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ANALYSIS OF METHODS AND ALGORITHMS FOR QUADROTOR POSITION CONTROL

The object of research is the system of position control of a quadrotor unmanned aerial vehicle (UAV) as a nonlinear multi-input multi-output (MIMO) system with strong cross-channel coupling and high sensitivity to parametric and structural uncertainty. The problem addressed is the lack of robust and computationally efficient control algorithms that can ensure stability under uncertainty and be implemented on embedded platforms with limited resources.

This study presents an analytical review of modern control methods for quadrotor position stabilization. The methods analyzed include classical proportional-integral-derivative (PID) controllers, linear optimal, robust, adaptive, and intelligent systems (neural networks, fuzzy logic). The analysis focuses on the structure, sensitivity to uncertainty, computational complexity, and feasibility of implementation on STM32-based flight controllers.

As a result of the review, it was established that classical PID controllers, while widely used, are highly sensitive to model variations and sensor noise. Intelligent systems show better adaptability but exceed the computational capacity of low-cost microcontrollers. The most promising direction is identified as energy-based control methods that minimize local functionals of instantaneous energy values. These methods allow generating closed-form control laws, avoid signal differentiation, and maintain robustness with minimal processor load.

The comparative evaluation shows that the proposed algorithm has the potential to improve control quality by more than 7% and reduce the impact of parametric disturbances by an average of 10% compared to traditional PID-based systems. The results are recommended for UAV control systems operating under limited computational capacity, absence of GPS, or in disturbed environments, such as tactical drones, FPV platforms, and autonomous navigation systems.

Keywords*: quadrotor control, parametric and structural uncertainty, energy-based control, nonlinear MIMO systems.*

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1. Introduction

In modern conditions, there is a growing need for high-precision, autonomous and reliable control of unmanned aerial vehicles (UAVs), in particular quadrotors. High maneuverability, the ability to perform vertical take-off and landing, as well as adaptability to various operating conditions have made quadrotors typical representatives of unmanned systems for performing various tasks: reconnaissance, monitoring, cargo delivery, etc. in many areas of activity.

However, the implementation of high-quality control of the quadrotor position is complicated by a number of factors: the nonlinear nature of the dynamics of the device, the strong coupling of control channels, the variability of parameters (mass, moments of inertia, aerodynamics) and the presence of disturbances, noise and delays.

Modern control methods include both classical proportional-integral-derivative controller (PID), Sliding Mode Control algorithms and intelligent approaches: neural networks, fuzzy logic, predictive control. For example, Sliding Mode Control provides high robustness to external influences [1], and neural networks are able to approximate unknown system dynamics [2].

However, most of these methods have limitations: they require precise knowledge of the object model or are too computationally expensive to implement on board quadrotors with limited computing resources.

To overcome these problems, alternative control principles are proposed. For example, a single-step predictive controller for stabilizing the height of vertical take-off and landing unmanned aerial vehicles(VTOL-UAVs) under variable load conditions is proposed in [3]. Its main advantage is a closed-loop control principle without the need for online optimization, which allows for real-time implementation.

In work [4], a PID controller with an adaptive wavelet neural network for controlling UAVs with a suspended load is developed. The method does not require a full mathematical model, but requires complex online identification.

In the study [5], it was demonstrated that Type-2 fuzzy neural network (T2FNN) is superior to Type-1 in robustness to noise and parameter changes, but has high computational complexity. In paper [6] an adaptive fuzzy control system with compensation of unmodeled dynamics based on a backstepping approach is proposed. This approach ensures signal boundedness even with actuator quantization.

In [7], it is considered a hybrid approach that combines radial basis function neural network (RBFNN) with integral sliding mode control (SMC) and allows for effective compensation of model uncertainties and disturbances in real time. A similar idea is implemented in Adaptive Wavenet PID, which provides trajectory tracing in complex conditions, but requires training algorithms that complicate implementation on low-cost platforms.

Literature analysis [8] shows that even modern geometric stabilization methods on special orthogonal group in 3 dimensions (SO(3)) demonstrate limited effectiveness in the case of loss of sensory information or uncertainties in the dynamics structure.

Recent decades have been characterized by active attempts to integrate intelligent methods into classical control systems. The combination of neural networks, fuzzy logic or machine learning algorithms with traditional approaches promises to increase accuracy, adaptability and robustness to disturbances. However, the practical implementation of such hybrid systems remains problematic due to high power consumption, the need for large training samples, and significant computational complexity that exceeds the capabilities of embedded microcontrollers typically used in quadrotors.

Methods based on the minimization of instantaneous error or energy functionals (one-step-ahead predictive control) [9] look more promising. They allow obtaining simple stabilizing control laws in closed form with a low load on the microcontroller. Against this background, interest is growing in methods that allow achieving high efficiency without excessive resource requirements. One of these is the approach based on the inverse dynamics problem combined with the minimization of local instantaneous energy functionals [10, 11]. A feature of this approach is the ability to construct a closed-form control law without the need for signal differentiation, numerical optimization, or exact knowledge of the full mathematical model of the object. This approach demonstrates high robustness to a wide range of parametric and coordinate uncertainties, and also allows to reduce the load on computational resources. This, in turn, allows to use the released resource for implementing additional tasks, in particular computer vision, navigation, trajectory planning or sensor data fusion.

Quadrotors are often subject to particularly stringent requirements for control algorithms. Quadrotors must operate stably without GPS, even if some sensors fail. They should also handle sudden changes in load or operate under active electronic warfare conditions. In such cases, control algorithms must be simple, energy-efficient, and adaptive. Algorithms based on energy functionals gain not only scientific interest but also strategic significance. Their implementation can significantly increase the autonomy, survivability and reliability of Ukrainian UAVs in special conditions.

Scientific aim of the research: to formulate a methodology for synthesizing the law of UAV position control based on the minimization of local functionals of instantaneous energy values under conditions of structural and parametric uncertainty. It is expected that such an approach will allow creating an algorithm without using an exact mathematical model, with dynamic decomposition of control channels and with weak sensitivity to parametric and external disturbances.

Practical aim of the research: to ensure the implementation of the control algorithm on modern flight controllers with low computational load, while saving resources for the integration of functions such as computer vision, trajectory planning or target detection, especially relevant in special application conditions.

2. Materials and Methods

The object of research is electromagnetic and electromechanical processes in the position control system of an unmanned aerial vehicle, in particular a quadrotor with a cross-shaped configuration (X4). Particular attention is paid to the analysis of the position of the aircraft as a controlled MIMO system with pronounced nonlinearities, strong interdependence between channels, and high sensitivity to parametric and structural uncertainty.

The subject of research is methods for constructing and implementing UAV position control algorithms that can be embedded in modern hardware platforms with limited resources, in particular STM32-class microcontrollers.

Given the goal of identifying the most promising and practically feasible control strategies, an analytical and comparative review was chosen as the main research method. This approach is justified by the following factors:

1) the diversity and fragmentation of modern control methods (classical, robust, adaptive, intelligent) requires systematization before selecting an optimal approach;

2) experimental testing of each method is impractical at this stage due to the volume and resource intensity, especially when working with embedded systems;

3) the aim is to reduce the implementation complexity on resource-constrained platforms, which necessitates a theoretical analysis of structure, computational requirements, and adaptability of methods;

4) a large volume of high-quality, peer-reviewed sources is available in open-access repositories and databases, enabling a comprehensive literature-driven evaluation.

The study is therefore of a review and theoretical nature, based on open sources of technical, scientific, and applied literature.

The analyzed control algorithms include both classical (linear) and nonlinear, adaptive, and intelligent methods. The source database consisted of:

1) scientific articles from Scopus, IEEE Xplore, and ScienceDirect (1999–2024);

2) technical documentation for Ardupilot (Copter 4.3), Betaflight (SpeedyBee F405 V3), STM32-based platforms;

3) review publications on embedded implementation;

4) open-source repositories such as Betaflight and Ardupilot.

The following methods were applied:

1) classification of control approaches by criteria: linear/nonlinear, robust/adaptive, intelligent/classical;

2) comparative analysis of implementation efficiency (computational resources, robustness, adaptability, noise resistance);

3) structural interpretation of control schemes from open platforms (e. g., PID-FF in Ardupilot);

4) analytical generalization to identify trends and bottlenecks.

Additionally, an analysis of software and hardware compatibility of control algorithms with platforms such as STM32F405/STM32F743, Pixhawk 6C, Pixhawk PX4, and SpeedyBee F405 V3 was performed.

All research was conducted in source-based analytical mode, without modeling or empirical validation. The theoretical orientation of the study reflects its current status as a preparatory stage for future experimental implementation, which is planned as a follow-up. The applied nature of the research is aimed at increasing the operational efficiency of UAV platforms in real-world deployment conditions.

3. Results and Discussion

Results and discussion were systematized into three main groups of control methods:

1) classical linear methods PID, linear quadratic regulator (LQR), linear quadratic Gaussian (LQG), which provide basic stability, but demonstrate low resistance to model changes and disturbances; SWSS;

2) robust methods (sliding mode control, H-infinity control ($H\infty$)), which increase stability, but have a complex mathematical implementation and cause chattering phenomena;

3) adaptive/intelligent approaches such as model reference adaptive control (MRAC), radial basis function neural network (RBFNN), Type-2 fuzzy neural network (T2FNN), which demonstrate flexibility and adaptability, but are not suitable for implementation on low-cost microcontrollers due to high computational costs.

Let's consider how the spatial position is worked out in the Ardupilot project [12]. Fig. 1 shows a high-level control diagram that shows how the spatial position control is performed [13]. In the modern architecture of the ArduCopter V4.3 autopilot platform, a three-level system for stabilizing the position of an unmanned aerial vehicle is implemented, which consists of an input data processing subsystem (input translation), angular position control loops (angle controllers), and internal angular velocity control loops (body frame controllers). This structure provides multi-stage processing of control commands with high accuracy and adaptability to environmental changes.

The first level, input translation (Fig. 1), processes commands coming from the remote control. Signals along each axis of the quadrotor (roll, pitch, yaw) pass through target rate with jerk and acceleration conditioning blocks, which perform smoothing, filtering, and limiting the rate of change (jerk) to avoid sudden movements. As a result, a target angular velocity vector is formed, which is transmitted to the next level.

The second level, angle controllers (Fig. 1), is responsible for converting the target orientation into the desired angular velocities. The target position quaternion block represents the desired orientation in the form of a quaternion. Next, this value is compared with the real orientation provided by the extended Kalman filter (EKF), and the position error is calculated. This error is processed by proportional controllers along each axis, which generate the desired angular velocity. Importantly, these controllers have acceleration limits, which increases stability in the event of sudden disturbances.

The third level of body frame controllers (Fig. 2) implements PID control of angular velocities. Each of the quadrotor axes (roll, pitch, yaw) has its own PID controller, which operates in the body coordinate system of the device. The control signals of these controllers are transmitted to the Motor Mixers block, then through electronic speed controllers (ESCs) to the electric motors. This level operates at high frequencies from 400 Hz to 1000 Hz, which allows achieving high accuracy in dynamic conditions.

The lower part of Fig. 2 shows the architecture of the PID design block, which includes four branches: feed forward (FF), proportional (P), integral (I) with I_{MAX} limitation, and differential (D). Each control branch contains a dedicated low-pass filter: FLTT – filter of target, FLTE – filter of error, FLTD – filter of derivative error. These filters help to minimize the influence of high-frequency noise on the control process.

Angular velocity data is obtained from the inertial measurement unit (IMU). This data passes through three types of filters: dynamic harmonic notch filter, fixed notch filter, and low-pass filter (LPF).

After filtering, the signal undergoes decimation, which reduces its sampling rate. The processed data is then transmitted to the proportional-integral-derivative (PID) control loop for generating actuator commands.

As can be seen, in typical autopilot systems, in particular in ArduPilot Copter V4.X, position stabilization is implemented using a hierarchy of PID controllers, which are responsible for controlling the orientation (angle controllers) and angular velocities (body frame controllers). Despite their practical effectiveness, classical PID controllers have a number of fundamental limitations associated with high sensitivity to changes in dynamics, the need for fine-tuning of parameters, as well as limited ability to adapt under conditions of parametric and structural uncertainty.

The approach proposed in this study, based on the concept of inverse dynamics problems in combination with the minimization of local instantaneous energy functionals, allows to effectively replace individual components of the standard ArduPilot architecture. In particular, it can completely replace the proportional angular control modules, which are responsible for determining the set angular velocities based on the position error. In addition, it is possible to partially or completely replace the internal PID controllers of angular velocities (roll rate PID, pitch rate PID, yaw rate PID), which control the dynamics of the device in the body coordinate system.

Reasons for the feasibility of replacing the control algorithms of classical PID controllers with the proposed algorithms based on inverse dynamics problems in combination with the minimization of local functionals of instantaneous energy values:

1) PID architecture provides for accurate identification of the dynamic model of the control object and requires periodic reconfiguration;

2) high dependence on the quality of sensor signals forces the use of complex filtering structures (LPF, notch filters), especially for the D-part;

3) in difficult conditions of quadrotor operation or unstable environment, typical PID solutions demonstrate a decrease in efficiency when changing mass, load, configuration or sensor failures.

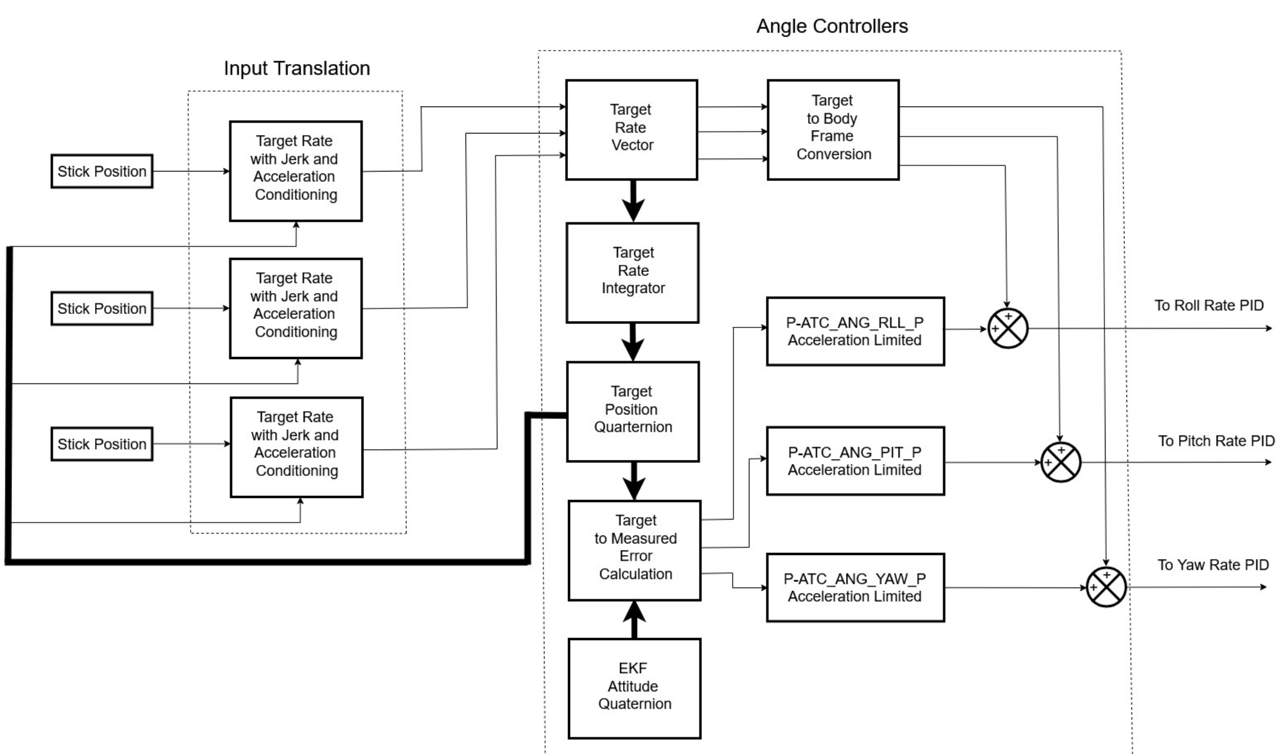

Fig. 1. High-level spatial position control diagram [13]

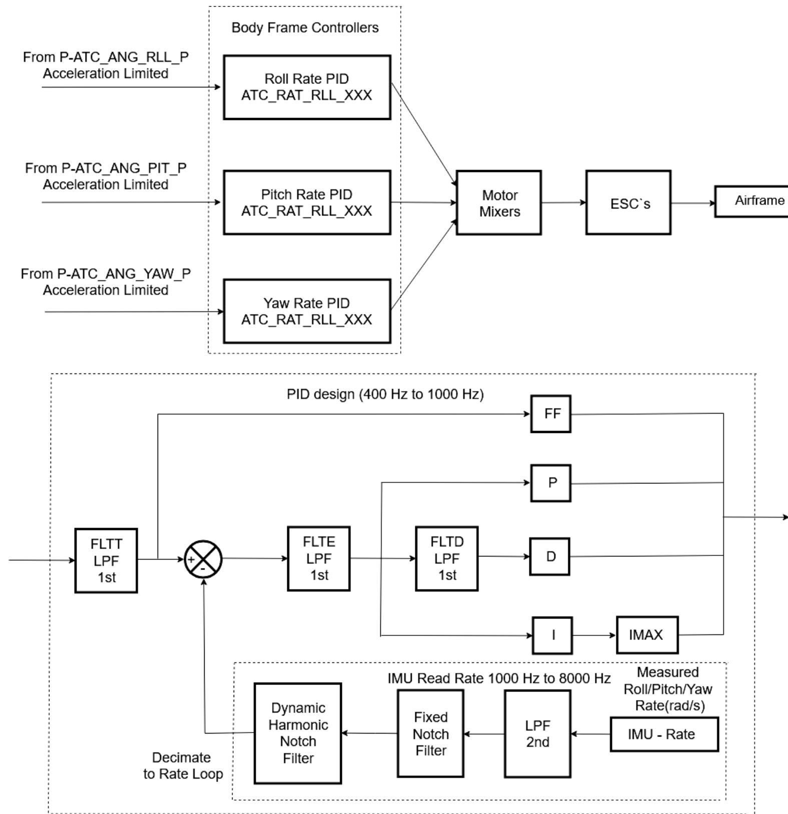

Fig. 2. Block diagram of the system for caking by one of the angles of pitch, roll or height of the quadrotor [13]

Instead, the proposed approach forms a control effect without the need for signal differentiation and without using a full mathematical model of the object. Control is implemented through analytical tracking of the desired dynamics, given in the form of an ordinary differential equation of a certain order, during which the local energy functional is minimized, which determines the generalized energy of the system error.

Advantages of replacing PID blocks with energy-oriented blocks:

1) does not require an accurate mathematical model of the control object, since the control algorithm is synthesized based on the structure of the desired dynamics;

2) does not contain differential links, which significantly reduces the impact of noise and reduces the need for complex filtering;

3) provides weak sensitivity to parametric disturbances without the use of complex identification or adaptation algorithms, in particular, demonstrates robustness when changing mass, moment of inertia, weather conditions;

4) performs dynamic decomposition of an interconnected control object, as a result of which processes in individual channels proceed almost automatically;

5) easy to implement in embedded environments such as STM32, because the control algorithm requires a minimum of computing resources and is implemented in the form of a closed analytical formula;

6) easily adapts to changing flight conditions and does not require re-setting of parameters when changing the hardware configuration or environment;

7) provides smooth error decay without oscillations due to the formalized structure of the dynamic quality of the closed loop.

Therefore, the integration of the energy-oriented method into the ArduPilot structure not only allows to maintain compatibility with existing sensor and actuator modules (IMU, Motor Mixers, ESC), but also significantly increases the stability and robustness of the quadrotor attitude control system. This is especially important for unmanned platforms operating in conditions of limited computing resources, limited sensor support, or conditions with a high level of uncertainty.

Thus, in popular open-source projects such as ArduPilot and Betaflight, the stabilization of the attitude of unmanned aerial vehicles is carried out on the basis of PID-FF circuits. In such systems, the P-regulator forms the target angular velocity based on the position error, and the lower-level PID block controls the dynamics of the electric motors. The Feed Forward component allows to implement reactive actions similar to those performed by the pilot in MANUAL mode, ensuring a fast response. However, the limitations of such PID controllers are their low adaptability to parametric changes, sensitivity to noise, and dependence on fine-tuning of parameters, which significantly reduces their effectiveness in complex conditions typical of special applications.

The proposed approach is based on the concept of inverse dynamics problems, which involves constructing the control effect not through model compensation, but through minimization of the local functional of instantaneous energy values. Unlike classical methods, where optimization of the global criterion is set and accurate knowledge of the parameters of the control object is required, the energy approach allows:

1) to avoid the use of differential operators in the signal path;

2) to obtain closed-form control algorithms without calculating derivatives;

3) to ensure asymptotic stability and weak sensitivity to changes in mass, inertia, or environmental conditions;

4) to implement dynamic decomposition of the system without linearization;

5) to maintain a simple implementation in C/C++ on STM32 microcontrollers without digital signal processors (DSPs) or graphics processing units (GPUs).

The essence of the method is to define the desired system behavior using a differential equation. This equation describes the target dynamics with the required quality. Then, a controller is constructed to make the real system follow this target behavior. It does so by minimizing a specific local energy functional.

Instead of precisely achieving a global minimum, as in classical optimization approaches, an acceptable technically justified minimization

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is achieved, which guarantees stability and quality without overloading the system with calculations.

Such controllers do not depend on the transfer functions of the object, which eliminates the need for re-tuning when changing the configuration of the device or load. Compared to classical PID blocks, they provide better quality of transient processes even with significant disturbances or changes in parameters. Given these advantages, the proposed method can replace classical PID controllers in systems such as ArduPilot and Betaflight, increasing:

1) resistance to uncertainties;

2) minimal regulatory load on the processor;

3) flexibility to the configuration variability of the quadrotor (load, weather conditions).

The proposed control method is based on the concept of inverse dynamics problems. It also uses minimization of local functionals of instantaneous energy values.

This approach is promising for improving UAV stabilization systems. It is especially relevant in special conditions where response time, reliability, and limited computing resources are critical.

As a result of the analytical review, it was found that the least studied, but promising, are approaches based on the minimization of local functionals of instantaneous energy values. They allow obtaining closed-form control algorithms, do not require the construction of a complete mathematical model of the object, and are resistant to a wide class of uncertainties. The analyzed methods are grouped into three main categories: classical, robust, and intelligent-adaptive. A comparison of key indicators of the methods is presented in Table 1.

The comparative Table 1 was compiled based on the results of a structured analysis of more than 40 scientific and technical sources outlined in the Introduction. These include peer-reviewed publications, applied research, and open technical documentation describing practical implementations of various control strategies for quadrotors. The estimates of resistance to disturbances, parameter sensitivity, model dependence, computational complexity, and suitability for embedded STM32-based platforms were derived from a critical review of control structures, performance benchmarks, and reported experimental outcomes. Particular attention was paid to data from [1–11], which provide comparative characteristics of classical, robust, adaptive, and intelligent control systems used in UAV applications.

The application of the research results can be implemented in the following areas:

1) *embedded flight controllers*: easy-to-implement control algorithms on STM32F4, STM32F7, STM32H7 without the need for DSPs or GPUs;

2) *autonomous navigation in disturbance conditions*: the algorithm provides stabilization even in the absence of Global Positioning System (GPS) or with incomplete sensor support;

3) *mobile platforms*: due to low power consumption, the algorithm is suitable for use in all types of quadrotors;

4) *research platforms*: adaptation in Ardupilot or Betaflight as an alternative stabilizer (Energy-mode).

Research limitations:

1) the lack of numerical modeling does not allow a quantitative assessment of efficiency;

2) there is no testing on a physical model or hardware platform;

3) the comparison is based only on overview and descriptive characteristics of methods from literature sources;

4) interaction with high-level trajectory planning or computer vision tasks is not taken into account.

Martial law in Ukraine not only did not become a limitation for the research, but, on the contrary, increased its relevance and strategic significance. The sharp increase in demand for autonomous, maneuverable and energy-efficient quadrotors, caused by military operations, brought the issue of UAV stabilization in real operating conditions to the forefront. Increasing the country's defense capability and creating a military advantage on the front line are priority tasks that require the use of modern, effective and technologically accessible approaches to equipment control. At the same time, most of the existing control algorithms, in particular adaptive and intelligent methods such as radial basis function neural network (RBFNN), Type-2 fuzzy neural network (T2FNN), require a powerful computing environment (DSP, GPU) and are unsuitable for implementation on a typical microcontroller, such as STM32.

The approach proposed in [10, 11, 14] method of minimizing local functionals of instantaneous energy values allows to avoid complex calculations, such as numerical differentiation or online optimization. This makes it possible to implement it directly into embedded platforms with minimal resource load.

Thus, computing power is freed up to perform additional combat or navigation tasks: video stream processing, target detection, obstacle avoidance, etc. In addition, the proposed method demonstrates low sensitivity to changes in mass, load, wind gusts, and inertial characteristics, which allows it to be used in unstable conditions without complex re-adjustment or calibration.

Martial law conditions have also generated a practical demand for the creation of new control architectures that:

1) operate on inexpensive, mass-produced hardware;

2) do not depend on external navigation sources (GPS);

3) have a high level of reliability in conditions of radio interference and sensor failure;

4) can be used on both reconnaissance quadrotors and first-person view (FPV) platforms.

Thus, martial law served as a catalyst for rethinking approaches to the development of control algorithms, contributing to the formation of requirements for ease of implementation, autonomy and resilience to uncertainties. The results of this study have direct applied significance for increasing the technological capabilities of the defense industry and creating an intellectual advantage on the battlefield.

Table 1

Analysis of methods for controlling the position of the rotor in space

Method	Resistance to disturbances	Sensitivity to parameters	The need for a model	Computational complexity	Suitability for STM32
PID	Low	High	No	Low	Yes
LQR/LQG	Middle	Middle	Linear model	Middle	Perhaps
Sliding mode control (SMC)	High	Low	Yes	Middle	Perhaps
Adaptive backstepping	High	Middle	Yes	High	Limited
Neural network (RBFNN)	High	Low	Teaching	High	No
Type-2 fuzzy logic (T2FNN)	High	Low	Teaching	High	No
Nonlinear model predictive control	High	Low	Yes	Very high	No
One-step-ahead predictive control	High	Low	No	Low	Yes
Proposed method	High	Low	No	Low	Yes

Prospects for further research:

1) creation of a MATLAB/Simulink model with thrust, inertia, and load subsystems;

2) implementation in an STM32 microcontroller using code generation and profiling in CubeIDE;

3) integration into Ardupilot or Betaflight through its own stabilization module;

4) testing in real flight conditions with comparison with classic PID;

5) publication of results in professional journals of Ukraine and publications of the IEEE transactions on control systems technology, robotics and autonomous systems level, participation in international conferences.

Thus, the research results pave the way for the creation of a new class of energy-efficient, disturbance-resistant, and simply implemented algorithms that take into account hardware limitations and real-world operating conditions of autonomous UAVs.

4. Conclusions

As a result of the analytical study, a systemic vision of the current state of methods for controlling the position of unmanned aerial vehicles under conditions of parametric and structural uncertainty was formulated. The study covered the classification, comparison and critical analysis of existing algorithms, taking into account their implementation on resource-limited flight controllers. It was found that most modern approaches are either too complex for practical use in embedded systems, or do not provide sufficient stability to changes in parameters and disturbances.

As a promising direction, an approach to building control algorithms based on the concept of inverse dynamics problems in combination with minimization of local functionals of instantaneous energy values is proposed. This approach does not require differentiation operations for the implementation of control algorithms, has a simple analytical structure, does not depend on the full mathematical model of the object and is characterized by a low level of computational load. This makes it suitable for implementation on microcontrollers such as STM32, which are used in the Ardupilot, Betaflight platforms.

The research results are explained by the desire to ensure a balance between ease of implementation and high quality of control, taking into account the needs of modern applications in both the civilian and special sectors. The obtained analytical conclusions may be useful for:

1) engineers-developers of embedded UAV systems;

2) researchers in the field of control theory and robotics;

3) practical teams working on flight controllers for light UAVs in real-time conditions;

4) defense sector specialists interested in creating effective, autonomous and resource-saving solutions.

The subsequent stages of the study involve the mathematical synthesis of the control algorithm, modeling its operation in the MATLAB/Simulink software environment, implementation on a microcontroller and experimental comparison with existing approaches. The implementation of the developed method will allow to increase the efficiency of UAV control systems, make them more stable, robust and suitable for operation in conditions of uncertainty, which is critically important in modern conditions of technogenic, defense and humanitarian interaction.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

Financing

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors used artificial intelligence technologies within the permissible framework to provide their own verified data, which is described in the research methodology section.

References

1. Besnard, L., Shtessel, Y. B., Landrum, B. (2007). Control of a Quadrotor Vehicle Using Sliding Mode Disturbance Observer. *2007 American Control Conference*. New York: IEEE, 5230–5235. https://doi.org/10.1109/acc.2007.4282421
2. Dierks, T., Jagannathan, S. (2010). Output Feedback Control of a Quadrotor UAV Using Neural Networks. *IEEE Transactions on Neural Networks, 21 (1)*, 50–66. https://doi.org/10.1109/tnn.2009.2034145
3. Hedjar, R., Al Zuair, M. A. (2019). Robust Altitude Stabilization of VTOL-UAV for Payloads Delivery. *IEEE Access, 7*, 73583–73592. https://doi.org/10.1109/access.2019.2919701
4. Barrón-Gómez, R. A., Ramos-Velasco, L. E., Espinoza Quesada, E. S., García Carrillo, L. R. (2017). Wavelet neural network PID controller for a UAS transporting a cable-suspended load. *IFAC-PapersOnLine, 50 (1)*, 2335–2340. https://doi.org/10.1016/j.ifacol.2017.08.419
5. Kayacan, E., Maslim, R. (2017). Type-2 Fuzzy Logic Trajectory Tracking Control of Quadrotor VTOL Aircraft with Elliptic Membership Functions. *IEEE/ASME Transactions on Mechatronics, 22 (1)*, 339–348. https://doi.org/10.1109/tmech.2016.2614672
6. Wang, H., Xiaoping Liu, P., Xie, X., Liu, X., Hayat, T., Alsaadi, F. E. (2021). Adaptive fuzzy asymptotical tracking control of nonlinear systems with unmodeled dynamics and quantized actuator. *Information Sciences, 575*, 779–792. https://doi.org/10.1016/j.ins.2018.04.011
7. Li, S., Wang, Y., Tan, J., Zheng, Y. (2016). Adaptive RBFNNs/integral sliding mode control for a quadrotor aircraft. *Neurocomputing, 216*, 126–134. https://doi.org/10.1016/j.neucom.2016.07.033
8. Lee, T. (2013). Robust Adaptive Attitude Tracking on SO (3) With an Application to a Quadrotor UAV. *IEEE Transactions on Control Systems Technology, 21 (5)*, 1924–1930. https://doi.org/10.1109/tcst.2012.2209887
9. Hedjar, R. (2015). Robust one-step-ahead model predictive control of VTOL-UAVs. *The 27th Chinese Control and Decision Conference (2015 CCDC)*. Qingdao: IEEE, 3053–3058. https://doi.org/10.1109/ccdc.2015.7162445
10. Ostroverkhov, M., Pyzhov, V., Korol, S. (2017). Control of the electric drive under conditions of parametric uncertainty and coordinates' interrelation. *2017 International Conference on Modern Electrical and Energy Systems (MEES)*. Kremenchuk: IEEE, 64–67. https://doi.org/10.1109/mees.2017.8248953
11. Ostroverkhov, M., Pyzhov, V. (2019). Control of the Electric Drive with Field Regulated Reluctance Machine. *2019 IEEE 6th International Conference on Energy Smart Systems (ESS)*. Kyiv: IEEE, 277–282. https://doi.org/10.1109/ess.2019.8764206
12. *ArduPilot*. Available at: https://ardupilot.org/
13. Copter Attitude Control. *ArduPilot*. Available at: https://ardupilot.org/dev/docs/apmcopter-programming-attitude-control-2.html
14. Satskyi, I. S., Ostroverkhov, M. Ya. (2025). Improving the quality of unmanned aerial vehicle attitude control under conditions of parametric and structural uncertainty. *Development priorities for technical sciences in the modern world*. Riga, 54–57. https://doi.org/10.30525/978-9934-26-542-6-14

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