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ENERGY-CENTRIC CONTROL FOR AUTONOMOUS MOBILE NODES TO ENHANCE FUNCTIONAL STABILITY UNDER TURBULENT

This paper proposes a conceptual approach to the autonomous takeoff and landing control of autonomous mobile nodes (AMN) based on the Total Energy Control System (TEC_dology. The study aims to enhance the operational efficiency and survivability of unmanned aviation by utilizing the aircraft's energy state as a fundamental control invariant. The proposed approach overcomes the limitations of traditional systems, specifically their high sensitivity to stochastic disturbances and degraded stabilization accuracy under atmospheric turbulence. The control algorithm is optimized based on two criteria: minimizing the deviation of the AMN total energy from the reference flight trajectory and minimizing the imbalance between kinetic and potential energies to stabilize the rate of descent (or climb). Simulation results demonstrate that the implementation of this method provides robust resilience to external dynamic disturbances, mitigates the human factor, and enables mission execution under adverse weather conditions without rigid dependence on ground-based airfield infrastructure. Future research will focus on scaling the approach to multi-agent systems, integrating adaptation methods based on random projections, and field testing on fixed-wing platforms.

Keywords: *autonomous mobile nodes,, autonomous takeoff and landing (ATOL), total energy control system (TECS), energy state, atmospheric turbulence, functional stability, aircraft survivability.*

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Introduction

In recent years, unmanned aerial vehicles have evolved into a distinct class of complex dynamic systems characterized by high functional density and scalability in application. The integration of advanced sensory instruments, including multispectral and inertial measurement subsystems, has enabled the continuous generation of large data arrays regarding flight parameters, onboard system status, and environmental characteristics.

A key factor in this qualitative transition has been the implementation of high-performance onboard computing and communication complexes capable of real-time processing, aggregation, and interpretation of sensory information using filtering, state estimation, and adaptive forecasting methods. This has significantly reduced latency within the control loop and enhanced the reliability of information support for decision-making.

Consequently, the necessary prerequisites have been established for a substantial increase in flight efficiency through the development and implementation of high-precision automatic control systems. A defining feature of autonomous mobile nodes (AMNs) is the ability to perform autonomous maneuvering, following a defined route. This alleviates the need for ground station operators to constantly monitor numeros motion parameters (flight in the case of UAVs, movement in the case of ground systems, surface and underwater travel in the case of water-based AMNs, etc.). Instead, they start with the initial, final and intermediate points of the route along with several additional characteristics of the AMN movement. The remaining parameters are computed by the onboard control system and transmitted to the respective actuators.

Autonomous UAV flight encompasses stages such as automatic take-off and landing, trajectory calculation, and subsequent path following, integrated with high-level decision-making processes depending on mission objectives. Every flight includes two stages characterized by both intensive maneuvering and limited control resources required to reach specific terminal states. Every nominal UAV flight is inherently accompanied by the essential stages of launch (take-off) and landing.

For modern aviation complexes, a degradation in control precision can be observed during take-off and landing under atmospheric turbulence, manifesting as increased deviations from set flight regimes and reduced stability in regulation loops. Such systems demonstrate insufficient adaptability to high-frequency turbulent effects, leading to accumulated control errors, increased load on actuators, and a decline in overall flight stabilization efficiency.

Literature Review

Currently, considerable attention is paid to the UAV take-off and landing methods development and implementation. There are several main methods of UAV take-off: hand launch; use of a catapult; vertical take-off; “aircraft-style” take-off [3–6].

Launching a UAV glider using human physical strength, without specialized devices, is carried out when the UAV weighs less than 5 kg. The main advantage of the method is simplicity, but at the same time the main disadvantage is safety for both the glider itself and the operator at the UAV launch.

Today, a significant number of UAVs are launched using catapults. But this method has both advantages and disadvantages. For example, a gunpowder catapult, for all its positive characteristics, such as simplicity, reliability and power availability also has significant disadvantages, such as lack of stealth, increased danger to service personnel. A gunpowder catapult is practically irreplaceable during the launching of heavy UAVs with a jet engine, but its use for launching mini UAVs is not advisable [6, 7].

Another take-off method is a vertical take-off. Among the existing UAVs, a special group is made up of UAVs that have the ability to take-off and land vertically. This ability of UAVs not only significantly simplifies the problem of its basing, but also expands the capabilities of UAVs both in terms of areas of application and tactics of its usage. When designing automatic control systems for such UAVs, difficulties arise in ensuring their stabilization around the center of mass. Additionally, there is a large fuel consumption during the vertical take-off procedure, which shortens the radius of application of the UAV [8].

Take-off according to the aircraft pattern can be carried out automatically or under the operator control. Known methods of UAV landing [9, 10] can be reduced to such basic schemes as: landing like an airplane (on a runway); landing like a helicopter (on a site); landing with a parachute; landing in a capture device.

For aircraft-type UAVs, classic landing systems are used that are also used for a manned aircraft landing, for example, such as the course-glide system and centimeter-range landing systems.

The landing process is divided into five stages: descent, leveling, holdoff, and rollout. During the descent, the UAV approaches the ground at a safe speed. The flare stage is designed to offset the vertical rate of descent, during which the UAV is transferred to horizontal flight mode. During the holding phase, the flight speed at a constant altitude is further offset due to an increase in the drag coefficient. The developed technology for autonomous take-off of aircraft-type UAVs conditionally divides the take-off process into three phases, showing the sequence of the main stages of UAV take-off from the beginning of the ground roll to the transition to the route (Fig. 1).

In order to land at a designated or intended location, operators perform complex calculations to maneuver the UAV horizontally and vertically during the landing procedure [10].

Methods for systems that provide autonomous take-off and landing of various type UAVs are proposed at [11, 12]. Such systems are called ATOL, which is an acronym for the words Autonomous Take-Off and Landing. Take-off and landing without operator intervention will sig-

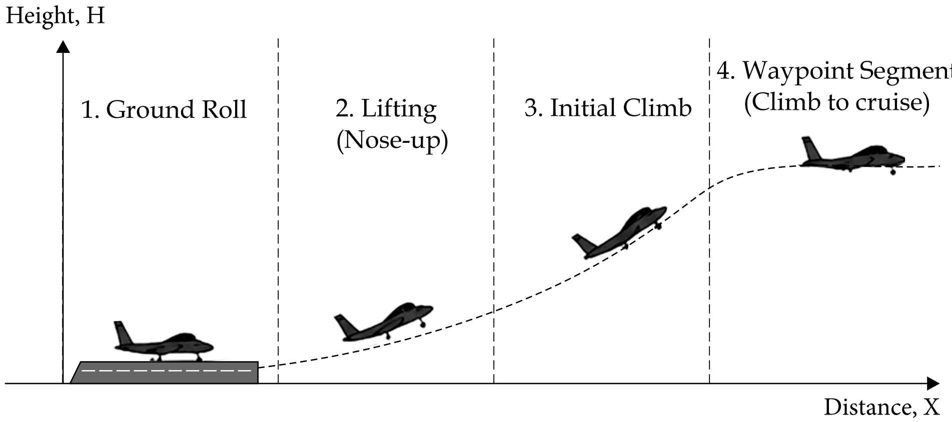

Fig. 1. Stages of UAV take-off

nificantly simplify the simultaneous use of several vehicles. The autonomous take-off and landing function will in the future become a standard function in an advanced ground control system for UAVs. This function minimizes errors caused by the human factor during the take-off and landing stages of UAVs and reduces the cost of operator training.

It should be noted that at the core of the conflict within non-autonomous aviation complexes lies the degradation of control precision under atmospheric turbulence, which leads to a decrease in the operational efficiency of unmanned aviation. Classical approaches, oriented toward rigid adherence to predefined trajectories, demonstrate insufficient adaptability to high-frequency stochastic environmental disturbances [13]. To resolve this issue, an approach based on the intellectualization of take-off and landing processes is proposed, transitioning from trajectory-based to energy-centric control [14]. Unlike traditional systems that focus on the geometric parameters of motion, such as the virtual glide slope, the proposed concept utilizes the aircraft's energy state as a fundamental control invariant. This approach provides inherent robustness to the system by minimizing the imbalance between the kinetic and potential components of total energy, rather than attempting direct compensation for every individual disturbance [15]. The implementation of energy-centric control achieves a comprehensive systemic effect, ensuring the intelligent compensation of external disturbances by interpreting them as fluctuations in the system's energy budget. This reduces the human factor by delegating complex tasks to algorithms and enhances the overall survivability of unmanned aerial vehicles by transforming adverse meteorological conditions from a category of critical constraints into a category of controllable environmental parameters. Thus, autonomous energy-state management serves as a systemic mechanism for increasing the autonomy and functional stability of unmanned aircraft systems in conditions of uncertainty.

Autonomous Control of the Uav on the Take-Off Stage

At the take-off stage, it is critically important to ensure efficient acceleration within the runway (RWY) limits, followed by a transition to a safe climb gradient as determined by airworthiness standards and the presence of obstacles along the flight path. Simultaneously, during the final landing phase, there arises a need for the precision dissipation of kinetic energy to a level that ensures safe taxiing and the accident-free termination of the flight mission. Both stages are viewed as processes of dynamic transformation of the aircraft's energy state under conditions of limited temporal and spatial resources.

To ensure the theoretical rigor of the proposed approach, the optimization criteria for synthesizing the control laws are formalized within the UAV state space. The total energy of the aircraft's motion is defined as the sum of its kinetic and potential components:

$$E_{tot} = 1/2mV^2 + mgh.$$

The cost function of the adaptive algorithm is formulated as a problem of minimizing a quadratic performance index over a finite time interval:

$$J = \int_{t_0}^{t_f} \left(\alpha\Delta E_{tot}^2(t) + \beta\Delta E_{bal}^2(t) + \gamma u^2(t)\right) dt,$$

where:

• J is the cost function (generalized performance index) that the UAV onboard computer attempts to minimize;

• [t_0, t_f] is the time interval over which the integral computes the cumulative "cost" of all errors and control expenditures;

• $\Delta E_{tot}(t) = E_{tot}(t) - E_{ref}(t)$ represents the total energy error of the aircraft, reflecting the deviation of the UAV's actual total energy from the target value defined by the virtual glide slope;

• $\Delta E_{bal}(t)$ is the energy imbalance, which accounts for how the energy is distributed between its kinetic and potential components;

• $u(t)$ is the control energy, represented as a control signal vector consisting of changes in control surface positions (pitch) and engine thrust;

• α, β, γ, are the autopilot tuning coefficients (weighting factors).

The parameter $\Delta E_{tot}(t)$ represents the current deviation of the total energy from the reference profile of the virtual glide slope, whereas $\Delta E_{bal}(t)$ determines the instantaneous imbalance between the airspeed (kinetic) and altitude (potential) channels. The control vector $u(t)$ forms coordinated commands for adjusting engine thrust and the pitch angle, while the weighting coefficients α, β, γ ensure the asymptotic stability of the closed-loop system under high-frequency stochastic atmospheric disturbances. The developed technology for autonomous take-off of aircraft-type UAVs conditionally divides the take-off process into three phases, illustrating the sequence of the main stages of UAV take-off from the beginning of the ground roll to the transition to the route (Fig. 1).

Phase I lasts from the beginning of the runway run-up to the set of take-off speed V_{to} = 30 m/s. During this stage, the UAV roll angle γ and pitch υ are stabilized at zero by the control laws until the take-off from the runway moment. The thrust value is set to the take-off value.

Phase II begins of the stage occurs when the UAV reaches the take-off speed V_{to} = 30 m/s. The UAV takes off from the runway. In this case, the pitch angle is set to 5°. The roll angle is controlled to stabilize the UAV flight path (ψ), which at this stage should be equal to the runway course (ψ_{rw}). The end of the stage occurs when the take-off height H_{to} = 50 m is reached. The thrust retains the take-off value.

Phase III begins after reaching the take-off altitude, the UAV is controlled using algorithms that are provided for UAV flight control. Namely, altitude and speed control can be performed using the UAV full energy control method, which produces pitch angle control signals υ_{cmd} and engine thrust δ_{th}, trajectory control can be performed using nonlinear adaptive roll angle control logic, which operates in the UAV flight mode along waypoints and produces UAV roll angle control signals (γ_{cmd}).

Autonomous Control of Unmanned Aerial Vehicle on the Landing Stage

Any UAV landing system, regardless of the chosen implementation strategy, must ensure the resolution of two fundamental systemic tasks. First is the task of precision guidance of the UAV to a specified spatial point, while adhering to the boundary values of orientation angles, as well as linear and angular velocities, which corresponds to the classical formulation of the terminal control problem. Second is the task of the complete dissipation of the aircraft's residual kinetic energy, provided that its structural integrity and functionality are preserved.

The instrumental framework used for the informational support of the landing stage for fixed-wing UAVs includes acoustic sensors (sonars) and laser rangefinders for high-precision altitude determination, satellite navigation system receivers, as well as video cameras for visual orientation or the implementation of computer vision systems, which collectively form the data field for automatic landing. The implementation of the energy-centric approach allows for the integration of data from these heterogeneous sensors into a unified energy-state model, ensuring control stability even under conditions of temporary degradation of individual information channels.

The developed UAV landing technology is designed to perform UAV landing in autonomous mode when the UAV control system is given an approach command at any time and at any flight trajectory interval. A significant difference between the developed technology and those described in [11-15] is that such technology uses algorithms implemented in widely used autopilots to calculate the landing maneuver before the UAV leveling stage. For example, altitude and speed control can be performed using the UAV full energy control method, which produces pitch angle control signals υ_{cmd} and engine thrust δ_{th}. Trajectory motion control can be performed using nonlinear adaptive roll angle control logic that produces the UAV roll angle control signals γcmd.

To enable autonomous landing, the UAV autopilot generates an array of virtual glide slope parameters based on the runway (RWY) threshold coordinates, heading, glide slope intercept altitude, and the rollout point. These data are essential for ensuring the stable operation of the UAV control algorithms, spatial synchronization, and the formation of the landing course according to the virtual glide slope geometry (Fig. 2). Additionally, the following key trajectory nodes are defined programmatically: the landing decision point — the UAV's location at the moment the approach command is received, which triggers the nonlinear adaptive roll control logic to intercept the pre-landing flight level; and the touchdown point—a point on the runway where the virtual glide slope passes at a distance d from the threshold. The distance d is determined by the specified glide slope angle and flare altitude, and is calculated using the following formula:

$$d = h_{в} / tg\mu,$$

where $h_{в}$ — leveling height (height above the runway end point at which the UAV leveling (flare) phase begins); μ — virtual glide slope angle;

• glidepath point is the point of UAV entry into the virtual glidepath, which is located at the height h_{ge} of the virtual glidepath.

The developed autonomous UAV landing technology works with the following parameters: $h_{в}$ = 3m, μ = 4, d = 42.9 m.

The glide slope intercept point and the rollout point define a functional spatial segment essential for ensuring the UAV's precision entry into the virtual glide slope window at a target altitude h_{ge}, aligned with the runway (RWY) vector. The length of this interval is a dynamic parameter adapted to the temporal constraints of the landing operation. It is determined by the UAV's approach angle relative to the RWY axis and its maneuvering capabilities; specifically, a sharper intercept angle requires a longer distance to complete transition processes and achieve course stabilization, though it must not fall below the technical minimum required for the turn. The target flight altitude within this segment is fixed at the glide slope entry level h_{ge}, allowing for the minimization of energy state fluctuations before the commencement of the final descent.

To prevent runway excursions or off-runway landings, the nonlinear adaptive roll control logic is integrated with a dynamic lateral offset compensation mechanism (activated after passing the glide slope intercept point). This mechanism provides precision heading adjustments to align the aircraft parallel to the longitudinal axis of the RWY with minimal lateral deviation. As a result of the synergetic operation of both algorithms, the UAV stabilizes on the final approach path after passing the glide slope point, maintaining the trajectory under zero-roll and zero-sideslip con-

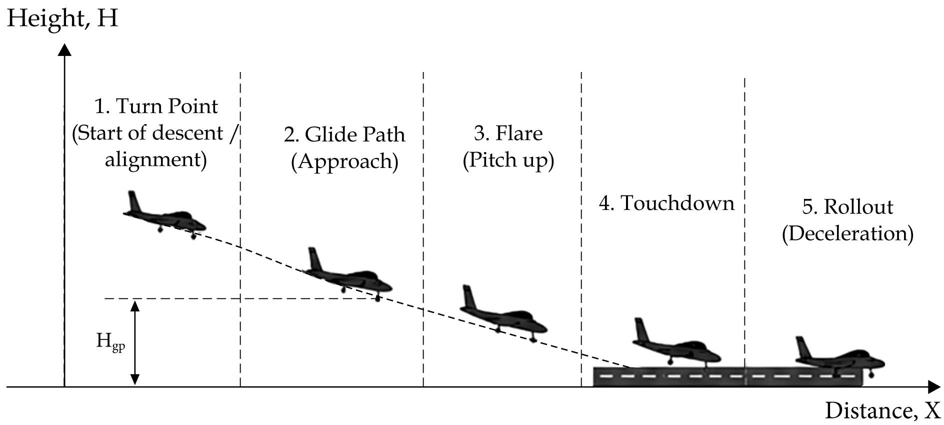

Fig. 2. Stages of UAV landing

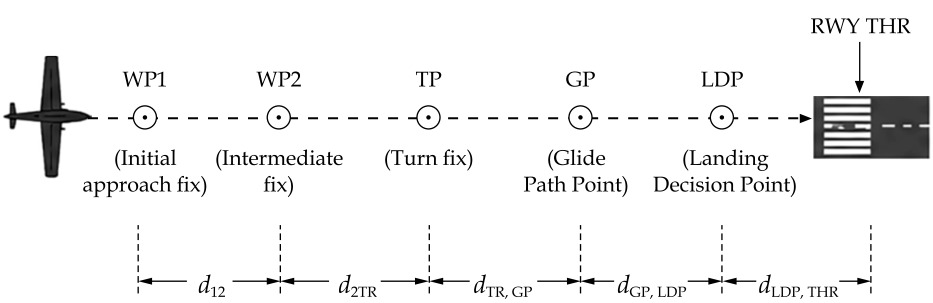

Fig. 3. Horizontal structure of the UAV landing approach route

ditions to ensure a safe touchdown. Such intelligent stabilization is critical for neutralizing the impact of sudden lateral wind gusts, which the system interprets as energetic perturbations of the motion vector.

A diagram of the UAV trajectory control is represented on Figure 3. In this case, UAV 1 and UAV 2 flew along a given trajectory at waypoints. At the moment of passing waypoint 1 for UAV 1 and waypoint 3 for UAV 2, a command to land was received. The dashed lines show the new automatically calculated approach trajectories in the UAV control system, in which the next waypoint is chosen also as the turn point.

The nonlinear adaptive roll control logic initiates the aircraft's transition onto a virtual trajectory connecting the decision point with the rollout point. Upon reaching a distance of 150 m, an iterative waypoint switching procedure is activated: first, to intercept the segment between the rollout point and the glide slope intercept point, and subsequently, to guide the UAV to the final touchdown location (Fig. 4). Simultaneously, in the vertical plane, the Total Energy Control System (TECS) performs precision monitoring of altitude and airspeed, ensuring motion stabilization along the target profile throughout all stages of the landing operation. Vertical descent parameters are determined by the platform type and its dynamic potential, while the flight itself is executed at a constant landing speed $V = V_{set}$.

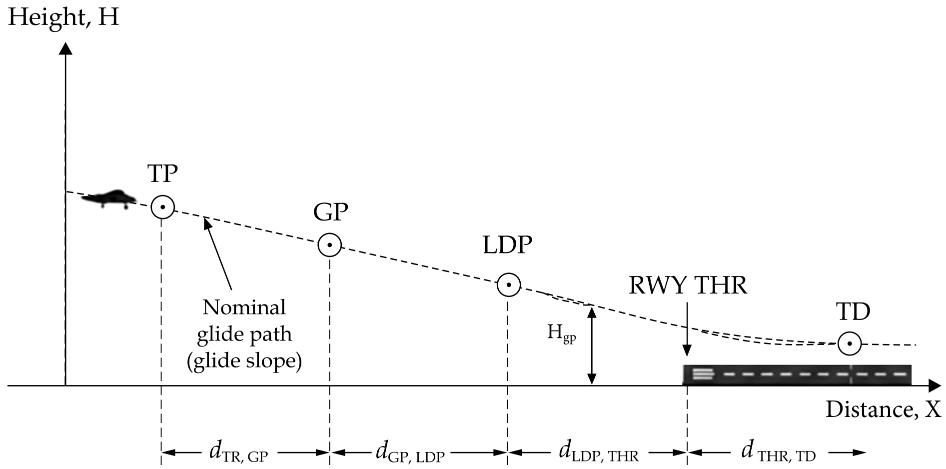

Fig. 4. Vertical profile of the UAV landing approach

After passing the runway end point, the control algorithm sets the pitch angle value to 0° and operates in the mode of holding this value, the engine thrust is set to 0 ($\delta_{thr} = 0$). The specified flight speed of the UAV after passing the runway end point acquires the value: $V_{зад} = 0$ (Fig. 4).

During the holding phase, due to increasing drag, the speed and flight altitude decrease, the UAV touches the runway surface, performs the run-up phase and makes a final stop within the runway.

Analysis of the Efficiency of Autonomous Uav Total Energy Control During the Takeoff Phase

The implementation of autonomous control algorithms based on the principles of controlling the UAV's energy status allows moving from the manual control stochastic nature to a deterministic process with a high level of repeatability. A feature of the proposed approach is the distribution of control logic according to the phases of flight dynamics.

During the I and II stages, the main advantage is to minimize the risk of accidents caused by untimely reaction to crosswinds during the run. The key parameters are identified at Table 1:

• Runway heading error ($\Delta\psi_{rw}$), defined as the angular difference between the direction of actual UAV movement (track angle) and the run-

Table 1. **Take- off stages performance metrics**

Take-off stage	Name, measurement units of the parameter	Manual control	Autonomous control
I stage	Runway flight path error ($\Delta\psi_{rw}$), °	± 3.0…5.0	± 0.5…1.0
II stage	Pitch angle accuracy ($\Delta\upsilon$), °	± 2.0…3.0	± 0.2…0.5
III stage	Full energy error ΔE_{tot}, (m²/s²)	± 15…20	± 2.0…4.0

way axis, which characterizes the accuracy of trajectory maintenance during the run-up, including the impact.

• Pitch angle error ($\Delta\upsilon$) is defined as the absolute deviation of the current pitch angle from the set value υ_{ref} at the lift-off moment, which is important to prevent a stall or tail strike.

On the stage III of take-off and during landing, the Total Energy Control System (TECS) method was applied [16], where the key metrics were defined as:

• Total energy error (ΔE_{tot}): defined as the deviation between the set and actual values of the total mechanical energy of flight ($E_{tot} = E_{pot} + E_{kin}$), which characterizes the efficiency of thrust and pitch control within the TECS under the influence of external disturbances.

Traditional control systems can enter a mode where the altitude contour requires an increase in pitch, and the speed contour requires a thrust increase that leads to overshooting and irrational energy consumption. Therefore, to increase the UAV durability, it is appropriate to use a full-energy control system. Its difference is that the altitude and speed control channels do not operate in isolation, TECS integrates them into a single energy contour. It allows the algorithm to harmonize the operation of the engine ($\Delta\delta_{th}$) and elevator ($\Delta\upsilon_{cmd}$), considering the vehicle as a holistic system that exchanges kinetic energy for potential and vice versa. This approach eliminates the "conflict" of contours in a turbulent environment, prevents overshooting and ensures a stable flight profile under difficult meteorological conditions.

In general, the transition to energy-centric autonomous control provides a significant unmanned aircraft operational efficiency increase. Quantitative analysis of the indicators confirms that the accuracy of trajectory maintenance and the softness of the landing touchdown increase compared to manual control mode. It not only reduces the working load of the operator, but also directly affects the technical resource of the glider.

The implementation of autonomous energy state control algorithms allows to transfer the takeoff and landing process from the category of subjectively controlled operations to the dimension of high-precision technological processes. The considered approach to automation provides rigid stabilization of spatial position and course that reduces risks associated with untimely operator reaction. This guarantees high repeatability of takeoff and minimizes the probability of emergency situations, such as premature stalling or runway overrun.

Discussion of the Results

The integration of autonomous take-off and landing algorithms demonstrates a qualitative transition from stochastic manual control to a deterministic technological process. The analysis shows that during I and II stages the algorithm provides rigid stabilization of roll and pitch that minimizes the risks associated with the human factor.

The transition to stage III and the subsequent landing phase highlight the main advantage of the full energy control system, where, unlike traditional PID-based architectures, TECS harmonizes the pitch ($\Delta\upsilon$) and thrust ($\Delta\delta_{th}$) control signals. By considering the UAV as a single energy system that balances kinetic and potential energy, the algorithm eliminates control conflicts in a disturbed environment.

The results of the conducted analysis indicate a significant reduction in total energy error (ΔE_{tot}) and the stabilization of the vertical descent rate during landing, demonstrating the high predictability of the developed algorithms. These improvements directly translate into increased operational efficiency and overall UAV survivability under conditions of high environmental uncertainty. By neutralizing the human factor and effectively compensating for stochastic external disturbances, the proposed technology enables the reliable execution of missions in complex meteorological conditions that are typically critical for manual control or traditional automatic systems. A detailed experimental verification of the landing phase and the validation of the proposed mathematical models are the subjects of a separate extended study currently in preparation for publication.

To objectively evaluate the scientific novelty of the proposed technology, an analytical comparison was conducted between the developed energy-centric method — based on the Total Energy Control System (TECS) — and conventional Model Reference Adaptive Control (MRAC), as well as modern intelligent algorithms based on Reinforcement Learning (RL). Unlike AI-based methods, which exhibit high sensitivity to the completeness of the training dataset and present a “black box” problem due to the low physical interpretability of their models, the energy-centric approach is rooted in fundamental physical invariants of motion. This enables the achievement of a high level of robustness to critical wind gusts without requiring significant computational resources from the onboard computer. Compared to MRAC algorithms, which are prone to error accumulation and high-frequency oscillations during intensive maneuvering in a turbulent environment, the proposed logic ensures natural disturbance rejection through its direct interpretation as fluctuations in the system’s energy budget (Table 2).

Despite the demonstrated efficiency, the operation of the proposed energy-centric control loop is constrained by several critical boundary conditions of both aerodynamic and hardware nature. First, the system’s capacity for energy fluctuation compensation is directly limited by the actuator saturation effect and the dynamic range of the propulsion system. The algorithm operates under the assumption that the aerodynamic control surfaces and the engine possess sufficient power margins; therefore, in cases where wind-induced stochastic disturbances exceed the maximum available thrust of the propulsion system ($T_{\max}$), a degradation in flight stabilization quality inevitably occurs. Second, the stability of the non-linear adaptive roll control logic critically depends on the

Table 2. **Comparison of Adaptive Control Methods**

Control Approach	Computational Cost of Onboard Computer	Data/Training Dependency	Robustness to Wind Gusts	Physical Interpretability of Models
Conventional MRAC	Moderate	Low (Requires plant model)	Moderate (Prone to high-frequency oscillations)	High
AI/ Reinforcement Learning (RL)	Extremely High	Critically High (Massive datasets required)	High (Strictly within the trained domain)	Low ("Black box" problem)
Proposed Energy-Centric (TECS)	Low	None (Physics-invariant)	High (Inherent robustness)	Excellent (Direct energy-state control)

update frequency of the sensory subsystems, as continuous state estimation requires a minimum sampling rate of the information fusion matrix at 50 Hz to prevent phase lag under turbulent atmospheric conditions. Finally, a significant limitation is the aerodynamic configuration of the aircraft, since the current mathematical model is tailored exclusively for fixed-wing UAVs and their inherent monotonic profiles of kinetic and potential energy interchange, which precludes its direct transfer to multirotor platforms without a complete restructuring of the power distribution matrices.

Conclusions

The paper proposes a conceptually new approach to the autonomous take-off and landing of unmanned aerial vehicles (UAVs) based on the energy-centric control paradigm. By applying the energy-based flight control method, the developed technology eliminates the drawbacks of traditional systems, such as low precision in turbulent atmospheric conditions and stability degradation under high-frequency stochastic disturbances. The control criteria in this approach are the minimization of total energy deviation from the reference value set by a virtual glide slope, and the minimization of the imbalance between the kinetic and potential components of total energy, effectively utilizing the aircraft's energy state as a fundamental physical invariant. This approach provides inherent robustness to the autonomous system through the intelligent interpretation of external disturbances as fluctuations in the energy budget. Furthermore, the findings demonstrate a reduction in human-factor errors during take-off and landing by delegating cognitively demanding stabilization tasks to automated algorithms, which lowers operator requirements and training costs. The developed technology does not require complex landing maneuvers and significantly enhances operational autonomy across a wide range of initial conditions by eliminating the mandatory reliance on ground-based airfield infrastructure. This substantially expands the permissible conditions for routine and emergency landings, transforming complex meteorological factors from critical constraints into controllable environmental parameters. Consequently, it increases the flexibility, efficiency, responsiveness, as well as the overall survivability and functional stability of the UAV in uncertain environments. Future work will focus on scaling the technology for multi-agent systems (UAV swarms) of the fixed-wing type, ensuring compatibility with a broader range of existing autopilots, and implementing rapid adaptation methods based on random projections to create a unified intelligent control loop.

DECLARATIONS.

O.Ye. Volkov developed the core conceptual approach based on the Total Energy Control System (TECS) methodology, defined the control invariants, supervised the research, and revised the manuscript for critical intellectual content.

I.V. Popov designed the control algorithms for the takeoff and landing stages, developed the simulation models, analyzed the performance metrics under atmospheric turbulence, prepared the figures and tables, and wrote the original draft of the manuscript.

AI and Tools Usage. The authors acknowledge the use of the Gemini (Model 1.5 Flash/Pro) artificial intelligence system during the preparation of this manuscript. The involvement of the AI system was strictly limited to technical and linguistic aspects of material preparation in the following sections:

• Section "Analysis of the Efficiency of Autonomous UAV Total Energy Control During the Takeoff Phase": The AI system was utilized for the translation of specialized technical terms, ensuring their correspondence with international aerospace standards, and for the stylistic refinement of the description of the energy-state control approach.

• Section "Discussion of The Results": The AI system was employed for the linguistic optimization of the English text, professional stylistic editing, and verification of aerospace terminology compliance with IEEE standards.

The authors declare that the use of AI was confined solely to technical and linguistic enhancements. All scientific content, mathematical formulations, interpretation of simulation results, formulation of conclusions, and final verification of data accuracy were performed personally by the authors. The authors bear full responsibility for the reliability and integrity of the submitted work.

Volkov O.Ye. has a potential conflict of interests as a Deputy Editor-in-Chief of the Journal. Popov I.V. has no known competing financial interests or personal relationships conflicts of interests.

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ЕНЕРГОЦЕНТРИЧНЕ КЕРУВАННЯ АВТОНОМНИМИ МОБІЛЬНИМИ ВУЗЛАМИ ДЛЯ ПІДВИЩЕННЯ ФУНКЦІЙНОЇ СТАБІЛЬНОСТІ В УМОВАХ ТУРБУЛЕНТНОСТІ

Вступ. За останні роки безпілотні літальні апарати перетворилися на окремий клас складних динамічних систем, що характеризуються високою функційною щільністю та масштабованістю в застосуванні. Інтеграція передових сенсорних приладів, включно з мультиспектральними та інерціальними вимірювальними підсистемами, дала змогу безперервно генерувати великі масиви даних щодо параметрів польоту, стану бортових систем та характеристик навколишнього середовища. Ключовим фактором цього якісного переходу стало впровадження високопродуктивних бортових обчислювальних та комунікаційних комплексів, здатних обробляти, агрегувати та інтерпретувати сенсорну інформацію в реальному часі з допомогою методів фільтрації, оцінювання стану та адаптивного прогнозування. Отже, створено необхідні передумови для суттєвого підвищення ефективності польоту завдяки розробленню та впровадженню високоточних систем автоматичного керування. Рух автономних мобільних вузлів (АМВ) охоплює такі етапи, як автоматичний зліт та посадка, обчислення траєкторії та подальше слідування за траєкторією, інтегровані з процесами прийняття рішень високого рівня залежно від цілей місії. Для сучасних авіаційних комплексів під час зльоту та посадки в умовах атмосферної турбулентності може спостерігатися погіршення точності керування, що проявляється збільшенням відхилень від заданих режимів польоту та зниженням стійкості в контурах регулювання. Такі системи демонструють недостатню адаптивність до високочастотних турбулентних впливів, що призводить до накопичення помилок керування, збільшення навантаження на виконавчі механізми та зниження загальної ефективності стабілізації польоту. Тому у статті запропоновано концептуальний підхід до автономного керування рухом АМВ. на основі методології повного керування енергією (*TECS*).

Метою роботи є підвищення експлуатаційної ефективності та живучості безпілотної авіації завдяки використанню енергетичного стану апарата як фундаментального інваріанта керування.

Результати. Запропонований підхід нівелює обмеження традиційних систем, зокрема їх високу чутливість до стохастичних збурень та втрату точності стабілізації під час турбулентності. Алгоритм керування оптимізовано за двома критеріями: мінімізацією відхилення повної енергії АМВ від опорної траєкторії польоту та мінімізацією дисбалансу між кінетичною та потенційною енергіями для стабілізації швидкості зниження (сходження).

Висновки. Результати моделювання свідчать, що впровадження методу забезпечує стійкість до зовнішніх динамічних збурень, мінімізує вплив людського фактора та дає змогу виконувати місії за несприятливих метеоумов без жорсткої залежності від наземної аеродромної інфраструктури. Подальші дослідження спрямовані на масштабування підходу для багатоагентних систем, інтеграцію методів адаптації на основі випадкових проєкцій та натурне тестування платформ із фіксованим крилом.

Ключові слова: *автономний мобільний вузол,, автономний зліт і посадка (ATOL), повне керування енергією (TECS), енергетичний стан, атмосферна турбулентність, функціональна стабільність, живучість літальних апаратів.*