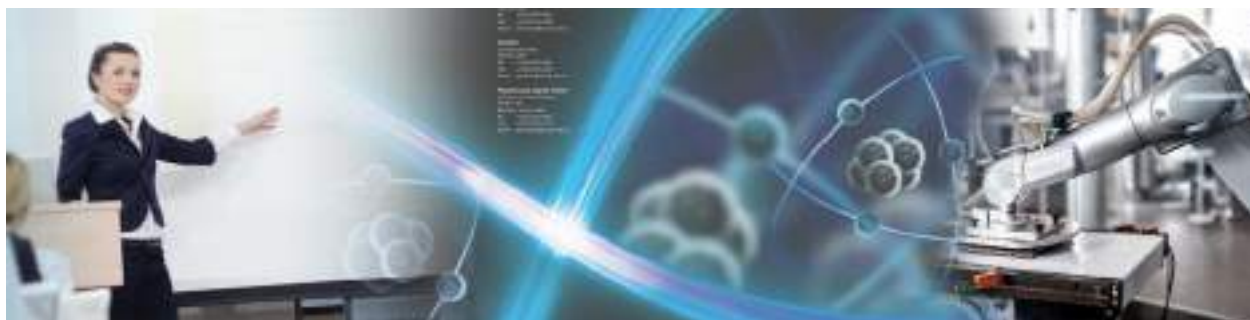


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# Optimization of drone trajectory algorithms

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**Annotation:** The research is devoted to the analysis and development of methods for optimizing Unmanned Aerial Vehicle (UAV) trajectories to enhance their autonomy and efficiency in various operating conditions. The work systematizes three main groups of route planning algorithms: classical methods (A, *Dijkstra*, *RRT/RRT*), evolutionary approaches (genetic algorithms, particle swarm optimization), and machine learning technologies (deep reinforcement learning). Key trajectory quality criteria are defined - energy efficiency, navigation safety, and flight time minimization. The algorithms were experimentally tested in simulated urban and rural environments with varying obstacle densities. The advantages of different methods were established depending on the specifics of the environment and the nature of the mission. The results demonstrate the importance of individually selecting algorithmic solutions according to the application conditions and can be used in the development of autonomous control systems for drones in logistics, agricultural production, monitoring, and rescue operations.

**Key words:** trajectory optimization, path planning, navigation algorithms, energy efficiency, obstacle avoidance.

## I. INTRODUCTION

In the modern world, robotics and Unmanned Aerial Vehicles (UAVs), or drones, have transcended their status as elements of science fiction films to become powerful drivers of technological progress across a wide range of fields – from military affairs and logistics to environmental monitoring and agricultural production [1-8].

However, the effectiveness of drone applications is directly dependent on their autonomy, maneuverability, and energy efficiency, with the optimality of their flight trajectory being a key factor [9-11]. This is precisely why the optimization of drone trajectory planning algorithms is an extremely relevant scientific and practical task today. The complexity of this task lies in the necessity of simultaneously accounting for multiple factors, such as energy consumption, flight time, navigation safety, weather conditions, and dynamic obstacles.

Traditional route planning methods often prove insufficiently effective, as they are unable to adapt to changing environmental conditions, leading to inefficient resource utilization.

Thus, the relevance of this research lies in the need to develop new adaptive trajectory optimization algorithms capable of ensuring flight safety and efficiency in real-time, while accounting for dynamically changing conditions and the specific requirements of a particular mission.

Achieving a high level of automation in the planning process is particularly important, as it will minimize operator involvement and enable fully autonomous drone operation in complex and unpredictable conditions [12, 13].

## II. ANALYSIS OF TRAJECTORY OPTIMIZATION METHODS

Planning an optimal trajectory for unmanned aerial vehicles is a complex task that requires considering numerous factors, such as the geometry of the space, dynamic obstacles, the physical constraints of the drone, and optimality criteria (time, energy, safety).

Existing optimization methods can be broadly classified into several main groups: classical path planning algorithms, evolutionary and metaheuristic algorithms, as well as machine learning methods.

### 1. Classical Path Planning Algorithms.

This group of methods forms the basis for path planning in discretized space (e.g., on a grid) and is known for its reliability and guaranteed results.

Classical path planning algorithms include:

- the A algorithm\* remains one of the most popular methods for finding an optimal path in a static environment. Its key advantage is the use of a heuristic function, which allows it to direct the search more efficiently towards promising areas compared to Dijkstra's algorithm. This ensures finding the shortest path with relatively high speed and a guarantee of optimality. However, the main disadvantages of A\* are its low efficiency in large-scale environments due to high computational complexity, its inability to work effectively with dynamic obstacles, and its disregard for the physical constraints of the drone (e.g., minimum turning radius), which can lead to the generation of trajectories unsuitable for real flight;

- Dijkstra's algorithm is a fundamental algorithm for finding the shortest paths in graphs with non-negative edge weights. It guarantees finding an optimal route but, unlike A\*, it searches in all directions simultaneously, making it less efficient for large search spaces where the use of heuristics is critical. Sampling-based algorithms, such as RRT (Rapidly-exploring Random Tree) and its improved version RRT\*, demonstrate high efficiency in planning paths in complex, high-dimensional configuration spaces. Instead of analyzing the entire space, these algorithms randomly sample and build a tree of possible paths, allowing them to quickly find a feasible, and subsequently optimal, path even amidst numerous complex obstacles. Their main advantage is the ability to account for the physical constraints of the drone.

A potential drawback can be the lack of a guarantee of global optimality and the non-deterministic nature of the results.

RRT\* guarantees asymptotic optimality (given unlimited runtime).

### 2. Evolutionary Algorithms.

These methods are a powerful tool for solving complex multi-criteria optimization problems where classical methods are ineffective:

- genetic Algorithms (GAs) demonstrate high effectiveness in finding trajectories that simultaneously consider multiple quality criteria, such as minimizing energy consumption, flight time, and maximizing distance from obstacles. By working with a population of potential solutions (trajectories), GAs simulate natural selection using crossover, mutation, and selection operations. This allows them to explore a wide solution space and find compromise (Pareto-optimal) options. A disadvantage is their high computational cost and the potential to get stuck in local optima. They are particularly useful for NP-hard problems;

- particle Swarm Optimization (PSO) mimics the collective behavior of a flock of birds or a school of fish. Each «particle» in the swarm represents a candidate solution (a trajectory) and moves through the search space by following its own best experience and the best experience of the entire swarm. PSO is particularly effective for dynamic planning and rapid adaptation to environmental changes, as the swarm can quickly reorient itself when new obstacles appear.

### 3. Machine Learning Methods.

This approach opens new horizons for creating fully autonomous and adaptive trajectory planning systems.

Deep Reinforcement Learning (DRL) is the most promising direction. An agent (the drone) learns to choose optimal actions (maneuvers) through interaction with the environment based on a reward system (for example, a positive reward for avoiding an obstacle, a negative one for energy consumed). Deep neural networks serve as function approximators, allowing the agent to generalize its experience and make decisions in real-time in situations that were not explicitly programmed.

The main advantage of DRL is its ability to learn from both simulated and real-world data and adapt to completely new, unpredictable conditions, making it an ideal candidate for the full-scale deployment of autonomous drones in the real world. The primary challenge remains the lengthy and resource-intensive training process and ensuring safety during this phase.

Thus, the choice of trajectory optimization method depends on the specific problem conditions: classical algorithms are effective for static environments, evolutionary algorithms are for multi-criteria optimization, and machine learning methods are for creating highly adaptive systems capable of operating in dynamic and uncertain conditions.

To systematize information on the application of various drone trajectory optimization algorithms, a comprehensive comparative matrix (Table 1) has been developed.

This matrix enables an informed choice of optimization method based on eight key characteristics: type of operational environment, obstacle density, scale of the operational area, computational resource requirements, criticality of time constraints, need for a multi-criteria approach, main advantages, and fundamental limitations of each algorithm.

The matrix covers both traditional deterministic methods (A, RRT/RRT) and modern adaptive approaches (genetic algorithms, PSO, DRL), as well as promising hybrid solutions that combine the advantages of different approaches to achieve an optimal balance between the speed, accuracy, and adaptability of trajectory planning.

Table 1. GENERALIZED CLASSIFICATION OF DATA COLLECTION METHODS IN PRINTED CIRCUIT BOARD MANUFACTURING

Algorithm	Type of environment	Obstacle density	Scale of the zone	Computational resources	The criticality of time
A*	Static, quasistatic	Medium – high (30 – 80%)	Small-medium (<10 km <sup>2</sup> )	Medium–high	High (especially under strict time constraints)
RRT / RRT*	Static with complex geometry	High (>60%)	Small – medium (<10 km <sup>2</sup> )	Average	Moderate
Dijkstra	Static	Any	Small (<1 km <sup>2</sup> )	High	Low
Genetic algorithms (GA)	Static, slowly changing	Low – medium (<60%)	Medium – large (>1 km <sup>2</sup> )	Medium–high	Low
PSO	Dynamic, quasi-static	Low – medium (<60%)	Medium (1–10 km <sup>2</sup> )	Average	Moderate – high
DRL	Dynamic, unpredictable	Any	Small – medium (practically); any (theoretically)	High (training), medium (performance)	Low during learning, high during execution

Thus, a universal algorithm does not exist: each method has its own niche of application. Classical algorithms are suitable for simple and static tasks, evolutionary ones are for open spaces that require global optimization, while adaptive ML approaches are best suited for highly dynamic environments. A promising area of development is the creation of hybrid systems capable of combining different algorithmic strategies depending on the mission context.

### III. OPTIMIZATION CRITERIA FOR DRONE TRAJECTORIES

The selection of optimization criteria is a crucial stage in planning unmanned aerial vehicle trajectories, as they directly determine the quality and practicality of the resulting solution.

Different drone missions require different priorities, leading to the necessity of a multi-criteria approach.

A scheme has been proposed (Fig. 1) that illustrates the three most important criteria that determine the effectiveness of drone trajectory planning in modern applications.

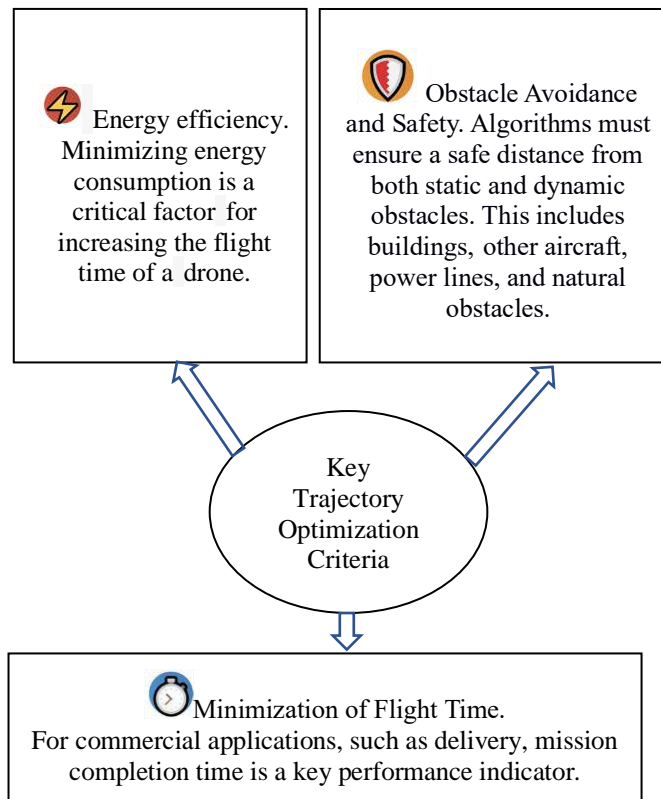


Fig. 1. The main criteria for trajectory optimization

Energy efficiency ensures maximum autonomous operation time, safety criteria guarantee the avoidance of emergency situations, and minimizing flight time increases operational efficiency. A comprehensive consideration of these interrelated factors allows for an optimal balance between performance, safety, and cost-effectiveness in the use of drones across various applications.

Studies show that a properly optimized trajectory can increase flight time by 15-25 %. In practice, it is rare to use only one criterion. Most often, multi-criteria optimization is applied, which requires:

- determining the relative importance of each criterion for a specific mission;
- using Pareto optimization methods to find compromise solutions;
- applying weighting coefficients or lexicographic ordering of criteria.

#### IV. EXPERIMENTAL RESEARCH ON THE EFFECTIVENESS OF DRONE TRAJECTORY OPTIMIZATION ALGORITHMS

To conduct a comprehensive assessment and comparison of the effectiveness of various trajectory optimization algorithms, a series of experiments were carried out in simulated urban and rural environments. The testing included scenarios with different obstruction densities, weather conditions, and mission types, allowing for an objective view of the advantages and disadvantages of each approach.

The experimental platform – a remote drone control and monitoring system in simulation – was built on a client-server model using native web technologies and a proprietary physics engine. For each algorithm, 100 test runs were conducted with different initial conditions, ensuring the statistical reliability of the results.

An urban environment was used as the starting point.

In densely built-up urban areas with a high concentration of obstacles (buildings 15-50 m tall, obstacle density covering 65-80 % of the area), the best results were shown by hybrid algorithms that combine A\* for global planning with machine learning methods for local optimization.

The analysis revealed that the advantage of the hybrid approach lies in the ability of A\* to quickly find a general route between buildings, while the DRL component optimizes local maneuvers within «urban canyons». This led to a reduction in the number of sharp turns.

Hybrid algorithms proved particularly effective in navigating areas with irregular construction, where traditional methods often generated suboptimal zigzag trajectories.

The rural environment was then chosen for further research.

In open rural areas with low obstacle density (predominantly natural objects: trees, hills, power lines), genetic algorithms demonstrated better efficiency due to their ability to optimize long straight-line segments of the trajectory. The improvement in energy efficiency reached 22 %.

A key advantage of genetic algorithms in rural terrain was their capacity for global optimization while accounting for the terrain's elevation profile and wind conditions.

#### V. CONCLUSIONS

The conducted research confirmed that the task of optimizing unmanned aerial vehicle trajectories is multi-criteria and has no universal solution. The effectiveness of the applied algorithms significantly depends on the characteristics of the flight environment and the requirements of a specific mission.

The main research results are:

1. In complex urban environments with high density of dynamic obstacles, hybrid approaches combining deterministic methods (particularly A\*) for global route planning and adaptive machine learning methods (e.g., DRL) for real-time local trajectory correction proved to be the most effective. This combination ensures both the overall optimality of the route and the ability to react quickly to unforeseen changes in the environment.

2. For open spaces, energy efficiency is the priority criterion. In rural areas dominated by static obstacles, evolutionary methods, particularly genetic algorithms, demonstrated the ability to form globally optimal routes considering terrain topography and wind conditions, which contributes to extending drones' autonomous operation time.

3. Trajectory optimization is inherently multi-criteria. A compromise between flight duration, energy consumption levels, and safety indicators is always necessary.

Methods capable of generating a set of Pareto-optimal solutions hold higher practical value, as they allow the operator to select a trajectory based on the current mission priorities.

Prospects for further research:

- development of adaptive hybrid architectures capable of switching planning strategies depending on the dynamics of external conditions (e.g., when transitioning from open space to dense urban environments);

- deeper integration of machine learning methods with physical models, particularly the use of transfer learning and online learning with limited data to enhance operational reliability in real-world conditions;

- optimization of group missions, involving cooperative trajectory planning in swarm architectures, inter-agent collision avoidance, and minimization of costs for the entire system;

- enhancing the computational efficiency of complex algorithms for implementation on resource-constrained onboard computers through model quantization, the use of hardware accelerators, and distributed computing between the drone and a ground station.

The practical significance of the work lies in defining the criteria for selecting and evaluating trajectory planning algorithms, which is useful for developers of drone autonomous control systems. The obtained results can be used to enhance the efficiency, safety, and autonomy of unmanned aerial vehicles in the fields of logistics, critical infrastructure monitoring, precision agriculture, and search-and-rescue operations.

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