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# SYNTHESIS OF A REGULATOR FOR UAV MOTION CONTROL SYSTEM UNDER UNCERTAINTY

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***Abstract***—*This article represents the study of uncertainties inherent in motion control systems for unmanned aerial vehicles. Both external and internal disturbances acting on moving objects are considered. Expressions for the turbulent wind are given. The analysis of structured and non-structured uncertainties is presented. Results of studying different types of regulators are given, including PID regulators, LQR regulators, robust regulators, and regulators based on non-linear approaches and artificial intelligence methods. The procedure of H infinity synthesis is described. The block diagram of the conversion a continuous regulator in discrete one is represented. The comparative analysis of application LQR and H infinity regulators in loops of tracking by a given trajectory for conditions of the normal and disturbed atmosphere is given. The appropriate graphical dependencies are shown. The obtained results can be useful for aerial objects of a wide class.*

**Keywords**—Motion control system; uncertainties; turbulent wind; regulators; robust structural synthesis; tracking trajectory.

## I. INTRODUCTION AND PROBLEM STATEMENT

Nowadays, unmanned aerial vehicles (UAVs) are widely used in both civil and military applications. The basic features of UAVs’ usage are uncertainties in both the design and operation of these moving vehicles. Therefore, the research on designing motion control systems in conditions of uncertainty is of great importance.

Taking into consideration these features, it is possible to improve performances of UAV motion control systems and to increase flight safety. The increased accuracy of tracking trajectory and altitude stabilization ensure successful implementation of the flight mission.

The main goal of the article is to analyse uncertainties inherent in designing UAV regulators. The external disturbances in the form of the turbulent wind are analysed. A review of internal disturbances has been done. The possible types of regulators are analysed, and the choice of the robust control is grounded.

## II.REVIEW OF PUBLICATIONS

The comparative analysis of PID regulator applications in automation systems is presented in the article [1]. The possibility of improving the quality of PID regulators is considered in the paper [2]. In this publication, the PID regulator is supplemented by the FIR (finite impulse response) filter. Coefficients of the filter were determined using the genetic algorithm. An approach to the design of a linear quadratic regulator for robots is described in the article [3].

The full description and analysis of motion control systems with feedback, including robust approaches, is given in the textbook [4]. The solution of the problem that deals with the synthesis of the robust inertially stabilized platform based on $H_2/H_\infty$ approach is presented in the article [5]. The $H_\infty$ synthesis (robust structural synthesis) of the robust regulator for the same object is given in the articles [6], [7]. The article [6] deals with designing the two-degree-of-freedom robust controller based on the mixed sensitivity approach and loop-shaping. The approach to the multi-criteria synthesis of the robust multi-dimensional system is given in the article [8]. The improvement of the mathematical description for the synthesis of robust systems is represented in the article [9]. In this article, uncertainties during $H_\infty$ synthesis are studied. The image distortion effect is taken into consideration.

The non-linear regulator based on an adaptive approach is represented in the paper [10]. In the article [11], the described position controller is characterized by specific functions that ensure low-speed positioning with a given speed, as well as tuned, accurate positioning with a definite rate curvature. An approach to the synthesis of a robust controller for the mechanized robot based on fuzzy logic is represented in [12]. In the paper [13], a new approach to the synthesis of automatic control systems by artificial intelligence methods is proposed. In this paper, an automatic way of determining plant dynamics, reference signals, and expected disturbances is described. The procedure for the synthesis of an optimal neural-network controller is proposed.

## III. ANALYSIS OF UNCERTAINTIES

### *A. External Disturbances*

Real UAV flight conditions are characterized by atmospheric disturbances, primarily stochastic turbulent wind. The tasks of creating UAV control systems require the use of external disturbance models, for example, the standardized Dryden turbulent wind models [14]. For such models, the parameters are determined experimentally across different flight modes (cruising, landing). Therefore, when modelling UAV flight control systems in a turbulent atmosphere, the use of such models is a mandatory stage of their analytical design.

Dryden models are analytical expressions of the spectral densities of stochastically disturbed linear and angular velocities and aerodynamic flight angles. During modelling, the task of solving such stochastic disturbances is carried out using forming filters. White noise with a unit spectral density enters the filter input. The filter output signal is a "colored" noise with a spectral density determined by the Dryden model. For example, the models of turbulent lateral wind speed (or slip angle) and yaw angular velocity can be represented by the following transfer functions

$$H_v(s)=\frac{\sigma_v\sqrt{\frac{1}{\pi}\cdot\frac{L_v}{V}}\left(1+a_1s+a_2s^2\right)}{1+b_1s+b_2s^2+b_3s^3},\qquad(1)$$

where $a_1=2.7478\left(L_v/V\right)$, $a_2=0.3398\left(L_v/V\right)^2$, $b_1=2.9958\left(L_v/V\right)$, $b_2=1.9754\left(L_v/V\right)^2$, $b_3=0.1539\left(L_v/V\right)^3$.

$$H_r(s)=\frac{\frac{s}{V}}{1+\left(3\mathrm{b}/\pi V\right)s}H_v(s),\qquad(2)$$

where $L_v$ is the turbulence scale; $V$ is the aircraft's constant speed; $\sigma_v$ is the root-mean-square deviation of the lateral velocity component; $b$ is the aircraft's wingspan.

Models (1), (2) can also be represented as state-space models. The parameters $L_v$ and $\sigma_v$ are determined depending on the flight altitude and the state of the atmosphere. If the UAV state model contains the slip angle $\beta_g$ instead $v_g$, the numerator of expression (1) should be divided by $V$, and the numerator of expression (2) must be multiplied by $V$.

### *B. Internal Disturbances*

Uncertainties of models of linear stationary systems are divided into structured (parametric) and unstructured (unmodeled dynamics). Accordingly, to take into account these uncertainties, variations of the system matrix or the inclusion of some additional fractional-linear link in the feedback of the system can be used.

The uncertainty of the mathematical description of the synthesized system has many sources, in particular:

*1)* errors in determining the parameters of the linear model;

*2)* unaccounted for nonlinearities and changes in operating conditions;

*3)* unaccounted-for time delays and energy dissipation processes;

*4)* imperfection of measuring devices;

*5)* the use of reduced models to simplify the synthesis procedure;

*6)* impossibility to take into account the peculiarities of the dynamics of the model's functioning processes at high frequencies;

*7)* reduction of the regulator order and inaccuracy of its implementation.

The above-mentioned sources of uncertainty in the mathematical description of the model can be divided into three groups [15]:

*1)* parametric or structured uncertainties, when the parameters of the model with a certain structure and order vary in some given parameter space;

*2)* uncertainties of caused by unmodeled dynamics, usually at high frequencies, and the uncertainty of individual physical processes;

*3)* concentrated or unstructured uncertainties, caused by parametric uncertainty and unmodeled dynamics, combined into a single concentrated disturbance of a predetermined structure. The exact nature of this disturbance may be unknown, but they must be bounded.

Parametric uncertainty is defined for a set of parameters limited by some boundaries $[p_{\min}, p_{\max}]$. In this case, the set of parameters can be described by the expression [15]

$$p = p_{av}(1 + r\Delta),$$

where $p_{av}$ is an average value of a parameter; $r = \dfrac{p_{\max} - p_{\min}}{p_{\max} + p_{\min}}$; $|\Delta| \le 1$.

For $\Delta = 1$, the value of a parameter $p$ will be maximum, and for $\Delta = -1$ – minimum.

It should be noted that the mathematical description of parametric uncertainties for real systems is significantly complicated by the presence of a large number of uncertain parameters. To create such a description, it is necessary to have a model with a clearly defined structure. Usually, such a model does not take into account unmodeled dynamics. Therefore, it is advisable to perform an assessment of the robustness of such a system taking into account unstructured uncertainties after the completion of the parametric optimization process.

Unaccounted and unmodeled dynamics are more difficult to mathematically represent and usually it is necessary to use the frequency domain for the solution of the synthesis problem. The disturbance $\Delta$ is believed to be normalized by $\mathrm{H}_\infty$ norm. This means that the condition $\|\Delta\|_\infty \le 1$ must be carried out. In this case, we can write

$$\|\Delta\|_\infty = \sup_{\omega} |\Delta(j\omega)|.$$

## IV. ANALYSIS OF REGULATORS

The wide application of UAVs requires research of the motion control systems. It is necessary to take into consideration that the UAV's flight is implemented under conditions of intense turbulence; therefore, stabilizing the UAV’s attitude and altitude is of great importance.

The simplest way to solve this problem is to use PID regulators [1], [2]. The essential disadvantage of such an approach is the necessity of tuning the PID regulator. This is a labor-intensive and time-consuming computational procedure. Some heuristic methods can improve this procedure. For example, the Ziegler–Nichols method is based on the analysis of transient process indices, gain, and period of oscillations. Regulator tuning can be automated using MATLAB software, including Simulink Toolbox and the embedded programming language. The advantages of PID regulators are simplicity and clarity.

The concept of the PID regulator includes the possibility of using P, PI, PD, and PID regulators.

In designing UAVs, PI and PD controllers are used much more frequently, as P controllers are unable to provide the required suppression of low-frequency disturbances. PID controllers, on the other hand, demonstrate the best quality of low-frequency interference compensation, but are prone to oscillations when the control action is applied. Furthermore, when using them, it is necessary to consider the specific features of real-world systems, particularly the presence of resonances.

In general, PID controllers require improvement by additional means, for example, digital filters [2]. Nevertheless, the scientifically grounded solution of complex problems requires using optimization approaches to design regulators for automatic control systems. One of the most well-known methods is the so-called linear quadratic problem. In this case, it is possible to ensure definite advantages in the quality, first of all, accuracy.

LQR method determines the matrix of fixed feedback gain coefficients *K*. Consider a linear control object with dynamics described by the equations in the space of states [3], [4]

$$\begin{aligned} \dot{x}(t) &= \mathbf{A}(t)x(t) + \mathbf{B}(t)u(t), \\ y(t) &= \mathbf{C}(t)x(t) + \mathbf{D}(t)u(t), \end{aligned} \tag{3}$$

where *x*, *u*, and *y* are vectors of state, controls, and observations; **A**, **B**, **C**, and **D** are matrices of state, control, and observations.

Equations (3) represent a model of a linear non-time-invariant system.

The optimization criterion can be represented in the form

$$J = \frac{1}{2}\Big[x_f^{\mathrm{T}}(t)S(t)x_f(t) \int_0^{t_f} (x^{\mathrm{T}}(x)Q(t)x(t) + u^{\mathrm{T}}(t)R(t)u(t)dt\Big], \tag{4}$$

where $x_f(t)$ is the finite time; $S(t)$, $Q(t)$, and $R(t)$ are weighting matrices.

LQR optimization problem is grounded on the application of the maximum principle to the mathematical description (3) based on the optimization criterion (4).

Although the problem under consideration concerns nonlinear time-invariant systems and is of a more general nature, its application complicates the synthesis of complex control systems, since it requires the solution of the Riccati matrix differential equation. This equation belongs to the class of nonlinear equations due to the presence of a quadratic term.

In practical problems, optimal control of linear time-invariant systems is usually synthesized using a more traditional approach [3], [4]. In this case, all matrices of the mathematical model ($A$, $B$, $C$, $D$), as well as the matrices of the quadratic quality criterion ($S$, $Q$, $R$), are constant and do not depend on time. The process is considered on an infinite time interval $t \to \infty$ that excludes the presence of boundary conditions. The optimization functions can be represented in the form

$$J_d = \int_0^\infty (x^{\mathrm{T}} Qx + u^{\mathrm{T}} Ru)dt \qquad (5)$$

for deterministic systems and signals;

$$J_s = \int_0^\infty (\mathrm{M}[x^{\mathrm{T}} Qx + u^{\mathrm{T}} Ru])dt \qquad (6)$$

for stochastic systems and signals.

In expressions (5), (6), $Q$, $R$ are weighting matrices taking into account the influence of state variables and disturbances.

Under the condition of matrix constancy, the Riccati differential equation reduces to an algebraic one. The result of LQR optimization is a matrix of gains for the fixed feedback.

It should be emphasised that the LQR method is directed to the usage of linearized models of moving objects. Linearization of the UAV model will significantly simplify the task of synthesizing the motion control system and will provide access to the tools of the theory of linear systems. However, the downside to the linear model and linear control theory is that flight performance cannot be guaranteed for all flight modes. This is not less, since the trajectory of the UAV flight is surrounded by constructive advantages, but also by: a range of horizontal fluidity, a working height, a low lift, etc.; The line controller can be a correct and simple solution. The use of the linear quadratic regulator method to stabilize the late channel will ensure good system brightness from the point of view of height changes.

The LQR method ensures the synthesis of an optimal system. It is directed to achieving the high accuracy of the designed system. Nevertheless, this method has weak resistance to disturbances. This disadvantage can be mitigated using robust optimization based on the $H_\infty$ norm.

Solving this problem begins with the choice of an optimization criterion. This criterion must satisfy the following requirements:

*1)* Minimization of the mean square deviations of the UAV state variables caused by the action of stochastic turbulent wind.

*2)* The ability to withstand changes in the parameters of the UAV mathematical model when changing the altitude and flight speed, while maintaining the indicators of stability and control quality (robustness of the control system).

Parametric optimization of both the internal and external control loops can be performed based on the UAV lateral motion dynamics model, which can include a Dryden filter.

This approach can be implemented using $H_2/H_\infty$ parametric robust optimization [4], [5]. When applied to this problem, the optimization criterion has the form [5]

$$J = \lambda_2 J_{s2} + \lambda_\infty J_{d\infty} + PF, , \qquad (5)$$

where $J_{s2}$ is the $H_2$ norm of the stochastic system operator; $J_{d\infty}$ is the $H_\infty$ norm of the deterministic system operator; $\lambda_2$, $\lambda_\infty$ are weighting factors; $PF$ is the penalty function, used to maintain the stability of the closed-loop system when changing the regulator parameters during the optimization procedure.

By operators of deterministic and stochastic systems, we mean models of these systems in the state space. To perform the optimization procedure (5), it is necessary to ensure the stability of the closed-loop system under all possible variations of the controller parameters. For this purpose, a penalty function is added to the quality indicator, which ensures the location of all poles of the closed-loop system in the left half-plane of the complex plane.

The calculating algorithm directed to the minimization of the optimization criterion (5) represents an interactive procedure when weighting factors are changed to achieve the acceptable characteristics of robust performance and robust stability. Finally, weighting factors are selected after several executions of the calculation procedure to ensure acceptable values of the state variables of the closed-loop system. In the expression (5), the component $J_{s2}$ determines the tracking accuracy along a given UAV trajectory under the action of random disturbances, and the component $J_{d\infty}$ is a measure of the robustness of the system. These indicators have a contradictory meaning: an increase in one leads to a decrease in the other. By choosing the weighting factors $\lambda_2$ and $\lambda_\infty$, one can find the desired compromise between the requirements of robust performance and robust stability.

Nevertheless, a more efficient method of robust control is the robust structural synthesis, or the so-called $H_\infty$ synthesis [4]. Based on the analysis of many textbooks and publications, for example, [4], [6], [7], it is possible to choose the following approach to the solution of the robust control problem. The diagram of the problem statement of the proposed approach is presented in Fig. 1.

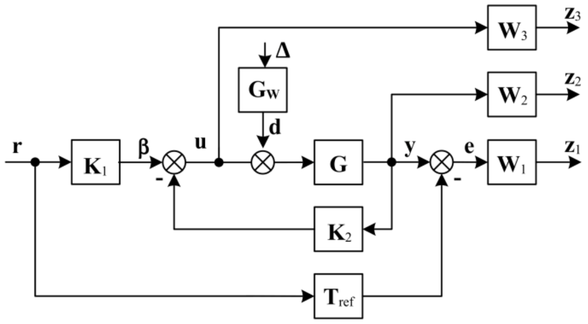

Fig. 1. The robust structural synthesis (problem statement)

The block diagram in Fig. 1 represents the control system with a two-degree-of-freedom regulator based on loop-shaping by the method of the mixed sensitivity.

Finally, the proposed control strategy is based on loop-shaping, a method of mixed sensitivity, and a two-degree-of-freedom regulator.

To solve the stated problem, it is necessary to minimize the optimization criterion, which represents the $H_\infty$ norm of the function of the mixed sensitivity

$$J_o = \left\| \begin{matrix} -W_1 T_{\mathrm{ref}} \\ +W_1 G K_1 (1+GK_2)^{-1} & W_1 G_w (1+GK_2)^{-1} \\ W_2 K_1 (1+GK_2)^{-1} & -W_2 K_2 G_w (1+GK_2)^{-1} \\ W_3 G K_1 (1+GK_2)^{-1} & W_3 G_w (1+GK_2)^{-1} \end{matrix} \right\|_\infty . \quad (7)$$

The optimization problem based on the objective function of the mixed sensitivity (7) can be formulated in the following way

$$J_o \to \min_{K_1 . K_2 \in K_{per}} , , \quad (8)$$

where $K_{per}$ defines the set of permissible regulators that ensure the stability of the motion control system.

The novelty of the proposed approach (8) lies in introducing a new mixed-sensitivity function with disturbance, modeled by a forming filter that represents the spectral density of the turbulent wind. The forming filter is represented by a transfer function $G_w$.

The advantage of the proposed approach is the strong resistance to both internal and external disturbances. The disadvantage lies in the dependence of the quality of the linearized model of a moving object.

The realization of $H_\infty$ synthesis can be implemented by MATLAB software [16]. In particular, Robust Control Toolbox is oriented on organization of appropriate calculation procedures. The typical procedure for the robust structural synthesis includes the following steps.

*1)* The creation of mathematical descriptions of the control object in the space of states (operator *ss*).

*2)* The choice of the weighting transfer functions $W_1$, $W_2$, $W_3$ to form the desired frequency characteristics of a control system (loop-shaping approach).

*3)* The creation of an augmented object by joining weighting transfer functions to the control object (operator *augtf*).

*4)* Carrying out a procedure of the robust structural synthesis (operator *hinfopt* or *hinfsyn*) with the representation of the synthesized optimal regulator in the space of states. The procedure realizes an automated iterative procedure that ensures the minimization of $H_\infty$ norm of the closed-loop system. As result of this procedure execution, some specific level $\gamma$ is minimized. This means that the condition $\|T\|_\infty < \gamma$ is carried out. Here $\|T\|_\infty$ defines $H_\infty$ norm of the closed-loop system.

*5)* The reduction of the order of the obtained regulator (operator *schmr*).

*6)* The analysis of characteristics and performances of the synthesized system, including transient processes, amplitude-frequency characteristics, and the index of robustness (operators *step, bode, hinfnorm*).

*7)* The transformation of a continuous regulator in discrete by MATLAB software. The appropriate algorithm is represented in Fig. 2. It should be mentioned that it is also possible to design a discrete regulator using operator *dhinfopt*. Nevertheless, practical research proved a priority of the first approach.

There are methods of designing regulators based on non-linear methods. One of these methods is sliding mode control, with such advantages as high resistance to disturbances and comparatively low requirements for the mathematical model. Unfortunately, there are definite disadvantages, such as the possibility of arising high frequency oscillations, decreasing the quality of transient processes during delays, and the necessity of smoothing controls to avoid worsening the accuracy.

Another non-linear method, the so-called backstepping method, can be applied to complex non-linear models, but it has significant sensitivity to the model's errors. At the same time, the method does not ensure strong resistance to disturbances. It is possible to consider that this method is convenient for studying essential non-linearities that influence the quality of control.

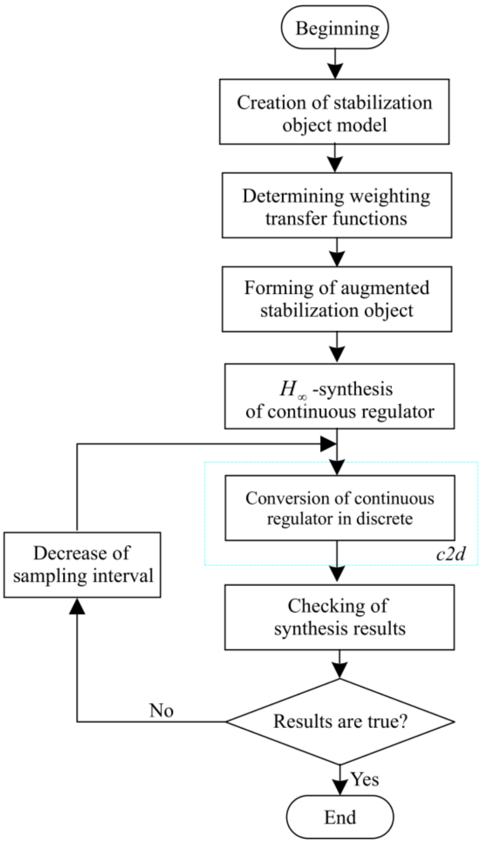

Fig. 2. The block diagram of designing a discrete H∞ regulator

There are also innovative methods for designing regulators, such as fuzzy logic and artificial intelligence methods [12], [13]. Fuzzy logic regulators could not require a mathematical description, which is the essential advantage for complex, non-linear, badly formalized objects. Fuzzy controllers are also stable to measurement noise. Nevertheless, these methods are based on heuristic approaches. These controllers become too complex for multidimensional systems. Moreover, fuzzy logic regulators have problems with ensuring stability. Therefore, it is not desirable to use such regulators in aerospace moving objects.

Nowadays, become widespread regulators based on artificial intelligence methods (neural networks, genetic algorithms) [13]. The powerful advantage of such methods is good adaptation to operation in conditions of uncertainty, including parameter variations and resistance to external disturbances. The basic disadvantages of such methods are poor interpretability, high requirements for computational burden, and the necessity of learning and large datasets. Nevertheless, it should be mentioned that some artificial intelligence methods can be successfully used for the implementation of design procedures of moving object controllers. For example, genetic algorithms can be a basis for the implementation of optimization procedures during the synthesis of robust controllers.

## V. CASE STUDY

The synthesis results for the motion control system based on the LQR method under normal and disturbed operating conditions are shown in Figs. 3 and 4.

The synthesis results based on the robust structural synthesis are given in Figs 5 and 6.

As follows from Fig. 3, control with LQR regulator gives a definite static error. This is caused by the impossibility of taking into consideration the cross-connection between different measuring channels.

The error of trajectory tracking in disturbed conditions (Fig. 4) increases due to the influence of the turbulent wind.

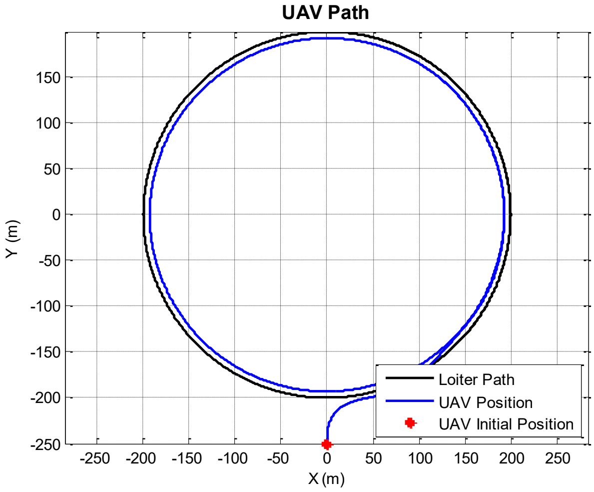

Fig. 3. The flight on the given trajectory in normal conditions (the initial altitude is 250 m)

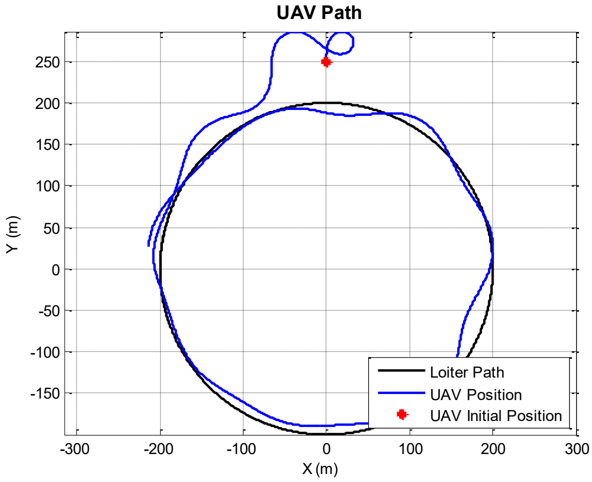

Fig. 4. The flight on the given trajectory in disturbed conditions (the initial altitude is 250 m)

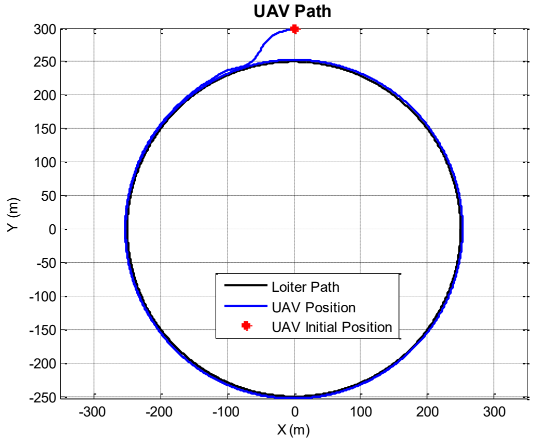

Fig. 5. The flight on the given trajectory in normal conditions (the initial altitude is 300 m)

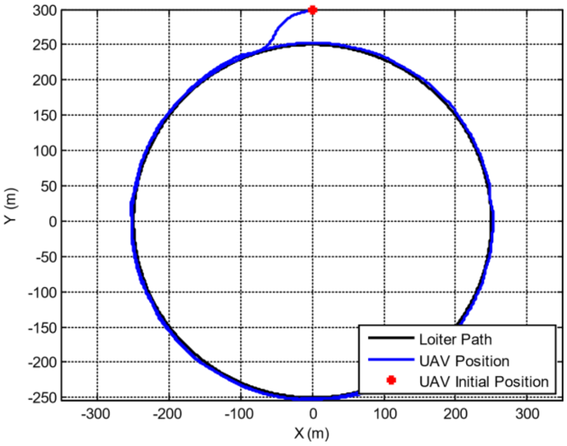

Fig. 6. The flight on the given trajectory in disturbed conditions (the initial altitude is 300 m)

Simulation results represented in Figs 5, 6 show the advantages of designing a motion control system by robust methods. These advantages are particularly evident in disturbing conditions (Figs 4, 6).

## VI. CONCLUSIONS

The analysis of uncertainties inherent in UAV motion control systems is represented. The mathematical representation of the turbulent wind is shown. The classification of parametric disturbances is given.

The comparative analysis of different types of controllers was implemented. The advantages of the robust controller as the best control unit for UAVs designed and operated in conditions of uncertainty are shown.

The basic stages of the calculation procedure for designing a robust controller are described.

The results of using LQG and $H_\infty$ methods for designing controllers for a trajectory-tracking system under normal and disturbed atmospheric conditions are presented.

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## REFERENCES

[1] R. Chen. “A Comprehensive Analysis of PID Control Applications in Automation Systems: Current Trends and Future Directions,” Highlights in Science Engineering and Technology, vol. 97, pp. 126–132, 2024. https://doi.org/10.54097/6q4xxg69

[2] R.V. Petrosian, I.D. Pilkevych, A.R. Petrosian. “Algorithm for optimizing a PID controller model based on a digital filter using a genetic algorithm,” *3rd Edge Computing Workshop*, April 7, 2023, Zhytomyr, Ukraine, pp 97-111. https://ceur-ws.org/Vol-3374/paper07.pdf

[3] L.G.B. Putra, F. Wahab, T.A. Tamba. “Design and implementation of linear quadratic regulator control for two-wheeled self-balancing robot,” *Bulletin of Electrical Engineering and Informatics*, vol. 14, no. 2, pp. 931–939, 2025. https://doi.org/10.11591/eei.v14i2.8689

[4] S. Skogestad, I. Postlethwaite. *Multivariable Feedback Control*, New York: John Wiley, 2004, 559 p.

[5] A. A. Tunik, O A. Sushchenko, ”Usage of vector parametric optimization for robust stabilization of ground vehicles information-measuring devices,” *Proceedings of the National Aviation University*, no. 4, pp. 23–32, 2013. https://jrnl.nau.edu.ua/index.php/visnik/article/view/5530/6249

[6] O. Sushchenko, “Synthesis of two-degree-of-freedom system for stabilization of information-measuring devices on moving base,” in *Proc. IEEE 3rd International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, Kyiv, Ukraine, pp. 150–154. 2014. https://doi.org/10.1109/MSNMC.2014.6979756

[7] O. A. Sushchenko, “Robust control of angular motion of platform with payload based on H∞-synthesis,” *Journal of Automation and Information Sciences*, vol. 48, no. 12, pp. 13–26, 2016. https://doi.org/10.1615/JAutomatInfScien.v48.i12.20

[8] B. I. Kuznetsov, T. B., Nikitina, and I. V. Bovdui, “Multiobjective synthesis of two degrees of freedom nonlinear robust control by discrete continuous plant,” *Technical Electrodynamics*, vol. 5, pp. 10–14, 2020. https://doi.org/10.15407/techned2020.05.010

[9] K. Hatada, M. Sato, K. Hirata. “Robust controller design with reduced conservatism for calibration-free

visual feedback systems and its experimental verification," *SICE Journal of Control, Measurement, and System Integration*. Article 2497612. 2025. https://doi.org/10.1080/18824889.2025.2497612

[10] W. Ruchun. "Nonlinear controller design for unmanned helicopter flight platform," *Scientific Reports*, 15. 2025. Article 40667. https://www.nature.com/articles/s41598-025-98132-72-7 https://doi.org/10.1038/s41598-025-98132-7

[11] X. Chen, J. Fang, J. Li, "Robust Control Design and Optimization for Under-Actuated Mechanical Systems Considering Fuzzy Uncertainties," *Processes*, vol. 13, no. 3, 609, pp. 1–29, 2025. https://doi.org/10.3390/pr13030609

[12] K. Kyslan et al. "A Nonlinear Controller for Point-to-Point Position Control," *Energies*, vol. 16, no. 17, 6339, 2023. https://doi.org/10.3390/en16176339

[13] C.O. Gorce. Automatic Controller Design: Using Artificial Intelligence Principles in Automatic Control. *Preprint* 2024. https://doi.org/10.20944/preprints202408. 0957.v1

[14] M. V. Cook. *Flight Dynamics Principles*. Amsterdam: Elsevier, 2007

[15] P. N. Paraskevopoulos. *Modern Control Engineering*, Boca Raton: CRC Press, 2001, 736 p.

[16] G. Balas, R. Chiang, A. Packard, M. Safonov, *Robust Control Toolbox User's Guide*. The Math Works Inc, 2005–2008.

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**О. А. Сущенко, Н. В. Якубовський. Синтез регулятора для системи керування рухом БПЛА в умовах невизначеності**

У статті досліджуються невизначеності, властиві системам керування рухом безпілотних літальних апаратів. Розглядаються як зовнішні, так і внутрішні збурення, що діють на рухомі об'єкти. Наведено вирази для турбулентного вітру. Представлено аналіз структурованих та неструктурованих невизначеностей. Наведено результати дослідження різних типів регуляторів, включаючи PID-регулятори, LQR-регулятори, робастні регулятори та регулятори на основі нелінійних підходів та методів штучного інтелекту. Описано процедуру H-нескінченного синтезу. Представлено блок-схему перетворення неперервного регулятора в дискретний. Наведено порівняльний аналіз застосування LQR та H-нескінченних регуляторів у контурах стеження за заданою траєкторією для умов нормальної та збуреної атмосфери. Показані відповідні графічні залежності. Отримані результати можуть бути корисними для повітряних об'єктів широкого класу.

**Ключові слова: с**истема керування рухом; невизначеності; турбулентний вітер; регулятори; робастний структурний синтез; відстеження траєкторії.

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