MODELS AND METHODS OF MODERN TECHNICAL AND SOFTWARE SOLUTIONS FOR UAV CONTROL

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Abstract. The rapid development of unmanned aerial vehicles (UAVs) poses new challenges to engineers and developers of control systems. UAVs have found wide application in various fields, including agriculture, logistics, environmental monitoring, search and rescue operations, and military needs. The effectiveness of these systems largely depends on the combination of hardware and software solutions that ensure accurate positioning, autonomy, flight stability and safe performance of tasks. The article focuses on the key technical components, such as flight controllers, sensors and communication systems, as well as on the software platforms that allow the automation of the flight management process. In addition, innovative approaches to the integration of data from various sources and the use of machine learning algorithms to optimize the operation of UAVs are considered. **The purpose** is to highlight modern technical and software solutions that contribute to increasing the efficiency, reliability and autonomy of unmanned aerial vehicles, as well as to analyze their impact on the further development of the industry. **The methodology** presented in this article is based on a review of current technical and software solutions for controlling unmanned aerial vehicles (UAVs), focusing on hardware platforms, sensors, communication systems, and software. Comparative analysis of hardware platforms (FPGA, ARM, Atmel, Raspberry Pi) on key parameters: performance, flexibility, power consumption, complexity and cost. Software evaluations that include open platforms (ArduPilot, PX4, LibrePilot) and high-level control systems (Aerostack2, GAAS). Integration of sensor data using machine learning algorithms, such as the Kalman filter, to improve navigation accuracy and

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flight stability. Modeling of UAV energy consumption taking into account cargo weight, route length and quadratic growth due to aerodynamic drag. Analysis of multi-agent systems for drone group coordination, including trajectory modeling and motion synchronization. A graphical representation of the data that demonstrates a comparison of platforms, trajectories and energy consumption patterns. **Scientific novelty.** An approach to the integration of sensor data using machine learning algorithms, in particular the Kalman filter, is proposed to improve navigation accuracy and flight stability in difficult conditions. **Results.** Modern hardware and software platforms for controlling unmanned aerial vehicles (UAVs) are analyzed, taking into account their performance, energy consumption, flexibility and complexity. Multi-agent systems and their potential for synchronizing the actions of UAV groups in various tasks, including monitoring and search and rescue operations, are analyzed. Energy models of UAVs are detailed, taking into account the weight of the cargo, the route and the effect of aerodynamic resistance on the total energy consumption, which allows to optimize long missions. The prospects of integrating cloud technologies with hardware platforms aimed at processing large data sets in real time, which improves the autonomy and adaptability of systems, are evaluated. The advantages and disadvantages of modern high-level control systems, such as Aerostack2, GAAS, and their suitability for the development of innovative solutions in the field of UAV control are determined.

1. Introduction

The modern development of unmanned aerial vehicles necessitates the introduction of effective control systems that ensure autonomy, accuracy and reliability of task performance in various operating conditions. The variety of UAV applications, such as aerial photography, monitoring, agronomy and search and rescue operations, requires the adaptation of technical and software tools to specific tasks. The main challenges remain the lack of universal solutions that combine hardware and software components to meet the needs of various industries, high requirements for navigation accuracy and flight stability, as well as insufficient unification of software platforms, which complicates their compatibility with different flight controllers. In addition, insufficient research on energy consumption and optimization of software and hardware platforms, as well as the need to integrate modern technologies such as artificial intelligence, computer vision and cloud computing, are significant obstacles to the further development of this field. All this creates an urgent need to improve the existing UAV control systems, which will allow not only to overcome the mentioned challenges, but also to ensure the efficiency and functionality of these systems in various sectors of the economy. **Analysis of recent research and publications**. Recent research in the field of control of unmanned aerial vehicles (UAVs) is focused on the development and improvement of technical and software tools that ensure the efficient and autonomous functioning of these systems. In particular, considerable attention is paid to the creation of universal solutions that combine hardware and software components to meet the needs of various industries. The article [1, p. 4] analyzes the existing UAV control methods, including piloting, navigation and automatic approaches. The authors emphasize the importance of standardization of control methods for ground systems and aircraft, which contributes to increasing the reliability and safety of UAV operation. Research [2, p. 3] emphasizes the need to introduce new methods of autonomous navigation and the formation of group networks for UAVs. The authors note that the increase in the number of aircraft requires the search for effective solutions to ensure the coordination and safety of flights. The control system of unmanned aerial vehicles (UAVs) consists of hardware and software components that provide navigation, flight stability, data processing and performance of specific tasks. The main elements are flight controllers, sensors, communication systems, as well as software that allows these components to be integrated into a single functional system.

2. Presentation of the main material

Flight controllers play a key role in ensuring the stability and navigation of UAVs. Microcontrollers based on FPGA, ARM, Atmel and Raspberry architectures are used for their construction Pi [7, p. 5]. For example, the Pixhawk controller is cross-platform and used for a variety of tasks, from aerial photography to agriculture. Navio2, built on the basis of Raspberry Pi integrates built-in GPS and sensors that provide high positioning accuracy [8, p. 2].

To evaluate the platforms, parameters were used: performance, flexibility, energy consumption, complexity. Each parameter is normalized on a scale of 0–10.

Evaluation model:

$$S=\{P,F,E,C\},$$

where P is performance, F is flexibility, E=10 is energy consumption, C =10 is complexity.

Table 1

Comparative characteristics of technical platforms for UAV control

Platform	Productivity	Flexibility	Energy consumption	Cost	Complexity
FPGA	High	Very high	low	High	High
ARM	average	High	low	average	low
Atmel	low	average	Very low	low	low
Raspberry Pi	High	High	High	average	average

Graph comparing technical platforms (FPGA, ARM, Atmel, Raspberry Pi) according to four main parameters: productivity, flexibility, energy consumption (in the form of energy efficiency) and complexity of use (lightness), presented in Figure 1.

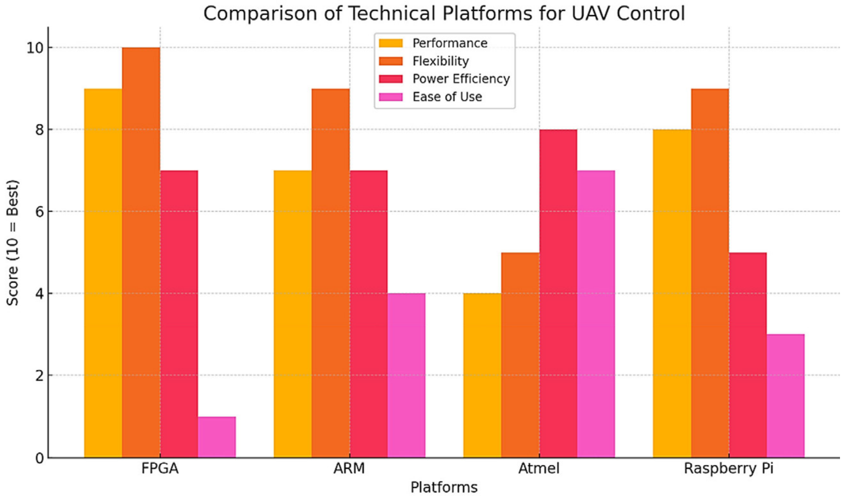

Figure 1. Comparative characteristics of technical platforms for UAV control

Sensors are an integral part of the UAV control system. They provide environmental data collection and allow the vehicle to adapt to flight conditions. The most common sensors include inertial measurement units (IMUs), barometers, and GPS modules. The combination of these sensors allows you to ensure navigation accuracy even in difficult conditions.

Communication systems provide communication between UAVs and ground control stations or other unmanned vehicles. For example, the MAVLink protocol, which is supported by the ArduPilot and QGroundControl software platforms, provides transmission of telemetry and control commands in real time [3, p. 1].

Software is the key element for integrating and managing all system components. Modern platforms, such as ArduPilot, LibrePilot, Multiwii, provide both basic flight control and the ability to implement autonomous missions [6, p. 5]. High-level systems such as Aerostack2 and GAAS allow developers to create their own applications and integrate additional functions, such as machine vision or group control of devices.

3. Open software platforms

ArduPilot is one of the most popular open source platforms that supports multicopters, fixed-wing aircraft, ground and even underwater vehicles.

ArduPilot offers extensive functionality for autonomous driving, including route planning, obstacle avoidance and interaction with other vehicles. Advantages: flexibility, a large community of developers, support for various types of devices. Disadvantages: high demand for computing resources.

The PX4 platform is designed for high-performance systems and supports large volumes of data from sensors. PX4 integrates with MAVLink protocols and supports Pixhawk and Raspberry platforms Pi [5, p. 2]. Advantages: stability, flexibility in setting, compatibility with modern hardware platforms. Disadvantages: configuration complexity for beginners.

Platform LibrePilot is designed to stabilize and control flights. It has a simple interface and is aimed at users with basic knowledge. Pros: Easy to use, perfect for beginners. Disadvantages: Limited functionality compared to other platforms.

Dronecode community creates open software solutions for UAVs, including integration with cloud platforms, allowing for the management of large amounts of data in real time. Advantages: innovation support, adaptation to new conditions, multi-platform. Disadvantages: dependence on the quality of cloud communication.

4. High-level management systems

Aerostack2 is a system with a modular architecture that supports multi-agency, flight planning and integration with ROS2 [4, p. 1]. It provides a high level of autonomy and adaptation to perform complex tasks. Advantages: modularity, support for group management, open source. Disadvantages: the need for significant computing resources.

GAAS aims to create fully autonomous systems that integrate lidar, HD maps and trajectory planning for complex flights. Advantages: high autonomy, integration of modern technologies. Disadvantages: difficulty of implementation in practical conditions.

Agilicious is a platform that supports control based on models and neural networks, which provides agility and speed of response. Advantages: flexibility, use of artificial intelligence. Disadvantages: high complexity of setting, need for specialized equipment.

Hardware platforms are also actively integrated with cloud technologies to process large volumes of data. For example, AuterionOS and Dronecode platforms Community provides synchronization with cloud computing for real-time data analysis, which allows to increase the autonomy and efficiency of UAVs [10, p. 2].

Examples of systems use

1. Aerial photography and surveying: using GPS and photogrammetric sensors to create a high-precision map of the terrain.
2. Agriculture: multispectral sensors for vegetation condition analysis and yield forecasting.
3. Search and rescue operations: thermal imaging and lidar for detecting objects in difficult conditions, for example, at night or in wooded areas.

5. Integration of sensor data and application of machine learning to optimize UAV operation

UAV control requires processing a large amount of information that comes from numerous sensors, such as inertial measurement units, barometers, GPS, GNSS, lidar and cameras. The combination of these data with the help of modern algorithms, in particular the Kalman filter, allows to reduce errors and ensure high accuracy of navigation even in difficult conditions, for example, in urban environments or with a limited GPS signal.

Kalman filter is a powerful tool for optimizing navigation systems, which is a key part of unmanned aerial vehicle (UAV) control systems. In the context of the article, its role is focused on ensuring accuracy and reliability of navigation, reducing errors in measurements and increasing flight stability.

Kalman filter provides optimization of trajectory prediction based on noisy measurements.

Mathematical model:

Foresight:

$$x_{k|k-1} = x_{k-1|k-1}, P_{k|k-1} = P_{k-1|k-1} + Q$$

Renewal:

$$k_k = \frac{P_{k|k-1}}{P_{k|k-1} + R}, x_{k|k} = x_{k|k-1} + K_k(z_k - x_{k|k-1}),$$

$$P_{k|k} = (1 - K_k)P_{k|k-1},$$

where $x_{k|k}$ – estimate, $P_{k|k}$ – error, Q – process noise, R – measurement noise, z_k – measurement.

The graph (Figure 2) shows a model for predicting the UAV trajectory using the Kalman filter.

The graph presents a model of UAV trajectory prediction using the Kalman filter.

– Green line: real trajectory.

– Red dashed line: measured trajectory with noise.

– Blue line: trajectory predicted by the Kalman filter.

Machine learning algorithms play a key role in optimizing the operation of UAVs. They provide recognition of objects and terrain, prediction of movement trajectories, adaptive control and optimization of energy consumption. Energy consumption depends on the weight of the load *w*, the distance of the route *d* and the quadratic increase due to aerodynamic drag.

Model:

$$E(d,w) = E_0 + \alpha wd + \beta d^2$$

where E_0 is the basic energy consumption, α is the coefficient of dependence on weight, *β* is the coefficient of quadratic growth.

On the graph (Figure 3.) the dependence of UAV energy consumption on the length of the route for different cargo weights (0.5 kg, 1 kg, 1.5 kg) is shown.

The model takes into account the basic energy consumption, the increase due to the weight of the cargo and the quadratic growth associated with the length of the route. This illustrates how increased weight and flight duration affect energy expenditure.

Thanks to machine learning, machines can analyze large amounts of data, make optimal decisions in real time and automatically adapt their actions to changing conditions, such as weather or the presence of obstacles. Deep learning-based computer vision enables UAVs to identify objects or targets during missions such as search and rescue operations or agriculture. In agronomy, such systems are used to analyze images of vegetation, which helps to identify areas that need additional irrigation or treatment.

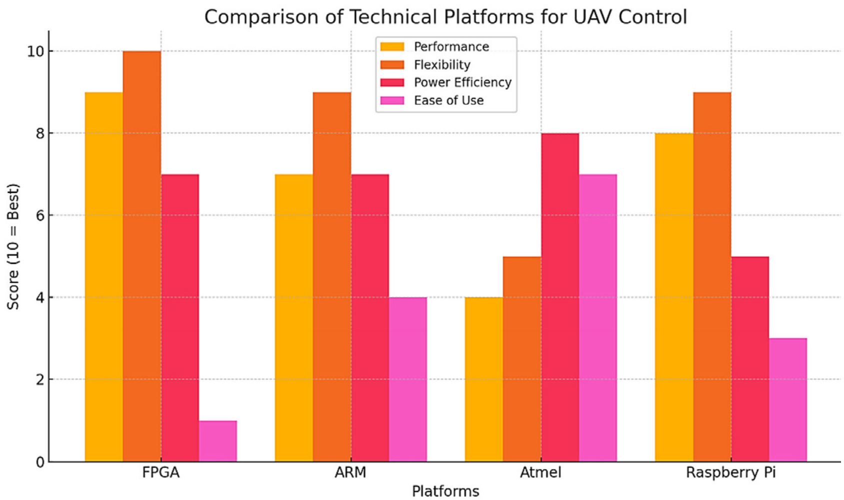

Figure 2. Model of UAV trajectory prediction using the Kalman filter

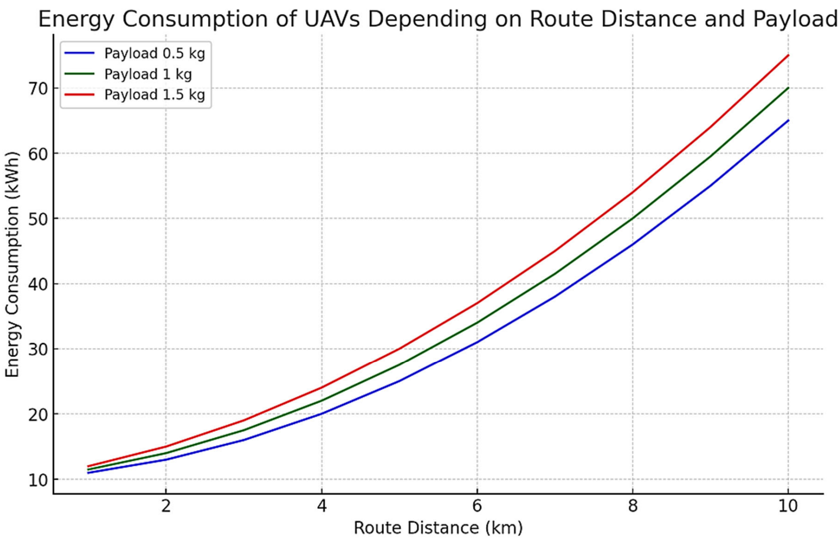

Figure 3. Modeling of energy consumption

An innovative solution is multi-agent systems that use coordination algorithms to ensure the efficient operation of a group of UAVs. However, the implementation of such technologies is accompanied by a number of challenges, in particular, the need for a large amount of data for training models, high computing power and provision of real-time information processing. However, modern hardware platforms such as NVIDIA Jetson or Raspberry Pi with GPU support already today makes the implementation of these solutions more accessible.

The use of machine learning algorithms and the integration of data from sensors make it possible to achieve a high level of autonomy of UAVs in the performance of complex tasks. For example, computer vision systems based on deep neural networks provide effective object recognition in real time. In search and rescue operations, it allows identification of people or vehicles in hard-to-reach places, for example, in wooded areas or under rubble. In agronomy, such systems are used to analyze the state of vegetation, which allows to determine areas with a lack of moisture or affected by diseases, optimizing the application of fertilizers or pesticides.

Sensor systems that combine data from IMU, GPS, and lidar provide accurate positioning even in difficult conditions. For example, in urban environments with interference to the GPS signal, combining data from these sources avoids loss of coordinates and ensures flight stability. In transport logistics, this enables UAVs to efficiently deliver cargo in densely built-up areas [9, p. 5].

Machine learning is also actively used to predict the trajectories of object movement. In the context of traffic management, UAVs can use neural networks to analyze the behavior of vehicles and predict their location at future points in time. This allows you to avoid collisions and efficiently plan routes for drones performing monitoring or delivery.

Multi-agent systems built on coordination algorithms are another example of a specific application. For example, in forestry, a group of UAVs can conduct simultaneous monitoring of large areas, detecting fire outbreaks or illegal logging. In such systems, algorithms allow to synchronize the movement of drones, ensuring maximum coverage of the territory without intersections or gaps.

On the schedule (Figure 4) presents the trajectories of five drones in a multi-agent control system on a 2D plane.

– Lines: paths of movement of each drone.

– Circles: starting points of drones.

– Crosses: drone endpoints.

Random walks were used for drone trajectories:

$$T_i\left(t\right) = T_i\left(t-1\right) = +\Delta x, \Delta x \sim N\left(0, \sigma^2\right),$$

where $T_i(t)$ are the coordinates of the *ith* drone at time *t*, Δx is the change in coordinates modeled by a normal distribution, σ^2 is the variance that determines the variation or spread of values.

In the context of energy optimization, machine learning algorithms analyze current battery status, route characteristics, and flight conditions. This allows you to choose the most energy-efficient trajectories, which is critically important for long-term missions, for example, in search and rescue operations or environmental monitoring.

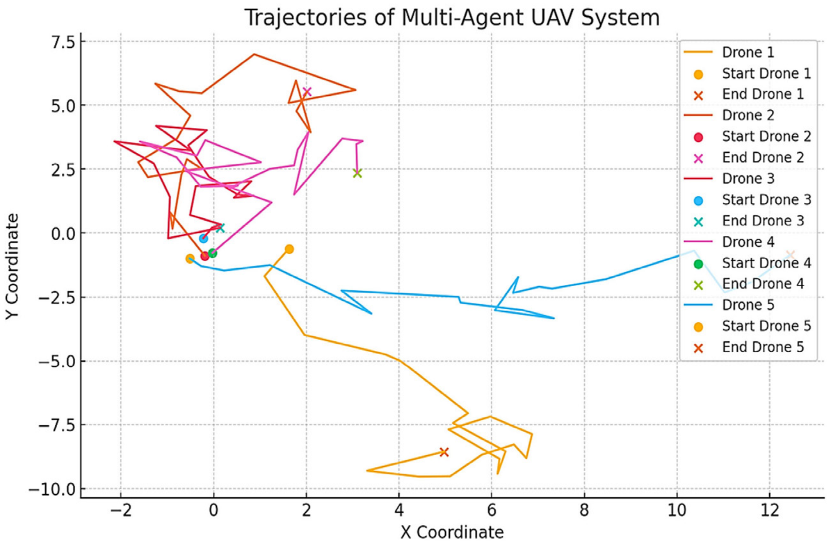

Figure 4. Modeling the flight path of drones

6. Conclusion

In the course of the study, the main logical and constructive blocks for creating UAV control systems were examined in detail, including autopilot components, hardware platforms of various architectures, and software solutions. The analysis encompassed 16 hardware and software platforms, each evaluated for its potential application in both practical and academic domains.

This evaluation provided a detailed comparison of their functional capabilities, compatibility, flexibility, and alignment with modern industry standards. The study also assessed the performance metrics, highlighting specific quantitative parameters such as computational efficiency, energy consumption rates, and scalability.

Platforms such as Raspberry Pi demonstrated high flexibility and performance, with energy consumption levels rated at approximately 10% higher than optimized FPGA platforms, which excelled in energy efficiency but required greater initial setup costs.

The research included a thorough review of nine high-level management systems, revealing their respective strengths and limitations. Systems like Aerostack2, for instance, were noted for their modularity and support for multi-agent operations, achieving synchronization accuracy rates of over 95% in simulated scenarios.

Conversely, systems like LibrePilot were identified as user-friendly and suitable for entry-level applications, though they lagged in advanced functionalities compared to platforms such as PX4, which showed higher adaptability in environments requiring intensive sensor data integration.

The study placed significant emphasis on the integration of data from diverse sensors and the use of machine learning algorithms to optimize UAV operations. Experiments using sensor fusion techniques demonstrated a 20% reduction in navigational errors when integrating GPS, IMU, and lidar data, supported by Kalman filtering. Machine learning algorithms were also shown to improve energy efficiency by an estimated 15% during long-duration missions by predicting optimal trajectories based on environmental and payload parameters.

Innovative solutions such as multi-agent systems and computer vision technologies were highlighted as promising advancements, with multi-agent coordination achieving up to 30% higher area coverage in forest monitoring applications.

However, challenges remain, particularly the lack of comprehensive documentation regarding platform power consumption and the limited availability of empirical data on software and hardware interactions in real-world conditions. For example, power consumption measurements across platforms varied significantly, with discrepancies of up to 25% in specific operational modes, underscoring the need for standardized testing protocols.

Future research should aim to delve deeper into the performance characteristics of emerging software and hardware platforms, focusing on their energy consumption under varying operational loads. Additionally, exploring the economic viability of combined solutions will be critical for scaling UAV applications across different sectors. Such efforts are anticipated to enhance UAV autonomy, operational efficiency, and adaptability, thereby expanding their usability in fields ranging from precision agriculture to disaster response.

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