AUTOMATIC CONTROL SYSTEMS

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OPTIMIZATION OF STABILIZATION PROCESSES OF QUADROCOPTER FOR MARITIME TRAFFIC'S MONITORING

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Abstract—*Solution that improves quadrocopter's control processes automation on the basis of variable structure of robust-optimal system under conditions of dynamic model of quadrocopter and environment uncertainty is considered in the report.*

Index Terms—Quadrocopter; wind disturbance; optimal stabilization trajectories; robust circuit; variable structure of feedback; optimized PID-regulators.

I. INTRODUCTION

Increasing intensity of ship exploitation in navigable channels and limited water areas requires high safety level while performing various tasks in technological operation regimes. Analysis of accident rate statistics during exploitation of marine transport allows us to conclude that about a third of accidents occur due to influence of human factor. Usage of unmanned aerial vehicles (e.g., quadrocopters) for navigational safety monitoring and ecological control of marine environment would increase manoeuvring and position's informative estimation of movable objects. This could help optimize control decisions made by boatmasters, pilots and operators of maritime traffic when extreme situations appear. The quadrocopter functions under conditions of marine environment influence and should provide manoeuvring with specified control quality indicators determined by the requirements of visual camera monitoring.

II. PROBLEM REVIEW

Development of robust-optimal control systems for movable objects is based on robust-optimal methods which are formed mainly in S.V. Emelyanov (1997, 2007), V.M. Kuntsevich (1986, 2004, 2016), A.B. Kurzhanskij (1977, 2013), I. Horowitz (1972, 2001), B.T. Poljak (2002, 2015) and other scientist's articles. Development of quadrocopter's control methods, including ship service and monitoring of marine environment, are described in articles by A.A. Tunik (2015, 2016), J.P. Ostrowski (2003, 2005), P. Castillo (2005), T. Fossen (2014, 2015) and other scientists.

In these papers problems of robust-optimal control systems design [1] and synthesis of effective PD, PID regulators were solved. Problem of quadrocopter stabilization in the functioning operating mode or during driving by the predetermined path involves creation of efficient and physically realizable applied control algorithms. There are some known approaches for feedback control [2] – [3]: stabilization of dynamic system motion by static feedback based on the usage of linear matrix inequalities; build a limited feedback and provide additional properties of transient processes; stabilization on basis of quantitative feedback theory and other approaches.

III. PROBLEM STATEMENT

Control of the quadrocopter (Fig. 1) for marine environment's monitoring requires optimal (in terms of energy consumption) control algorithms formation, together with limited power resource conditions. At the same time, the control problem is complicated by the need of taking into account stochastic nature of uncontrolled wind disturbance which is typical for agitated sea surface.

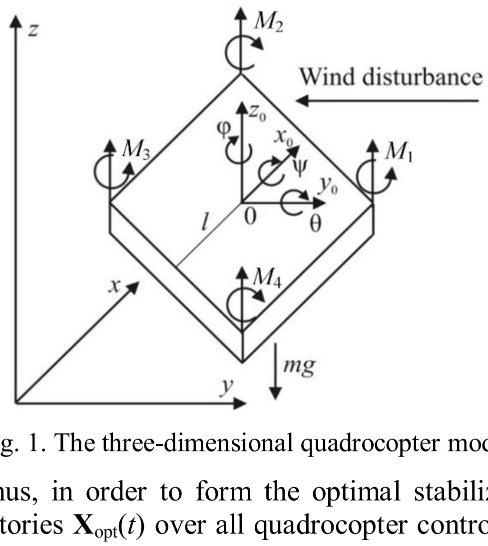

Fig. 1. The three-dimensional quadrocopter model

Thus, in order to form the optimal stabilization trajectories $\mathbf{X}_{\text{opt}}(t)$ over all quadrocopter controllable coordinates, an optimal criterion is set for minimum energy consumption

$$J = \int_0^T Q(\mathbf{X},\mathbf{U})dt = \min, \qquad (1)$$

where $Q(\mathbf{X},\mathbf{U})$ is the functional of energy consumption; **X** is the coordinates vector; **U** is the control vector; T is the time of control.

Requirements for the vector of control errors $\mathbf{E}(t)$, which arises from uncertain operating conditions of the quadrocopter, are set as

$$\ddot{\mathbf{E}}(t) + \mathbf{G}_1\dot{\mathbf{E}}(t) + \mathbf{G}_2\mathbf{E}(t) = 0\,, \qquad (2)$$

where $\mathbf{G}_1$, $\mathbf{G}_2$ are matrices of the weighting coefficients.

IV. Problem Solution

The quadrocopter's dynamics is described by the system with six differential equations of second order [4] – [7] and is considered in the field of wind disturbance. Because of the full description's complexity of wind disturbance's physical effect on the quadrocopter and in accordance with [8], the following types of disturbances are confined: high-frequency alternating effect; low-frequency piecewise constant effect with components in horizontal (constant wind) and vertical planes (ascending or descending flow). Taking into account the active wind disturbance, motion of the quadrocopter can be described by the system of the following differential equations [4].

$$\begin{cases} \ddot{x} = \left[\left(\sum_{j=1}^{4} F_j\right)(\cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi) - a_1\dot{x}^2 - c_1 f_x\right]/\,m; \\ \ddot{y} = \left[\left(\sum_{j=1}^{4} F_j\right)(\sin\varphi\sin\theta\cos\psi + \cos\varphi\sin\psi) - a_2\dot{y}^2 - c_2 f_y\right]/\,m; \\ \ddot{z} = \left[\left(\sum_{j=1}^{4} F_j\right)\cos\theta\cos\psi - F_g - a_3\dot{z}^2 - c_3 f_z\right]/\,m; \\ \ddot{\theta} = l\left(-F_1 - F_2 + F_3 + F_4 - a_4\dot{\theta}^2 - c_4 f_\theta\right)/\,J_1; \\ \ddot{\psi} = l\left(-F_1 + F_2 + F_3 - F_4 - a_5\dot{\psi}^2 - c_5 f_\psi\right)/\,J_2; \\ \ddot{\varphi} = c\left(F_1 - F_2 + F_3 - F_4 - a_6\dot{\varphi}^2 - c_6 f_\varphi\right)/\,J_3, \end{cases} \qquad (3)$$

where m is the mass of the quadrocopter; x, y, z are longitudinal, transverse and vertical coordinates; φ, ψ, θ are angles of yaw, roll and pitch; F_j are components of the lifting force's vector of each rotor; F_g is the gravity force; $f_x, f_y, f_z, f_\theta, f_\psi, f_\varphi$ are wind disturbance components; J_1, J_2, J_3 are moments of inertia with respect to the longitudinal, transverse and vertical axes; l is the distance from a rotor to the center of mass; c is the yaw's moment scalar coefficient; a_i, c_i are quadrocopter's model parameters.

Known relations are set the interdependence between lifting forces of rotors and control components as [5]

$$\begin{aligned} U_1 &= F_1 + F_2 + F_3 + F_4;\, U_2 = -F_1 - F_2 + F_3 + F_4, \\ U_3 &= -F_1 + F_2 + F_3 - F_4;\, U_4 = F_1 - F_2 + F_3 - F_4. \end{aligned} \qquad (4)$$

Systems (3), (4) for the quadrocopter's model in the form of vector-matrix equation, can be written as

$$\dot{\mathbf{X}}(t) = \mathbf{A_X}\mathbf{X}(t) + \mathbf{B_X}\mathbf{U}(t) + \mathbf{Cf}(t) - \mathbf{g}, \qquad (5)$$

where **X** is the state coordinates vector (6×1); $\mathbf{A_X}$ is the matrix (6×6) of quadrocopter's parameters that depends on the coordinates; $\mathbf{B_X}$ is the matrix (6×4) of control parameters that depends on the coordinates; **U** is the control vector (4×1); **C** is the coefficient matrix (6×6); $\mathbf{f}(t)$ is the vector (6×1) of the wind disturbance; **g** is the vector (6×1) with the gravity acceleration component.

It was assumed that the influence of uncontrolled wind disturbance would be compensated in the corrective robust control's channel. It should be noted that the arrangement of quadrocopter's rotors does not provide the possibility of forming optimal (program) trajectories along all controlled coordinates, because for complete controllability of the quadrocopter the controllability criterion [9] should be rank **B** = 6. One way to solve the problem of incomplete controllability of the system (5) is to isolate the leading coordinates (for which optimal control is formed) and the driven coordinates (controlled by the PID regulators [5]). Such division depends on the required functional tasks.

The transition of dynamic object from the initial segment to the predefined trajectory segment, taking into account the requirements of physical realizability of control, is described by the following equations for state coordinates vector

$$\mathbf{X}(t_i^s) = \mathbf{X}(t_{i-1}^s) + ... \pm \overset{(k)}{\mathbf{X}}(t_{i-1}^s)\frac{(t_i^s - t_{i-1}^s)^k}{k!}, \qquad (6)$$

where t_i^s are switching moments of control on ith segment of trajectory; k is the higher derivative's order.

Further forming of motion`s equations in the form (6) with the given boundary conditions for the quadrocopter's coordinates, using the expression for the control functions, stabilization process of quadrocopter in the given operating area, is provided. For the given boundary conditions and derivative's values of the object's coordinate vector defined within the constraints of the form (5) and based on the results of solving algebraic equations system (6) algorithms have been developed [10] – [11]. The trajectories, for the given boundary conditions, will be optimal (1) while object moves with minimum possible number of minimum possible values of coordinates vector's derivatives, considering restrictions on controlling action

$$\min_k \min_{\overset{(k)}{\mathbf{X}}(t_0)} \left\{ \dot{\mathbf{X}}[\overset{(k)}{\mathbf{X}}(t_0), t] \right\}.$$

To provide motion on the given segments of stabilization trajectory, the relevant controlling functions, using the differential transformation [10] of (5) with respect, for example, to the zero third derivative $\dddot{\mathbf{X}}(t) = 0$ of quadrocopter's coordinates vector and taking into account the requirements for physical realizability of controlling forces, are determined. It allows to form equations of force's (moment's) balance for second derivatives as

$$\mathbf{A_X}\ddot{\mathbf{X}}(t) + 2\dot{\mathbf{A}}_\mathbf{X}\dot{\mathbf{X}}(t) + \ddot{\mathbf{A}}_\mathbf{X}\mathbf{X}(t) + \mathbf{B_X}\ddot{\mathbf{U}}(t) + \dot{\mathbf{B}}_\mathbf{X}\dot{\mathbf{U}}(t) + \ddot{\mathbf{B}}_\mathbf{X}\mathbf{U}(t) = 0. \qquad (7)$$

After the vector-matrix transformations of (7) it can be written in the form that determines the vector of control actions and provides the movement of the quadrocopter along the optimal trajectories as

$$\begin{aligned}&\mathbf{B_X}\ddot{\mathbf{U}}(t) + (\mathbf{A_X}\mathbf{B_X} + 2\dot{\mathbf{B}}_\mathbf{X})\dot{\mathbf{U}}(t)\\ &+(\mathbf{A}_\mathbf{X}^2\mathbf{B_X} + 2\dot{\mathbf{A}}_\mathbf{X}\mathbf{B_X} + \mathbf{A_X}\dot{\mathbf{B}}_\mathbf{X} + \ddot{\mathbf{B}}_\mathbf{X})\mathbf{U}(t)\\ &= -(\mathbf{A}_\mathbf{X}^3 + 2\dot{\mathbf{A}}_\mathbf{X}\mathbf{A_X} + \mathbf{A_X}\dot{\mathbf{A}}_\mathbf{X} + \ddot{\mathbf{A}}_\mathbf{X})\mathbf{X}(t)\\ &+ (\mathbf{A}_\mathbf{X}^2 + 2\dot{\mathbf{A}}_\mathbf{X})\mathbf{g}.\end{aligned} \qquad (8)$$

Switching moments t_i^s of control functions (8) are static points, for which final values of the state variables for the ith segment of the trajectory determine jointly with the new value of the higher derivative of the coordinate are initial values of the (i+1)th segment of the trajectory.

Necessary initial values of the control functions $\mathbf{U}(t_i^s)$, $\dot{\mathbf{U}}(t_i^s)$, that provides quadrocopter's movement with the given initial conditions $\mathbf{X}(t_i^s), \dot{\mathbf{X}}(t_i^s), \ddot{\mathbf{X}}(t_i^s)$ by the corresponding segment of the trajectory, are obtained from the following algebraic equations

$$\begin{aligned}&\mathbf{U}(t_i^s) = \mathbf{B}_\mathbf{X}^{-1}[\dot{\mathbf{X}}(t_i^s) - \mathbf{A_X}\mathbf{X}(t_i^s) + \mathbf{g}],\\ &\dot{\mathbf{U}}(t_i^s) = \mathbf{B}_\mathbf{X}^{-1}[\ddot{\mathbf{X}}(t_i^s) - \mathbf{A_X}\dot{\mathbf{X}}(t_i^s) - \dot{\mathbf{A}}_\mathbf{X}\mathbf{X}(t_i^s) - \dot{\mathbf{B}}_\mathbf{X}\mathbf{U}(t_i^s)].\end{aligned} \qquad (9)$$

A. Syntesis of Robust Control

Solution of the robust control's problem of the quadrocopter, under conditions of uncertainty, is based on usage of the system with variable structure of feedback, which forms reference model for the object's motion. Control signal from the reference model sums with correction signal from the robust control circuit (that generated by comparing output signal from the reference model with output of the controlled object) and goes to the input of physical quadrocopter.

The proposed approach for permissible simplification of the robust correction control synthesis assumes linearization of the dynamics equations near nominal values of parameters in order to apply superposition principle for the resulting linear equations. In this case, optimal control and trajectories should be formed by taking into account nonlinearity of the model and the discrepancy that arose from linearization should be attributed to additional uncertainty that requires control correction. The differential equation of the physical quadrocopter (5) that includes the wind disturbance and uses the robust circuit, takes the form

$$\dot{\mathbf{X}}(t) = \mathbf{A}^*\mathbf{X}(t) + \mathbf{B}^*[\mathbf{U}_m(t) + \mathbf{U}_r(t)] + \mathbf{Cf}(t) - \mathbf{g}, \qquad (10)$$

where $\mathbf{A}^*$, $\mathbf{B}^*$ are matrices of linearized coefficients; $\mathbf{U}_m(t)$, $\mathbf{U}_r(t)$ is the vector of the optimal and robust control.

Equation (5) for the quadrocopter's reference model takes form

$$\dot{\mathbf{X}}_m(t) = \mathbf{A}^*\mathbf{X}_m(t) + \mathbf{B}^*\mathbf{U}_m(t). \qquad (11)$$

For determining the correction signal, based on (10) and (11), the approximate expression for the vector of control errors $\mathbf{E}(t)$ can be written in the form

$$\dot{\mathbf{E}}(t) \approx \mathbf{A}^*\mathbf{E}(t) - \mathbf{B}^*\mathbf{U}_r(t). \qquad (12)$$

Based on (2) and (12), the dependence of the correction robust signal $\mathbf{U}_r(t)$ on deviation of the system can be obtained as

$$\mathbf{B}^*\dot{\mathbf{U}}_r(t)+\left(\mathbf{G}_1+\mathbf{A}^*\right)\mathbf{B}^*\mathbf{U}_r(t) =\left[\left(\mathbf{A}^*\right)^2+\mathbf{G}_1\mathbf{A}^*+\mathbf{G}_2\right]\mathbf{E}(t). \quad (13)$$

$$\mathbf{A}^*=\begin{vmatrix} -0.2 & -0.06 & 0 & 0 & 0 & 0\\ -0.06 & -0.2 & 0 & 0 & 0 & 0\\ 0 & 0 & -1 & 0 & 0 & 0\\ 0 & 0 & 0 & -50 & 0 & 0\\ 0 & 0 & 0 & 0 & -50 & 0\\ 0 & 0 & 0 & 0 & 0 & -25 \end{vmatrix};$$

The functional task of surface monitoring of marine area determines the high-precision stabilization of the quadrocopter in the horizontal plane along the leading controllable coordinates $\overline{\mathbf{X}}(t)=\left|x(t)\quad y(t)\right|^{\mathrm{T}}$. To simplify the problem of synthesizing quadrocopter's control system, control principle for the driven coordinates z, θ, ψ, φ based on the optimized PID-regulators was used. The quadrocopter's control process modelling (Fig. 2, where CAVCU is the current angular values conversion unit; CSFU is the correction signal forming unit; SCU is the switch control unit; SW is the switch; $\overline{W}_k$ is the transmission function, described by (13); $\eta(t)$ is the parametric noise) was based on equations (8) and (9) with ± 15% parameters mismatch between the reference model and the physical model. The influence of the wind piecewise constant effect and the high-frequency component, formed by the white noise of the given intensity, were taken into account.

B. Modelling Results

The simulation process of the physical quadrocopter's motion, described by (10), was considered with usage of the following matrices (matrix **A*** is linearized).

$$\mathbf{B}_{\mathbf{x}}=\begin{vmatrix} \theta+\varphi\cdot\psi & 0 & 0 & 0\\ \varphi\cdot\theta-\psi & 0 & 0 & 0\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1 \end{vmatrix}.$$

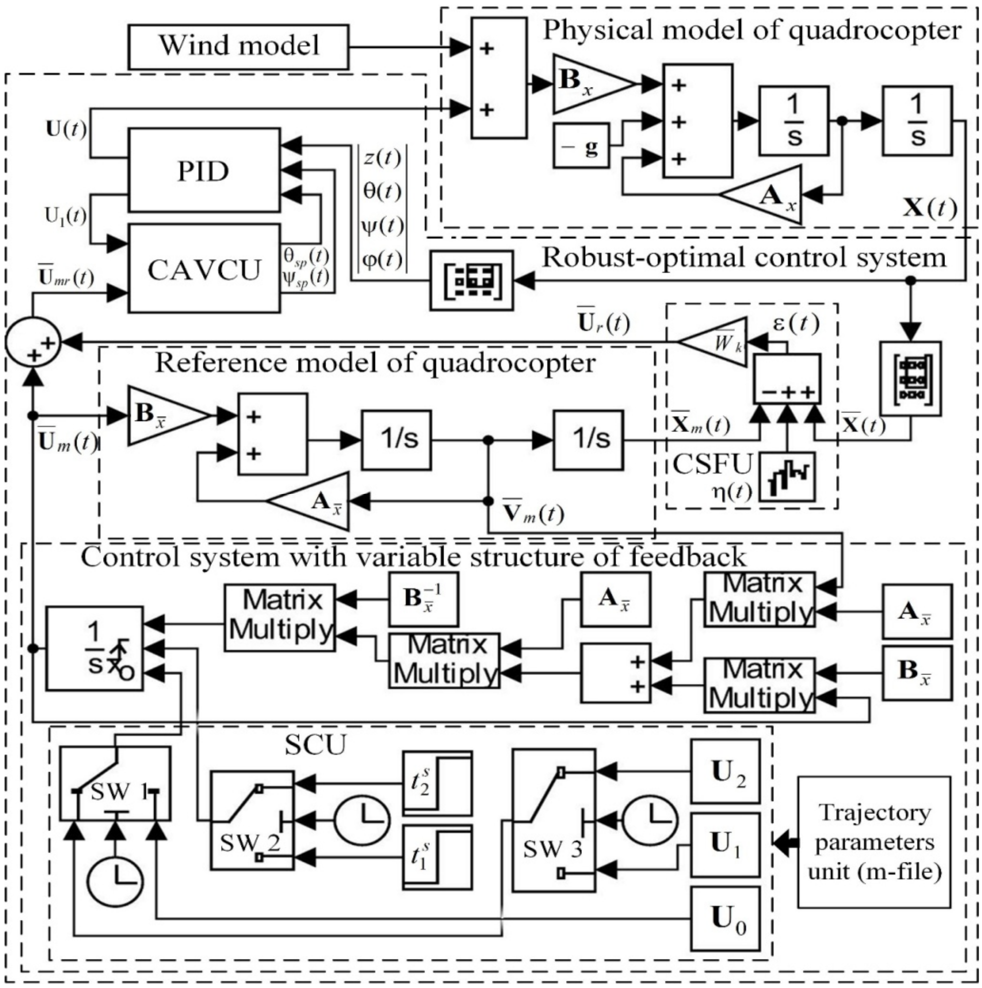

Fig. 2. Structure scheme of the robust-optimal control system

In the "CAVCU", setpoint values $\theta_{sp}(t)$ and $\psi_{sp}(t)$ for relevant PIDs are continuously (on each time step) calculated. Input for "CAVCU" are: control signal of z coordinate U_1 taken from "PID" and vector of robust optimal control $\overline{\mathbf{U}}_{mr}$. Optimal system with minimal energy consumption and in which optimal trajectories of leading coordinates and robust optimal control $\overline{\mathbf{U}}_{mr}$ are calculated, taking into account the necessity to fulfill the given boundary conditions and the given time of the transient process of quadrocopter's stabilization, is realized in the "Control system with variable structure of feedback". In "CSFU" deviation of the leading coordinates from the given optimal trajectory due to the action of the wind disturbance is compensated, – additional robust signal is formed. Process of correction is performed on each time step of quadrocopter's movement. Driven coordinates are corrected by "PID", while leading coordinated – by robust control system of quadrocopter. The boundary conditions were defined as: $\overline{\mathbf{X}}(0)=|0\,0|^{\mathrm{T}}$, $\dot{\overline{\mathbf{X}}}(0)=|0\,0|^{\mathrm{T}}$, $\ddot{\overline{\mathbf{X}}}(0)=|0.2\,0.2|^{\mathrm{T}}$, $\overline{\mathbf{X}}(T)=|10\,20|^{\mathrm{T}}$, $\dot{\overline{\mathbf{X}}}(T)=|1\,0.5|^{\mathrm{T}}$, $z(0) = 0$, $z(T) = 10$, $\varphi(t) = 0$; $\theta(t)$, $\psi(t)$ are small values, calculated from the given parameters of translational motion [5]. The trajectories, with respect to the coordinates x and y, for their third zero derivative $\dddot{x}(t)$ and $\dddot{y}(t)$, were formed. The simulation results of the quadrocopter's stabilization (Figs 3 and 4) demonstrate sufficiently small values of the control errors (Fig. 5).

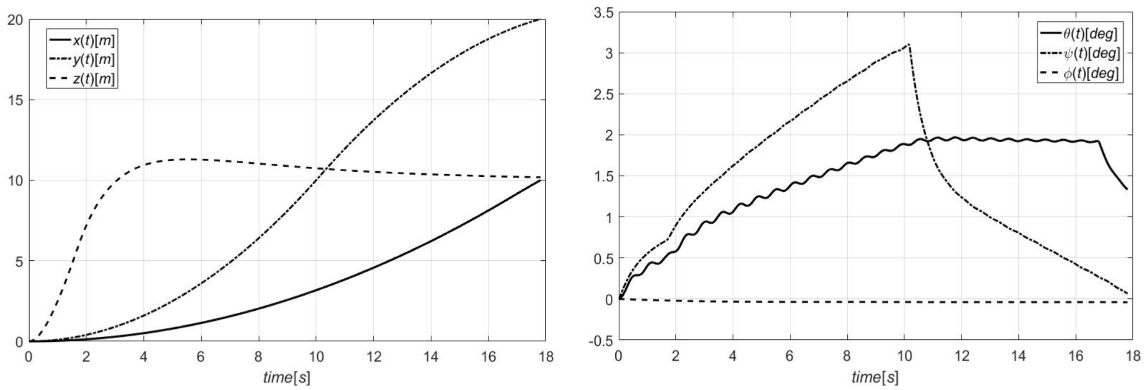

Fig. 3. Trajectories of controlled coordinates

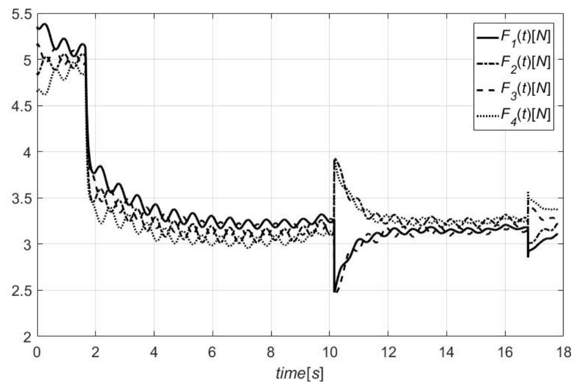

Fig. 4. Trajectories of lifting forces

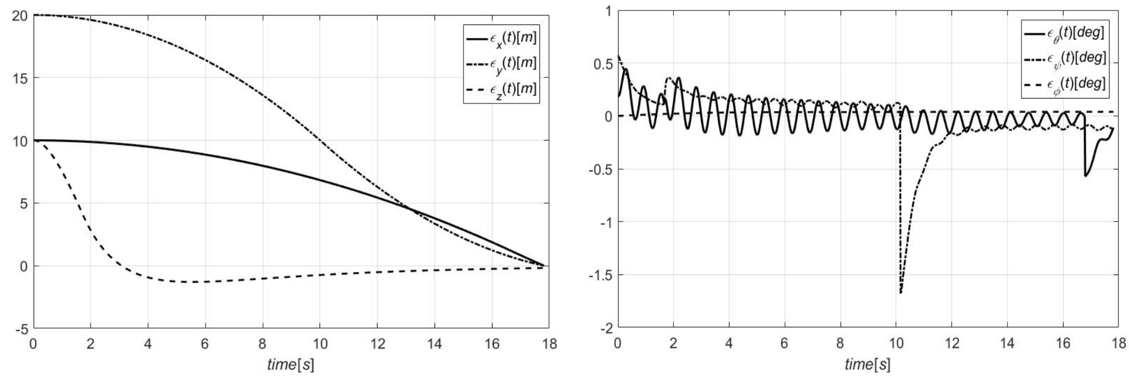

Fig. 5. Errors of controlled coordinates

V. CONCLUSIONS

The synthesis procedure of the quadrocopter's control has been proposed based on the system with variable structure of feedbacks and optimal criterion for minimum energy consumption. The required level of control invariance in conditions of incomplete informational content of the quadrocopter due to insufficient apriori information on an object parameters, parametric noises and action of uncontrolled external disturbances has been provided by robust correcting control holding the stabilization trajectory of the quadrocopter with the required accuracy in the vicinity of formed optimal trajectory. The required level of invariance to external uncontrollable disturbance and model uncertainty has been achieved. The modelling examples demonstrate the effectiveness of the approach in terms of minimum values of control's errors.

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В. Л. Тимченко, Д. О. Лебедєв. Оптимізація процесів стабілізації квадрокоптера для моніторингу морського трафіку

Представлено розв'язання задачі автоматизації процесів керування квадрокоптером на основі робастно-оптимальних систем змінної структури в умовах невизначеності та нелінійності параметрів моделі квадрокоптера і навколишнього середовища.

Ключові слова: квадрокоптер; вітрове збурення; оптимальні траєкторії стабілізації; робастний контур; змінна структура зворотних зв'язків; оптимізовані ПІД-регулятори.

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В. Л. Тимченко, Д. О. Лебедев. Оптимизация процессов стабилизации квадрокоптера для мониторинга морского трафика

Представлено решение задачи автоматизации процессов управления квадрокоптером на основе робаст-но-оптимальных систем переменной структуры в условиях неопределенности и нелинейности и параметров модели квадрокоптера и окружающей среды.

Ключевые слова: квадрокоптер; ветровое возмущение; оптимальные траектории стабилизации; робастный контур; переменная структура обратных связей; оптимизированные ПИД-регуляторы.

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