы принципы работы ПИД регулятора. Описаны и имплементированы модели движения квадрокоптера. Разработана модель ПИД регулятора для управления квадрокоптером в среде моделирования VRep. Обеспечено устойчивое движение квадрокоптера в полете. Представлены перспективы использования разработанной модели управления движением квадрокоптера.

**Ключевые слова:** квадрокоптер, регулятор, математическая модель, управление движением, устойчивость, среда VRep.

The problem of control of quadcopter Finken, that was created at department of Intellectual systems at Otto von Guericke University Magdeburg, was presented. The simulation environment VRep as 3D robot simulator was reviewed. The general mathematical model of copter was presented and the model of quadcopter Finken was created in VRep simulation environment. The principles of working continue and discrete PID controllers were described and analyzed. The models of motion of quadcopter Finken were reviewed and implemented in simulation environment VRep. The model of recommended PD controller for quadcopter Finken was described and implemented. The test flights were done and the stable flying motion of quadcopter was received. The conclusions about possible use such a model was made.

**Keywords:** quadcopter, controller, mathematical model, control of motion, stability, environment VRep.

**Introduction.** A quadcopter is a multirotor helicopter that lifted and propelled by four rotors. It is operated by varying the spin RPM of its four rotors to controls lift and torque. The thrust from the rotors plays a key role in maneuvering and keeping the copter airborne, its small size and swift maneuverability enables the user to perform flying routines that include complex aerial maneuvers. But for conducting such maneuvers precise handling is fundamental to flying by following a user-defined complex trajectory-based path and also while performing any type of missions [1].

This paper presents a model of quadcopter Finken, which real model was created in OVGU University Magdeburg. The described model is a copy of real one, was created in a VRep simulation environment. In paper also described its controlling system, which is implemented as a proportional-integral-derivative (PID) controller.

**VRep simulation environment.** Environment VRep is a powerful 3D robot simulator, which features several versatile calculation modules like inverse kinematics, physics/dynamics, collision detections, minimum distance calculations, path planning and many more to pen. It supports a distributed control architecture, i.e. an unlimited number of threaded or non-threaded control scripts and several extension mechanisms which include plug-ins and custom client application [2]. In this paper the Lua script language is used in the control scripts to realize the desired functionality.

**Description of quadcopter.** The control parameters of quadcopter Finken are presented in Table 1 and in Figure 1. The quadcopter has to be able to react to the surrounding environment. Thus, it needs a sensing

mechanism. The quadcopter has proximity sonar sensors pointing in different directions (front, back, left, right). The sensors have the shape of a cone. The detection area has a range of 3 meters and an angle of 90°.

Table 1 – Control parameters of the quadcopter

Throttle	Propeller speed, usually height control
Pitch	Forward or backward inclination angle
Yaw	Sideways inclination angle, either left or right
Roll	Rotation of the quadcopter either clockwise or anti-clockwise

A sensor measures the distance to the nearest detected object. The detected object can be either a quadcopter, a wall or the floor. The exact direction of the detected object is not provided by the sensors. Only the approximate direction left, right, front or back is known depending on which sensor detects the object.

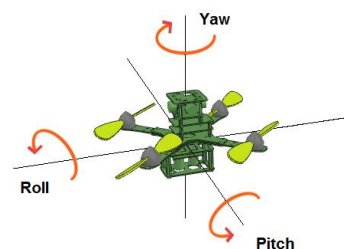


Figure 1 – Quadcopter angular parameters

**Mathematical model of quadcopter.** The angles and the structure of quadcopter Finken are presented in Figure 2 including the corresponding angular velocities, torques and forces, which are created by the four rotors (numbered from 1 to 4).

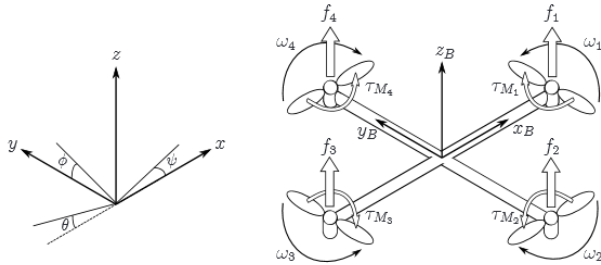


Figure 2 – The inertial and body frames of a quadcopter

The absolute linear position of the quadcopter is defined in the inertial frame axes  $x, y, z$  with  $\xi$ . The attitude, i.e. the angular position, is defined in the inertial frame with three Euler angles  $\eta$ . Pitch angle  $\theta$  determines the rotation of the quadcopter around the axis  $y$ . Roll angle  $\phi$  determines the rotation around the axis  $x$  and yaw angle  $\psi$  around the axis  $z$ . Vector  $q$  contains the linear and angular position vectors:

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, \quad q = \begin{bmatrix} \xi \\ \eta \end{bmatrix}.$$

The origin of the body frame is in the center of mass of the quadcopter. In the body frame the linear velocities are determined  $V_B$  by and the angular velocities by  $v$ :

$$V_B = \begin{bmatrix} v_{x,B} \\ v_{y,B} \\ v_{z,B} \end{bmatrix}, \quad v = \begin{bmatrix} p \\ q \\ r \end{bmatrix}.$$

The rotation matrix from the body frame to the inertial frame is

$$V_B = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix},$$

in which  $S_x = \sin x$  and  $C_x = \cos x$ .

The rotation matrix  $R$  is orthogonal thus  $R^{-1} = R^T$  which is the rotation matrix from the inertial frame to the body frame.

The transformation matrix for angular velocities from the inertial frame to the body frame is  $W_\eta$ , and from the body frame to the inertial frame is  $W_\eta^{-1}$ :

$$\dot{\eta} = W_\eta^{-1} v, \quad \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix},$$

$$v = W_\eta \dot{\eta}, \quad \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\phi & C_\theta S_\phi \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix},$$

in which  $T_x = \text{tg} x$ . The matrix  $W_\eta$  is invertible, if  $\theta \neq (2k-1)\pi/2, k \in Z$ . The quadcopter is assumed to have symmetric structure with the four arms aligned with the body  $x$  and  $y$  – axes. Thus, the inertia matrix is diagonal matrix  $I$  in which  $I_{xx} = I_{yy}$

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}.$$

The angular velocity of rotor  $i$ , denoted with  $\omega_i$ , creates force  $f_i$  in the direction of the rotor axis. The angular velocity and acceleration of the rotor also create torque  $\tau_{M_i}$  around the rotor axis:

$$f_i = k\omega_i^2, \quad \tau_{M_i} = b\omega_i^2 + I_M \dot{\omega}_i,$$

in which the lift constant is  $k$ , the drag constant is  $b$  and the inertia moment of the rotor is  $I_M$ . Usually the effect of  $\dot{\omega}_i$  is considered small and thus it is omitted.

The combined forces of rotors create thrust  $T$  in the direction of the body axis  $z$ . Torque  $\tau_B$  consists of the torques  $\tau_\phi, \tau_\theta$  and  $\tau_\psi$  in the direction of the corresponding body frame angles:

$$T = \sum_{i=1}^4 f_i = k \sum_{i=1}^4 \omega_i^2, \quad T^B = \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix},$$

$$\tau_B = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} lk(-\omega_2^2 + \omega_4^2) \\ lk(-\omega_1^2 + \omega_3^2) \\ \sum_{i=1}^4 \tau_{M_i} \end{bmatrix},$$

in which  $l$  is the distance between the rotor and the center of mass of the quadcopter. The roll movement is acquired by decreasing the 2nd rotor velocity and increasing the 4th rotor velocity. The pitch movement is acquired by decreasing the 1st rotor velocity and increasing the 3th rotor velocity. Yaw movement is acquired by increasing the angular velocities of two opposite rotors and decreasing the velocities of the other two [3].

To evaluate the Finken model simple movement patterns have been implemented. The different movement patterns are: landing motion of the quadcopter, horizontal movement always keeping the same height, circular movement and swing motion. The experiments show that manual control does not yield the required results. Same for a parameter which shall be kept constant at an exact value, which is physically impossible. This is called

steady-state-error. Therefore, it has been decided to control the quadcopter by a PID controller, which is able to compensate such problems.

**PID Controller.** Using only simple mathematical models to control a quadcopter does not work over time. There is the steady-state-error and inclinations, which do not follow a step function but are only performed gradually. The solution to this is to use a PID-controller which tries to minimize the error between set point and actual position [4].

Continues PD controller is presented in Figure 3.

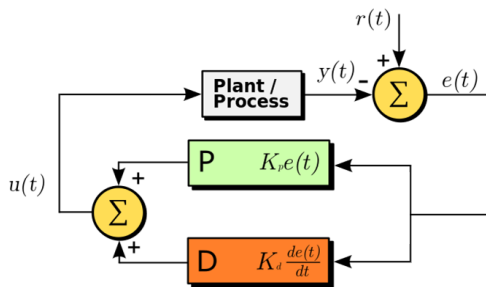


Figure 3 – Block diagram of a PD controller

In a control system, the parameter to be controlled is called the process variable  $y(t)$ . It is measured by a sensor and fed back to the control system. The desired value of the system is referred to as setpoint  $r(t)$ . The difference between setpoint and process variable  $e(t) = r(t) - y(t)$  is the error which is used to determine the actuator output to drive the system. A PID controller uses the error signal  $e(t)$  to compute the control signal  $u(t)$ . For this, derivative and integral of the error signal  $e(t)$  are needed. The control signal  $u(t)$  is computed as sum of following three coefficients [5]: the error signal multiplied by the proportional gain constant  $K_p$ ; the integral of the error multiplied by the integral gain constant  $K_i$ ; the derivative of the error multiplied by the derivative gain constant  $K_d$ . Model of PID controller is

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t).$$

In discrete case the integral of the error is calculated as sum over all previous errors and the derivative error as the difference of successive errors divided by timestep  $\Delta t$

$$u(t_k) = K_p e(t_k) + K_i \sum_{j=0}^k e(t_j) \Delta t + K_d \frac{e(t_k) - e(t_{k-1})}{\Delta t}.$$

To describe the effects of each component, some terminology has to be introduced. Most times, a step function is used to measure the response of the process variable. The time it takes to get from 10% to 90% of the final value is referred to as rise time. Overshoot is the percentual amount the process variable exceeds the final value. The time to settle to a value within a certain percentage in most cases 5% of the final value is called

settling time. Steady-state error is the final deviation of the process variable from the set point.

Changing the different components has different effect to the output function. The proportional component has the effect of reducing the rise time, but it will also increase the overshoot and it will never eliminate the steady-state error. The integral component can eliminate the steady-state error, but will also slow down the response time. The derivative component can reduce overshooting and improves the response and settling time. Hence, changes in one component have an effect to the other components which makes it difficult to find the right parameters for an unknown system.

It is not necessary to always have all components, sometimes only one or two components are used, e.g. only P, PI, PD or I. The controller is then named accordingly. In general, PD controller works as follows: the quadcopter shall move towards a given target position. Thus, the distance from the quadcopter to the target is given by the Euclidean distance between them. This distance is fed to the controller as the error which shall be minimized. The output is the desired parameter value and is applied to the quadcopter. For throttle, this is an acceleration, and for pitch and roll respectively, it is the desired angle. For calculating pitch and roll, only the distance in axis x and axis y between the quadcopter and target is needed. The height control is done using absolute height values. Because with relative coordinates the quadcopter's position would be the origin and practically, it's not possible to calculate the height. As a solution, a dedicated height sensor has been implemented to provide the distance to the floor as a sensor value. Using a PD-controller, the quadcopter reaches its target after some time and stays there until the target is changed.

**Controlling the copter.** The controller of the Finken only uses the proportional (P) and derivative (D) components. The integral component would calculate a cumulative error which is not appropriate and the Finken tries to compensate it and starts oscillating.

To find suitable parameters could be used Ziegler-Nichols or Chien-Chrones-Reswick methods. However, the P and D values have to be much smaller than proposed by these methods to guarantee a stable motion. Therefore, the values for P and D have been obtained experimentally. The output parameters of the PID controller have to be limited to a certain value such that the Finken does not destabilize. Pitch and roll are limited to the interval  $[-10^\circ, +10^\circ]$ . On the one hand, this ensures a stable flight and on the other hand, a relatively quick movement can be achieved. Throttle is limited to  $[0, 100]$ , which represents the technical constraints for throttle.

Such a model allows Finken to stable flying. The Finken can fly in all directions, make landing and flying up only by himself. The archived results are very satisfying. For further research, can be created a swarm motion of multiple quadcopters. Such motion can be also implemented in real for using in a cartography, scouting or research of motion swarm animals.

**Conclusion.** In this paper was briefly considered the simulation environment VRep. The real quadcopter Finken was described and the mathematical model of

quadcopter was considered. Also, was considered a simplest PID controller and the controller, which fits to described problem. The model of quadcopter was implemented and the necessary PID controller was also implemented. The test flies were made and on the ground of thus flies the parameters of whole model and also PID controller were adjusted. The stable motion of the quadcopter was achieved.

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#### Відомості про авторів / Сведения об авторах / About the Authors

**Северин Валерій Петрович** – доктор технічних наук, професор, Національний технічний університет «Харківський політехнічний інститут», професор кафедри системного аналізу та управління; м. Харків, Україна, тел.: (066) 847-83-70; e-mail: severinv@mail.ru.

**Северин Валерій Петрович** – доктор технических наук, профессор, Национальный технический университет «Харьковский политехнический институт», профессор кафедры системного анализа и управления; г. Харьков, Украина, тел.: (066) 847-83-70; e-mail: severinv@mail.ru.

**Severin Valeriy Petrovich** – Doctor of Technical Sciences, Professor, Professor, Department of Systems Analysis and Control of National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine; tel.: (066) 847-83-70; e-mail: severinv@mail.ru.

**Нікуліна Олена Миколаївна** – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри радіоелектроніка; м. Харків, Україна, тел.: (050) 100-79-65; e-mail: elena78\_02@inbox.ua.

**Никулина Елена Николаевна** – кандидат технических наук, доцент, Национальный технический университет «Харьковский политехнический институт», доцент кафедры радиоэлектроника; г. Харьков, Украина, тел.: (050) 100-79-65; e-mail: elena78\_02@inbox.ua.

**Nikulina Elena Nikolaevna** – Candidate of Technical Sciences (Ph. D.), Docent, Associate Professor, Department of Radioelectronica of National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine; tel.: (050) 100-79-65; e-mail: elena78\_02@inbox.ua.

**Буряковський Владислав Сергійович** – студент, Національний технічний університет «Харківський політехнічний інститут», кафедра радіоелектроніка; м. Харків, Україна, тел.: (093) 025-40-27; e-mail: vladislavbur@gmail.com.

**Буряковский Владислав Сергеевич** – студент, Национальный технический университет «Харьковский политехнический институт», кафедра радиоэлектроника; г. Харьков, Украина, тел.: (093) 025-40-27; e-mail: vladislavbur@gmail.com.

**Buriakovskiy Vladislav Serhiiovych** – student, National Technical University "Kharkov Polytechnic Institute", Department of Radioelectronica Kharkiv, Ukraine; tel.: (093) 025-40-27; e-mail: vladislavbur@gmail.com.