МИНИСТАРСТВО ОДБРАНЕ
И ВОЈСКА СРБИЈЕ

50.
СИМПОЗИЈУМ
О ОПЕРАЦИОНИМ
ИСТРАЖИВАЊИМА
SYM-OP-IS 2023
Тара, 18–21. 9. 2023.

UNMANNED AERIAL VEHICLES (UAV) PATH PLANNING TECHNIQUES AND CONSTRAINTS IN URBAN AIRSPACE INTEGRATION: LITERATURE REVIEW

UNA STANKOVIĆ[1] EMIR GANIĆ[2] TATJANA DAVIDOVIĆ[1] DRAGAN UROŠEVIĆ[1]

[1] Mathematical Institute of the Serbian Academy of Sciences and Arts, Belgrade, una@mi.sanu.ac.rs, tanjad@mi.sanu.ac.rs, draganu@mi.sanu.ac.rs

[2] University of Belgrade, Faculty of Transport and Traffic Engineering, Belgrade, e.ganic@sf.bg.ac.rs

Abstract: *Unmanned Aerial Vehicles (UAVs), commonly known as drones, have revolutionized numerous industries by offering unprecedented capabilities and possibilities. However, the widespread adoption of UAVs presents significant challenges related to safety, airspace management, and regulatory compliance. In this review paper, we emphasize the importance of UAVs and how the implementation of an efficient path-planning system will ensure safe and effective UAV operations. We provide an overview of the most recent methodologies found in the literature. Firstly, we present the wide range of applications that UAVs have found in various industries. Secondly, we highlight the most critical challenges that we must overcome to enable the seamless integration of UAVs into the airspace. Finally, we provide an overview of the most recent methodologies and approaches to tackle path planning. This analysis highlights the diversity of algorithms used for UAV path planning and provides insights into their strengths and limitations. Our main goal is to become acquainted with the problem variants, applied methodologies, and the state-of-the-art challenges in this field and to identify the possible points of improvements and potential contributions*

Keywords: *Drones, Delivery, Surveillance, Optimization problems, Metaheuristics.*

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), also known as drones, are autonomous aircrafts capable of completing missions without direct human intervention. They vary in size and capacity, ranging from small and lightweight to larger models capable of carrying heavy loads. UAVs can be classified into fixed-wing and rotary-wing types, with rotary-wing UAVs offering Vertical take-off and landing (VTOL) capabilities. UAVs offer high maneuverability and can be equipped with various sensors and actuators, expanding their applications in areas such as surveillance, data collection, navigation, healthcare, disaster response, delivery, agriculture, and more. VTOL properties found in some UAVs are especially useful for operations in densely populated areas. With the increasing number of registered UAVs, the development of scalable Unmanned Aircraft Traffic Management (UTM) systems becomes crucial. Planning the appropriate paths plays a vital role in UTM systems as it ensures risk avoidance and prevents mid-air collisions. Urban environments pose additional challenges due to obstacles, flight safety concerns, and privacy considerations. Path planning approaches can be categorized as offline or online, with offline planning occurring before takeoff and online planning adjusting the path during flight based on real-time data and obstacles. The most appropriate path is usually determined by balancing the objective function and meeting multiple constraints. Additional sources of information, such as risk maps indicating the risk level at different locations, can significantly improve path planning.

This paper provides an overview of challenges when integrating UAVs into urban airspace, path planning methodologies review from the most recent literature and constraints to be considered when it comes to UAVs path planning.

2. CHALLENGES

UAVs, operating either individually or in swarms, face challenges in achieving complete autonomous flying, particularly in path planning and obstacle avoidance, where navigating routes and avoiding collisions present significant difficulties. Path planning involves optimizing the flight trajectory while considering factors such as obstacles, path length, fuel or energy consumption, arrival time, flight risk, and mission planning. Paths can be in 2D or 3D environments, with 3D posing greater computational complexity. Scientists have proposed various algorithms to create autonomous trajectory planning methods with the goal of finding the most suitable path that meets multiple constraints and maximizes the objective function value [8, 12]. UAVs face the following challenges when it comes to path planning:

- **Computational complexity** - Long computations can result in delayed actions and the inability to react in unexpected situations. Combination with offline computational methods can be used to avoid this kind of problem.
- **Limited amount of energy** - UAVs spend significant energy on the flight itself and data storage, even more when additional weight is added to the UAV [6].
- **Obstacles** - In mid-air, UAVs have to manage different types of obstacles and other air-flying objects which can increase the risk of mission failure. Obstacles can come from different sources and can be either static or dynamic. Static obstacles can be trees, buildings, and other ground objects, while dynamic obstacles include birds, other flying objects, people, vehicles, etc. [5].
- **Population risk** - The increase in UAV operations in urban places and at low altitudes increases the risk of drone accidents affecting humans and/or vehicles on the ground [5].
- **Fly and no-fly zones** - These include forbidding or allowing flights over certain areas. UAVs may intrude on these or airport airspaces [14].
- **Safety** - Two priority safety concerns are related to mid-air collisions and loss of control over UAVs [1].
- **UAV communication channels** – The communication between UAV and remote monitoring/control system is mostly transmitted through the existing terrestrial wireless networks, cellular or Wi-Fi. UAV periodically transmits its coordinates and other relevant flight data [2]. Any interruptions to these communication channels may cause problems.
- **Meteorological conditions** – Meteorological conditions, such as wind or rain, can seriously impact flying UAVs in various aspects from performance to actual realization of mission. The actual route can significantly deviate from the initially planned [6].
- **Security and privacy issues** - UAVs are prone to malicious attacks due to their sensitive data collection. Drones equipped with cameras pose a significant privacy risk, since they can do unauthorized tracking or recording.

3. CURRENT PATH PLANNING ALGORITHMS

Majority of researchers try to find the best ways to create a path using different constraints, analyzing risks, and trying to improve the UAVs' path planning algorithms in their domain. The selection of papers here represents an introduction to path planning for UAVs and shows different approaches and usage of various algorithms to tackle the problem in both 2D and 3D environments. The authors of [5, 7, 9, 13] observed a 2D environment, while the authors of [3, 4, 8, 10, 12] focused their work on the 3D environment, whereas the authors of [11] tried both.

An overview of the considered path planning approaches, constraints, and environments is presented in Table 1.

Table 1: Path planning approaches overview

Paper	Environment	Approach used	Live	Constraints
[2]	2D	ILP	Offline	Destination; Capacity of wireless networks;
[3]	3D	ACO	Online	Flight path length; Movement; Overlapping area of the current path with paths of other UAVs;
[4]	3D	Theta *	Offline	Waypoints No-fly zone;
[5]	2D	Dijkstra; Modified A*; Modified ACO	Offline	Risk level: people on the ground, other vehicles, collision with manned aircraft;
[7]	2D	GA	Offline	Working hours; Delivery range; Fuel consumption; Capacity;
[8]	3D	PSO	Offline	Energy consumption; Flight risk; Maneuverability; Feasibility of the path; Aerial constraints; Restricted area; Collision avoidance
[9]	2D	Risk A* (offline); Borderland (online);	Offline/ Online	Risk level; No-fly zones; Movement;
[10]	3D	PSO	Online	Threat; Collision avoidance;
[11]	2D/3D	PRM improved with D* lite	Offline/ Online	Possible collisions;
[12]	3D	Improved GA and A*	Online	Horizontal and vertical error Positioning error correction
[13]	2D	ACO	Online	Flight path length; Threat cost; Movement restrictions; Intensity of the enemy threats;

De Filippis et al. [4] used the Theta* algorithm for the fixed-wing UAV in a 3D environment. They explored graph structure to represent solutions and proposed “mask” subroutine to select neighbors used for expanding the current node. The authors of [4, 5, 7, 8] have demonstrated offline path-planning methods, while online path-planning approaches have been explored in [3, 10, 12, 13]. The method used by Primatesta et al. [9] presents a hybrid approach combining offline path planning with online recomputation. The authors propose an algorithm called Borderland, which addresses risk-aware path planning in urban environments. This algorithm adjusts the path dynamically in areas with changing population risk using a check and repair approach. Offline path computation is performed using risk A* and a risk-map, while online recomputation utilizes the Borderland algorithm, suitable for high-dimensional scenarios. Although not providing the optimal solution, Borderland generates paths with lower motion cost and computation time compared to the previous path.

Many papers employ established approaches, such as the A* algorithm and its variations, to address path-planning optimization problems. In [5, 9, 12], A* and its modifications are used. Especially, [5, 12] combine various approaches. Zhou et al. [12] propose a 3D trajectory planning algorithm that combines A* and genetic algorithm (GA) to satisfy various constraints related to system positioning accuracy, as the error, when accumulated, may cause mission failure. The algorithm aims to minimize trajectory length and the number of corrections while considering restrictions imposed by the UAV's structure and control system capabilities. The proposed algorithm demonstrates faster computation, lower cost, and improved performance in terms of trajectory planning and the number of correction points compared to traditional methods.

Li et al. [7] employed GA to optimize UAV routing with traffic restrictions. They developed a model considering environmental factors to analyze the efficiency of UAV delivery in reducing cost and energy consumption. The study focused on a scenario where a delivery company in an urban area uses vehicles equipped with UAVs to deliver parcels. The GA approach facilitated the generation of an initial solution and customer grouping to distribute assignments among UAV and ground vehicle. The authors considered constraints like vehicle working hours and delivery within those hours while minimizing fuel consumption and CO_2 emissions. Notably, serving 200 to 400 customers without UAVs required 3 to 4 vehicles, whereas, with UAV utilization, only 2 or 3 vehicles were necessary.

Risk assessment models for UAV path planning in urban environments are proposed in [5]. The authors used a risk-cost map considering various risk categories and collision probability. They applied Dijkstra, modified A*, and modified Ant Colony Optimization (ACO) algorithms for cost-effective path planning. The modification of A* included redefining the heuristic distance based on the minimal risk cost in the map. ACO was used as a global optimization algorithm to search for the shortest path, with modifications to improve efficiency. Results showed that risk-cost-based path planning produced safer paths compared to traditional methods. The risk was highest in downtown areas, followed by sparse areas, while the airport area had the lowest risk. Modified A* performed best for finding paths with the lowest risk, while ACO was faster for time-critical operations with relatively low-risk paths. In [3], Cheng et al. proposed a cooperative path planner for UAVs using ACO. Each UAV's path was represented as a B-spline curve optimized through ACO to maximize total coverage. The 3D terrain was divided into a grid, and coverage was achieved by visiting each grid section. The optimization considered path length, minimum turning angle, maximum pitch rate, and overlapping areas with other UAVs' paths. The objective was to maximize path desirability. Results compared the cooperative and noncooperative path planners, showing that the cooperative approach achieved over 10% better coverage by considering overlapping areas during optimization. However, the path length, minimum turning angle, and maximum pitch rate of the cooperative paths were slightly degraded by up to 6% compared to the noncooperative planner. Zhang et al. [13] developed a new UAV path-planning method based on the ACO. The target position represents the food source, and it is up to the ants to find it. This is achieved by dividing the flying area into a grid and optimizing the path between starting and ending points. ACO takes a positive feedback mechanism by considering the intensity of the enemy threats on the path and the distance to the destination node. For the evaluation function, the authors considered the weighted sums of the flight path length, the threat cost, and the maximum restriction of the yaw angle. Updating the pheromone amounts on the paths is done according to the evaluation function values. Ants choose their next route based on pheromone amount. What they found to be the best UAV's flight path is represented by a group of node numbers, which is obtained by the ants finding the optimal route to the food source. Their simulation results proved that ACO effectively and quickly accomplishes UAV path planning, but still, smoothening process is necessary for real-life applications.

Ahmed et al. [8] proposed a trajectory planner based on the Particle Swarm Optimization (PSO) algorithm for distributed full coverage optimal path planning in the surveillance domain. PSO was implemented independently in each UAV to maximize the dynamic fitness function and minimize the cost function. This algorithm was used to generate the trajectory, while the Bresenham algorithm ensured full coverage of the operational area. The authors designed a multi-objective fitness function considering energy consumption, flight risk, maneuverability, and path feasibility. The results showed that the combination of PSO and the Bresenham algorithm facilitated the surveillance of the area of interest with multiple UAVs, generating optimized collision-free trajectories. In [10], Shao et al. improved the efficiency of PSO for UAV path planning with obstacle avoidance. They recognized the significance of the initial particle distribution and proposed using a logistic chaos map instead of random distribution. They also dynamically adjusted inertia and acceleration coefficients through an adaptation coefficient to influence convergence speed and search direction. Energy consumption was considered by including the path length ratio for calculating the shortest path. However, their approach has high time complexity and does not address re-planning of the path when encountering unexpected threats.

Xue et al. [11] improved the traditional Probabilistic Roadmap Method (PRM) approach by combining it with the D* lite algorithm. Their approach reduced the number of random points needed and addressed the failure probability issue. Although they ignored the constraints of UAVs in practical situations, the results showed that their method outperformed traditional PRM in terms of running time and path length, regardless of the number of obstacles. The experiments were conducted in both 2D and 3D environments using Matlab. An integer linear programming (ILP) formulation is proposed in [2] to adjust the UAV's trajectory based on destination and wireless network capacity. The authors considered trajectory constraints, such as the maximum ratio of lost messages during localization transmission. The authors used Matlab and CPLEX to analyze the impact of wireless control station density on the number of solutions and UAV trajectory.

4. CONCLUSION

The main contribution of this paper is highlighting the exponential growth of research in UAV path-planning and the expanding possibilities and problem variations in this field. It underscores the importance of carefully analyzing constraints for each specific application and suggests exploring the utilization of the same algorithm across different types of constraints and environments to uncover a wider range of possibilities in UAV path planning. By implementing and testing the algorithm under various conditions, a more comprehensive understanding of its capabilities and limitations can be gained. Such an approach allows researchers to explore a broader range of possibilities and make informed decisions when applying UAV path-planning algorithms to real-world scenarios. In addition, to address the constraints, our review emphasizes the critical challenges of safety, airspace management, and regulatory compliance that need to be overcome for the seamless integration of UAVs into various industries. Ensuring the safety of UAV operations, managing airspace congestion, and complying with relevant regulations are essential aspects that must be considered during the path planning process.

The most promising approach appears to be the one analyzed in the paper is the Borderland algorithm proposed by [9]. It offers a promising approach for risk-aware path planning in urban environments. By dynamically adjusting paths based on changing population risk, it improves safety and efficiency. However, it does not guarantee optimal solutions and relies on accurate risk assessment and timely updates. Addition investigation is needed to address these limitations and develop comprehensive path planning algorithms.

Future research should focus on addressing the identified shortcomings and exploring new approaches to further enhance the efficiency, adaptability, and robustness of UAV path planning algorithms.

For example, developing innovative approaches to tackle these challenges, providing robust and reliable solutions that facilitate the integration of UAVs into our daily lives seem as promising research topics. Overall, the exponential growth of research in UAV path planning and the increasing number of use cases for UAVs highlight the immense potential and benefits that these autonomous aerial vehicles can bring to various industries. However, to fully leverage their capabilities, it is crucial to address the challenges of constraint analysis, safety, airspace management, and regulatory compliance. By doing so, we can pave the way for a seamless integration of UAVs into our daily lives and unlock the full potential of this transformative technology.

ACKNOWLEDGMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia Agreements Nos. 451-03-47/2023-01/200029 and 451-03-47/2023-01/200128.

REFERENCES

[1] A. Global. (2016). Rise of the drones managing the unique risks associated with unmanned aircraft systems uas the nuts and bolts types of uas. The case of the drone industry, Allianz Global Corporate & Specialty SE, 89.

[2] Bekhti M, Abdennebi M, Achir N, Boussetta K. (2016). Path planning of unmanned aerial vehicles with terrestrial wireless network tracking. In Wireless Days (WD), 1-6.

[3] Cheng CT, Fallahi K, Leung H, Chi KT. (2009). Cooperative path planner for UAVs using ACO algorithm with Gaussian distribution functions. In IEEE International Symposium on Circuits and Systems, 173-176.

[4] De Filippis L, Guglieri G, Quagliotti F. (2012). Path planning strategies for UAVS in 3D environments. Journal of Intelligent & Robotic Systems, 65(1-4), 247-264.

[5] Hu X, Pang B, Dai F, Low KH. (2020). Risk assessment model for UAV cost-effective path planning in urban environments. IEEE Access. (2020), 8, 150, 162-173.

[6] Khan MT, Muhammad Saad M, Ru Y, Seo J, Kim D. (2021), Aspects of unmanned aerial vehicles path planning: Overview and applications. International Journal of Communication Systems, 34(10):e4827.

[7] Li Y, Yang W, Huang B. (2020). Impact of UAV delivery on sustainability and costs under traffic restrictions. Mathematical Problems in Engineering.

[8] K. C. Nafis Ahmed, Chaitali J. Pawase. (2021). Distributed 3-D Path Planning for Multi-UAVs with Full Area Surveillance Based on Particle Swarm Optimization. Applied Sciences [Internet], 11(8):3417.

[9] Primatesta S, Guglieri G, Rizzo A. (2019). A risk-aware path planning strategy for UAVs in urban environments. Journal of Intelligent & Robotic Systems, 95:6, 29-43.

[10] Shao S, Peng Y, He C, Du Y. (2020). Efficient path planning for UAV formation via comprehensively improved particle swarm optimization. ISA transactions, 97:4, 15-30.

[11] Xue Q, Cheng P, Cheng N. (2014). Offline path planning and online replanning of UAVs in complex terrain. In Proceedings of 2014 IEEE Chinese Guidance, Navigation and Control Conference, 2287-2292.

[12] Zhou H, Xiong HL, Liu Y, Tan ND, Chen L. (2020). Trajectory planning algorithm of UAV based on system positioning accuracy constraints. Electronics, 9(2), 250.

[13] Zhang C, Zhen Z, Wang D, Li M. (2010). UAV path planning method based on ant colony optimization. In 2010 Chinese control and decision conference, 3790-3792.

[14] Zhang Z, Zhang J, Wang P, Chen L. (2018). Research on operation of UAVs in non-isolated airspace. CMC-Comput. Mater. Continua, 57(1), 151-66.