Integration of Adaptive Algorithms for the Control of Unmanned Aerial Vehicles in Combat Conditions

Savin Yevgeniy Vladimirovich
National University of Uzbekistan named after Mirzo Ulugbek
Instructor at the Military Training Center
doi:https://doi.org/10.5281/zenodo.24361220

Abstract. This article addresses the challenge of enhancing the efficiency and stability of unmanned aerial vehicle (UAV) control within the context of modern combat operations. The study analyzes the limitations of traditional control systems in dynamic environments and substantiates the operating principles of adaptive algorithms as an alternative. Furthermore, conceptual models describing vehicle movement under conditions of external interference and electronic warfare—along with a modular software architecture (based on the ROS platform) designed for their implementation—have been developed.

The research demonstrates that the proposed integrated approach increases the level of UAV autonomy, enables adaptive control in real-time, and significantly strengthens system stability amidst uncertain technical and tactical conditions.

Keywords: unmanned aerial vehicles (UAVs), combat conditions, adaptive algorithms, conceptual modeling, modular software architecture, ROS platform, autonomous control, electronic interference.

The experience of modern military conflicts demonstrates that unmanned aerial vehicles (UAVs) have become a decisive tool for conducting reconnaissance, identifying targets, and executing strikes. However, the jamming of control signals by enemy electronic warfare (EW) systems significantly diminishes the effectiveness of conventional UAVs. Under such conditions, there is a pressing need to integrate intelligent, adaptive control algorithms that do not rely on an operator and can rapidly adjust to a changing environment. Traditional control systems—such as standard PID controllers—depend on stable communication channels and precise navigation data. In combat scenarios, however, the loss of communication links, the spoofing of GPS signals, or the impact of strong winds and mechanical damage are common occurrences. Consequently, integrating intelligent, adaptive control algorithms capable of real-time adjustment to dynamic environments into UAV onboard systems represents a critical scientific and technical challenge.

In the current landscape of global security and military conflict, the accurate and rapid collection of operational data stands as a key factor in determining strategic advantage. In this context, unmanned aerial vehicles (UAVs) are being widely utilized in modern military operations due to their ability to perform tasks without human intervention [1]. At the same time, the modern combat environment is characterized by a high degree of dynamism and uncertainty, as well as the presence of electronic warfare measures employed by the adversary and fluctuating meteorological conditions. Under such circumstances, traditional, static control systems—which operate based on pre-defined parameters—are unable to adapt sufficiently to external influences.

Research indicates that small-scale UAVs, in particular, are highly sensitive to uncertainties in the external environment, which diminishes their mission effectiveness [2]. Consequently, the stability of the vehicle may be compromised in conditions involving electronic interference or significant aerodynamic disturbances [3]. In this regard, the implementation of adaptive algorithms within UAV control systems represents a pressing scientific and practical challenge. The objective of this article is to analyze the potential for enhancing the autonomy and functional stability of UAVs in combat environments through the integration of adaptive algorithms into their control systems. The article focuses primarily on the logical structure of the control system, the principles of adaptive modeling, and the integration of these elements with modern modular software architecture (using the ROS platform as an example) [4]. The scientific novelty of the research lies in treating adaptive algorithms, conceptual models, and software architecture components as a single, integrated system. This approach enables the compensation of external disturbances in real time and ensures system stability.

The main types of adaptive algorithms and their associated combat tasks are summarized in Table 1 below. This classification clearly illustrates the scope of application for these algorithms, as well as the mechanisms they employ to overcome technical obstacles on the battlefield.

1-Table

Main types of adaptive algorithms and their combat tasks

Algorithm Type	Primary functions	Challenges Addressed (Electronic Warfare / Environment)	Technologies Used
Visual Odometry and SLAM	Mapping the environment and determining the drone's position in space	Jamming or spoofing (falsification) of GPS/GLONASS signals	Onboard cameras, LiDAR, inertial sensors (IMU)
Reinforcement Learning (RL)	Selecting optimal maneuvers and flight trajectories in hazardous situations	Anti-aircraft fire and unexpected dynamic obstacles	Deep neural networks
Computer Vision	Autonomously detecting, classifying, and tracking targets during the final phase	Complete loss of the communication link with the operator	(Deep Q-Networks)
Swarm Intelligence	Distributing tasks among multiple drones and coordinating their movements	Destruction of the central command hub or loss of connectivity	Convolutional neural networks
Adaptive PID and LQR Control	Maintaining flight stability and compensating for external influences	Strong winds, blast waves, or partial damage to the airframe/hull	(YOLO, SSD)

I. Structural-functional analysis of adaptive control algorithms. In combat conditions, the control system of an unmanned aerial vehicle (UAV) must not only ensure the stability of its flight trajectory but also provide a rapid and appropriate response to unexpected external influences. Traditional static algorithms (such as PID controllers) rely on pre-set control parameters. However, such systems often fail to adequately account for external changes—for instance, when the aerodynamic characteristics of the vehicle shift or when electronic interference affects sensor performance. Consequently, control errors may increase, potentially compromising the stability of the system [5]. The primary advantage of adaptive algorithms is that they continuously analyze the discrepancy between a reference model and the actual state of the system during the control process.

This process consists of the following key stages: Error detection—data obtained from sensors is compared against expected outcomes; Parameter adaptation—control parameter values are readjusted in real time to account for external influences; Compensation—an adaptive control action is generated to eliminate identified deviations. In combat conditions, the L1 adaptive control concept, in particular, demonstrates high efficiency. A unique feature of this approach is that the adaptation rate and system stability are controlled independently of one another. This enables the vehicle to adapt rapidly to quickly changing environmental conditions while minimizing the likelihood of excessive oscillations [4]. Consequently, adaptive algorithms enhance the functional stability of an unmanned aerial vehicle (UAV) control system and ensure reliable operation amidst uncertain and dynamic external environments. This significantly boosts the operational effectiveness of the vehicle.

II. Conceptual Modeling and Foundations of a Systems Approach. The effective operation of an unmanned aerial vehicle (UAV) performing reconnaissance tasks relies on a thorough and systematic modeling of the interaction between its internal control system and the external environment. In this context, the conceptual model is not viewed merely as a simple geometric or mathematical representation, but rather as a "cognitive map" that encapsulates the vehicle's information-analytical and decision-making capabilities.

This approach ensures the adaptive performance of the UAV under complex and dynamic conditions. Mechanisms for compensating for external influences and uncertainties: During reconnaissance operations, the dynamics of an unmanned aerial vehicle (UAV) are constantly subject to change due to external factors.

In particular, electronic warfare (EW) assets employed by an adversary can disrupt navigation signals or inject false information. Under such conditions, a conceptual model—utilizing an integrated analysis of motion parameters (based on inertia) and data from onboard sensors—enables the distinction between genuine and deceptive signals. Consequently, the vehicle is able to maintain a stable spatial orientation and minimize navigational errors [6].

The "Situation Awareness" model implies that the conceptual framework developed for a reconnaissance drone encompasses not only flight dynamics but also the overall safety status of the mission. In this model, factors such as energy reserves, altitude (in relation to remaining undetected by enemy radar systems), and the reliability of the data transmission channel are integrated into a single, unified system. Should the risk of detection via the communication channel increase, or if the level of electromagnetic interference rises, the system automatically decides to switch to "radio silence"

(emission control) mode. This serves to enhance the drone's stealth capabilities and ensure operational security.

Regarding the concept of an "adaptive digital twin," it can be noted that digital twin technology plays a significant role in modern conceptual approaches to unmanned aerial vehicle (UAV) design. Within this framework, the mathematical and algorithmic model of the aircraft operates in real-time, synchronized with its physical state. The digital twin is used to continuously analyze discrepancies between the ideal flight trajectory and the actual flight parameters.

If the system detects deviations—such as a drop in engine power, an increase in aerodynamic drag, or sudden shifts in external airflow—these are flagged as anomalies. Based on these conditions, adaptive control algorithms are automatically activated, restoring the system's stability [7]. In general, these conceptual modeling principles enable an Unmanned Aerial Vehicle (UAV) not only to execute pre-defined commands but also to make independent decisions under complex and uncertain conditions, while maintaining its own operational integrity.

III. Software Architecture and System Integration. In practice, adaptive algorithms and conceptual models are implemented within a real-world system through a high-performance software ecosystem. For UAVs deployed in combat environments, the software must handle not only flight control but also data processing, transmission, and the assurance of system security.

Modularity, scalability, and reliability are considered the primary criteria when selecting software platforms: 1. The ROS (Robot Operating System) platform. ROS is one of the software environments widely used in modern robotics and UAV systems. Its modular architecture allows functional components to be organized as individual nodes. This approach ensures that other modules continue to function stably even if a malfunction occurs in certain parts of the system [8]. 2. Allocation of onboard computer resources. Given the limited computational resources in combat UAVs, the software architecture must ensure efficient resource allocation in real time. To this end, C++ is used for low-level control processes, while Python is employed for high-level data processing and artificial intelligence algorithms. This combination allows for the optimization of the computational load. 3. Cybersecurity and data protection. In combat environments, cybersecurity is a critical component of the software. The system must incorporate mechanisms to detect and block external interference and unauthorized access attempts. This ensures the stable operation and operational reliability of the UAV [9].

Integrating adaptive algorithms into UAV onboard computers requires neuroprocessors that offer high computational power while consuming minimal energy. These algorithms process data from sensors in real time and issue direct commands to control surfaces and engines. The stages for integrating adaptive algorithms into the UUA system, along with the expected results, are summarized in Table 2 below. This table reflects the technical implementation mechanism and its direct impact on combat effectiveness.

2-Table

Stages of integrating adaptive algorithms into the UAV system and expected results

Integration Phase / Mechanism	Technical Implementation Method	Expected Outcome	Combat advantage

Hardware Adaptation	Integrating low-power neuroprocessors (NPUs) and graphics accelerators (GPUs) on-board	Processing large volumes of sensor data on-board the drone (Edge AI)	Eliminates the need to exchange data with a ground station
Sensor Integration (Sensor Fusion)	Consolidating data from cameras, LiDAR, radar, and inertial measurement units (IMUs) into a unified system	Obtaining accurate and continuous data regarding the external environment and the drone's status	Maintains target tracking even when GPS and radio communications are jammed
Real-time Decision-making	Connecting algorithms directly to the flight controller and actuators (motors, control surfaces)	Reducing the time required for obstacle detection and maneuvering to the millisecond level	Eliminates delays associated with the human factor and enhances survivability
Dynamic Route Optimization	Continuously recalculating the flight path while accounting for weather, terrain, and hazardous areas	Minimizing energy and fuel consumption	Extends flight range and endurance (time spent in the air)
Autonomous Final Control	Linking target recognition algorithms with the targeting and strike system	Independently tracking and neutralizing a target, even in the event of a loss of connection with the operator	Neutralizes the impact of electronic warfare (EW) systems

In conclusion, it should be noted that this research analyzed the integration of adaptive algorithms, conceptual models, and software architecture for unmanned aerial vehicles (UAVs) performing tasks in combat environments. Overall, this software approach establishes a seamless link between theoretical models and the actual hardware, creating a stable, adaptive, and secure operational environment for UAVs operating under combat conditions.

The results obtained lead to the following key conclusions: 1. Resilience and stability. The use of adaptive algorithms ensures that a UAV continues to operate reliably even when subjected to electronic interference, navigational disruptions, or uncertain external conditions. This approach enhances the operational reliability of the hardware compared to traditional static control systems.

2. The importance of modeling. Integrating "Digital Twin" and situational analysis models into the software system expands the UAV's autonomous decision-making capabilities. Consequently, the level of reliance on an operator is reduced, while the system's capacity for independent operation and its overall level of safety are increased. 3. The efficiency of the software architecture. The use of modular software platforms, such as ROS, enhances the flexibility and scalability of a system. This enables rapid adaptation and updates for various tasks without requiring structural modifications to the hardware. Overall, the integration of adaptive algorithms, conceptual modeling, and modern software architectures ensures that an unmanned aerial system (UAS) operates effectively and reliably in complex

environments. Furthermore, advancing research in this field by incorporating artificial intelligence methods and swarm intelligence technologies has the potential to further increase the system's autonomy and efficiency.

References

1. Korelov, G. V. (2018). Perspectives of using UAVs in modern reconnaissance missions. Journal of Military Science.
2. Beard, R. W., & McLain, T. W. (2012). Small Unmanned Aircraft: Theory and Practice. Princeton University Press.
3. Makarov, A. S. (2020). Analysis of EW impact on UAV control systems and communication channels. Technical Review.
4. Hovakimyan, N., & Cao, C. (2010). L1 Adaptive Control Theory: Guaranteed Robustness. SIAM.
5. Lavretsky, E., & Wise, K. A. (2013). Robust and Adaptive Control: With Aerospace Applications. Springer Science & Business Media.
6. Stevens, B. L., Lewis, F. L., & Johnson, E. N. (2015). Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems. Wiley.
7. Grieves, M., & Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. Springer.
8. Quigley, M., et al. (2009). ROS: an open-source Robot Operating System. ICRA Workshop on Open Source Software.
9. Javaid, A. Y., et al. (2012). A Cyber-Security Review of Unmanned Aerial Vehicles (UAVs). Journal of Intelligent & Robotic Systems.