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Review of Autonomous Flight Control Technology for Unmanned Aerial Vehicles in Complex Environments

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Abstract

With the rapid advancement of Unmanned Aerial Vehicles (UAVs) technology, its application value and penetration have been continuously enhanced in various fields, especially in surveying and mapping exploration, emergency rescue, logistics and transportation, and military fields. However, in some complex environments such as urban building clusters, indoor spaces, mountainous terrain, and areas with dynamic obstacles, achieving safe and efficient autonomous flight of UAVs still faces numerous difficulties and challenges. This paper systematically reviews the autonomous flight control technology of UAVs in these complex environments, elaborates on the core technical framework of this field, and introduces the latest research achievements and future development trends at home and abroad. It focuses on four key modules: environmental perception, path planning, obstacle avoidance, and robust control systems. Research shows that multi-sensor fusion technology for perception, intelligent path planning based on deep reinforcement learning, multi-UAV cooperative obstacle avoidance technology, and robust control technology driven by reinforcement learning have become the main research trends in this field. By comprehensively sorting out relevant research results at home and abroad, this paper constructs the context of technological development, hoping to provide certain reference for future research in the field of UAV autonomous flight control.

Keywords

Unmanned Aerial Vehicles (UAVs); Autonomous Flight Control; Complex Environments; Environmental Perception; Robust Control.

1. Introduction

UAVs have demonstrated unique application value in complex scenarios that are difficult to cover by traditional operation modes due to their significant advantages such as strong maneuverability, low deployment cost, and convenient operation. They have become an indispensable important equipment in modern production, life, and national defense construction [1]. Whether in indoor environments with blocked GNSS signals, rugged mountainous areas with complex terrain, or urban airspace with frequent dynamic obstacles, UAVs need to possess a high degree of autonomous flight control capability to complete scheduled tasks [1]. Currently, achieving safe and efficient autonomous flight of UAVs in these complex environments, including cities, indoor spaces, mountainous areas, and regions with dense dynamic obstacles, remains a research hotspot and technical difficulty jointly concerned by the academic and industrial communities [2-18]. The autonomous flight control system of UAVs is a highly complex multi-module collaborative working system, which must integrate key modules such as environmental perception, path planning, obstacle avoidance, and robust control to ensure that UAVs can perform adaptive flight when facing unknown and dynamic environments [2,5,11,12,16]. This paper will comprehensively review the core technologies, current research progress, and future development directions of UAV autonomous flight control, aiming to provide systematic reference for further research in related fields.

2. Key Technologies of UAV Autonomous Flight Control

The realization of autonomous flight control of UAVs in complex environments relies on the collaborative support of key technologies in multiple fields, including four core modules: environmental perception, path planning, obstacle avoidance, and robust control systems.

2.1. Environmental Perception

Environmental perception is the basic prerequisite for UAVs to achieve autonomous flight. Its core goal is to obtain and analyze surrounding environmental information in real time and accurately, providing reliable data support for subsequent decision-making [7,13].

2.1.1. Sensor Technology and Multi-Source Fusion

Due to the physical limitations of a single sensor, it is usually difficult to meet the perception requirements in complex environments. Therefore, multi-sensor fusion technology has emerged. By integrating the advantages of different types of sensors to achieve information complementarity and optimization, it has become the mainstream technical path in this field [4]. In indoor environments, the combined application of binocular cameras and LiDAR (Light Detection and Ranging) has achieved remarkable results: LiDAR can provide high-precision distance information and 3D point cloud data [7], while visual sensors can capture texture and color features of the environment. Their collaborative effect significantly improves the accuracy of obstacle recognition and positioning [4]. In scenarios without GNSS (Global Navigation Satellite System) signals, the tightly coupled LiDAR-inertial navigation system has shown excellent positioning performance, which can provide effective anti-interference autonomous flight control support for VTOL-UAVs (Vertical Take-Off and Landing UAVs) [9].

2.1.2. Environmental Modeling

The raw data collected by sensors needs to be processed through modeling to be converted into structured information understandable by machines, thereby meeting the requirements of path planning and obstacle avoidance algorithms. Currently, 3D occupancy grid maps and Euclidean Signed Distance Fields (ESDF) are the two most widely used environmental modeling methods [13]. Octomap adopts an octree-based data structure, which can efficiently store and update obstacle distribution and free space information in 3D space while balancing modeling accuracy and computational efficiency [13]. ESDF calculates the distance from each point in space to the nearest obstacle, providing an intuitive safety margin reference for path planning and significantly reducing the complexity of trajectory optimization [13].

2.2. Path Planning

Path planning is a core link in UAV autonomous flight control. Its main task is to generate an optimal or suboptimal flight trajectory from the starting point to the target point under the premise of satisfying the UAV's dynamic constraints, obstacle constraints in the environment, and task requirements (such as time limits and energy consumption requirements) [10,15,19].

2.2.1. Traditional Path Planning Algorithms

Traditional path planning algorithms are mainly divided into sampling-based methods (such as RRT*) and graph search-based methods (such as A*), which have mature application effects in known static environments [17]. However, such algorithms are difficult to cope with large-scale and high real-time tasks in unknown and dynamic environments [17]. To meet the needs of complex scenarios, the improved Harris Hawks Optimization (HHO) algorithm is proposed. By optimizing the search strategy, it achieves low-cost and high-speed path solving in complex 3D flight environments [15].

2.2.2. Path Planning Based on Evolutionary Computation

Evolutionary Computation (EC) algorithms have been widely used in UAV path planning in complex environments due to their strong global search capabilities and multi-objective optimization advantages [20]. Classic evolutionary algorithms such as Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) can simultaneously optimize multiple objectives such as path length, smoothness, safety, and energy consumption in complex 3D spaces [20-22]. They gradually approach the optimal solution by simulating operations such as selection, crossover, and mutation in the biological evolution process, and have low dependence on environmental models, making them suitable for path planning problems under multi-constraint conditions [21]. Figure 1 visually presents the application framework of evolutionary computation algorithms in UAV path planning, clearly demonstrating how these algorithms integrate environmental constraints, multi-objective requirements, and evolutionary mechanisms to generate feasible flight paths [21].

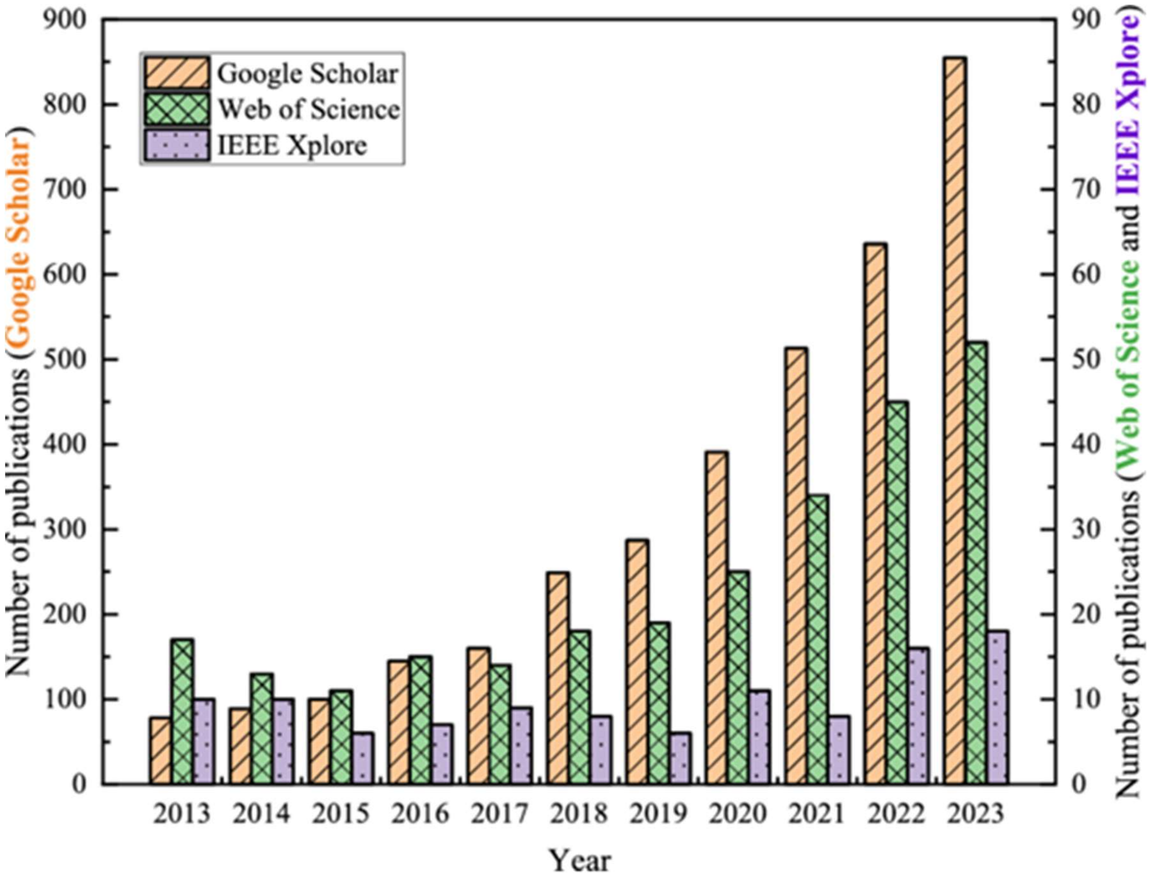

Figure 1. Application of evolutionary computation algorithms in UAV path planning, Source: [20]

2.2.3. Path Planning based on Deep Reinforcement Learning

With the improvement of computing power and the development of reinforcement learning theory, Deep Reinforcement Learning (DRL) has become a breakthrough technology for solving path planning problems in complex dynamic environments [6,17]. The DRL method does not rely on complete global environmental information. Through real-time interaction and trial-and-error learning between UAVs and the environment, it can generate adaptive 3D flight paths using only local perception data [17], enabling UAVs to have stronger dynamic response capabilities and obstacle avoidance robustness in low-altitude complex environments [6]. For example, the Task-Decomposed Multi-Agent Twin Delayed Deep Deterministic Policy Gradient (TD-MATD3) algorithm effectively solves the cooperative path planning problem of multi-UAVs in complex obstacle environments by optimizing the multi-agent collaboration mechanism and task decomposition strategy [10].

2.3. Obstacle Avoidance

Obstacle avoidance is a key technology to ensure the flight safety of UAVs. It requires UAVs to detect static and dynamic obstacles in real time and quickly adjust the flight trajectory to avoid collisions [2,7,11,12].

2.3.1. Single UAV Obstacle Avoidance Strategies

Researchers have proposed various efficient strategies for single UAV obstacle avoidance. The 3D obstacle avoidance algorithm based on collision cone and velocity obstacle determines the minimum velocity vector deflection angle by analyzing the motion state of obstacles to realize real-time trajectory adjustment [2,11]. The scheme combining Nonlinear Model Predictive Controller (NMPC) with airborne 2D LiDAR can quickly solve obstacle avoidance control commands in obstacle-dense environments, ensuring navigation continuity [5]. The EF-TTOA framework achieves unified processing of static and dynamic obstacles through sampling point analysis and velocity vector optimization, with good real-time performance and adaptability [2].

2.3.2. Multi-UAV Cooperative Obstacle Avoidance

Multi-UAV systems have efficiency advantages in complex tasks, but cooperative obstacle avoidance faces the dual challenges of motion coordination between UAVs and balance of task objectives [10,18]. In addition to avoiding environmental obstacles, it is also necessary to prevent collisions between UAVs [10,18,21]. The hierarchical weighted Vicsek model coordinates the flight attitude and speed of multi-UAVs through a hierarchical control strategy, achieving efficient obstacle avoidance while ensuring formation stability [10,21], and providing reliable technical support for the formation flight of multi-UAV swarms. Figure 2 illustrates the 3D space path planning scenario of multi-UAVs, highlighting the interaction between key modules such as path planning, obstacle avoidance, and information perception, as well as the data exchange of obstacles, target positions, and other UAV statuses in the collaborative process.

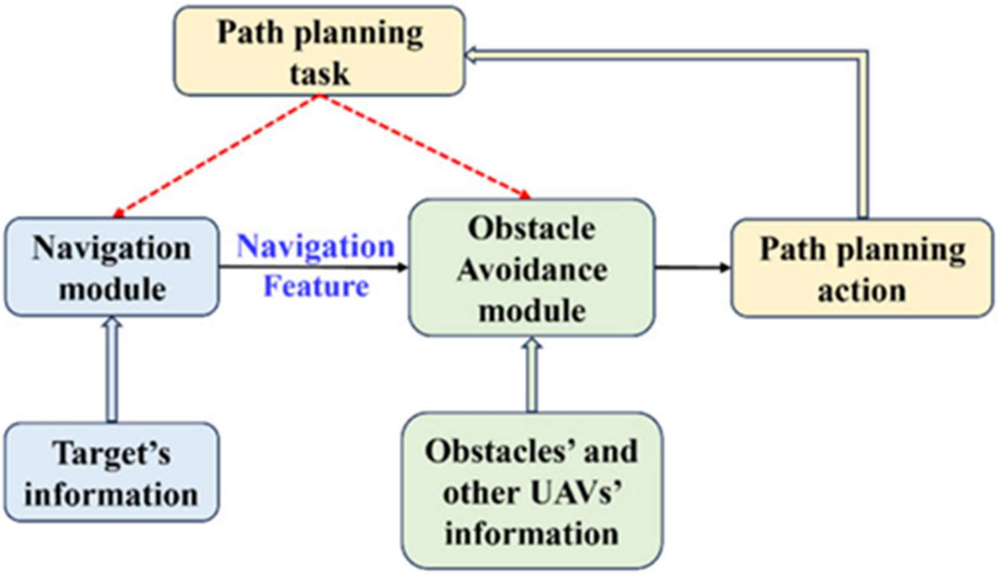

Figure 2. Path planning scenario of multi-UAVs in 3D space, Source: [10]

2.4. Robust Control Systems

To ensure the reliable flight of UAVs in complex environments, it is necessary to design a robust control system with strong adaptability and anti-interference capabilities [16,23]. Traditional

PID control and rule-based control methods have obvious limitations and are difficult to cope with the uncertainty of complex dynamic environments [23]. With the development of reinforcement learning technology and computing power, reinforcement learning-based control algorithms are increasingly used in UAV flight control, significantly improving the adaptability and control performance of the system [23]. Aiming at the needs of autonomous planning, navigation, and control of lightweight UAVs in obstacle-dense environments, a polynomial-based minimum snap trajectory generation method is proposed, which can ensure obstacle-free flight of UAVs with limited computing resources [16].

3. Research Progress at Home and Abroad

In recent years, scholars at home and abroad have carried out extensive explorations around UAV autonomous flight control in complex environments, and achieved a series of breakthrough results in real-time exploration, scenario adaptation, and multi-UAV collaboration.

3.1. Real-Time Autonomous Exploration and Trajectory Planning

To meet the demand for rapid exploration of unknown environments, researchers have proposed various robust planning frameworks. The planning framework based on the sparse Directed Frontier Points (DFP) information structure realizes efficient autonomous flight tasks in complex unknown environments under the constraint of limited onboard computing resources [5]. The STExplorer framework innovatively introduces a hierarchical spatiotemporal perception mechanism, which effectively solves the problems of rough cost budget, fuzzy information gain, and redundant backtracking in traditional exploration strategies, and significantly improves the efficiency of unknown environment exploration [13]. These studies provide key technical support for the application of UAVs in tasks such as search and rescue and unknown area surveying and mapping.

3.2. Autonomous Control for Specific Application Scenarios

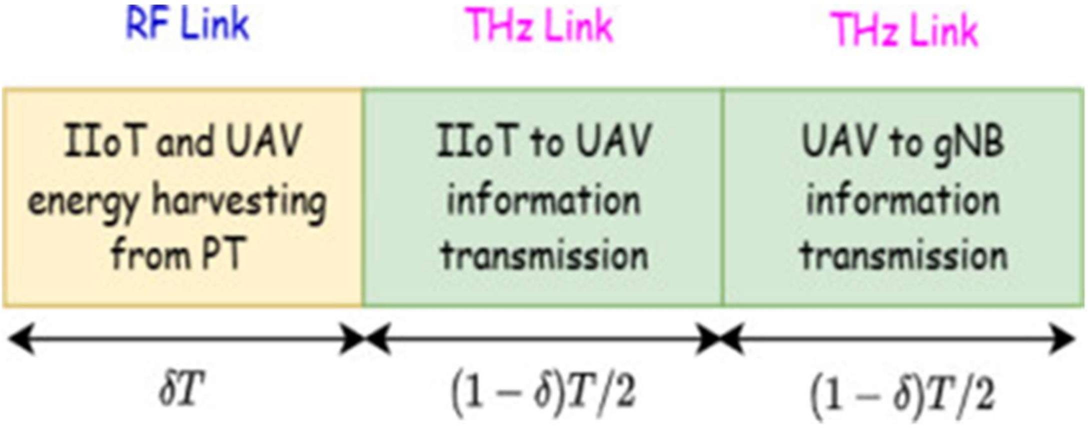

Figure 3. Time division of UAV-assisted terahertz relay network

The application scenarios of UAV autonomous flight control technology are constantly expanding. Aiming at the personalized needs of different scenarios, researchers have developed special control schemes. In remote sensing applications, the PISCFF-LNet lightweight road extraction method is used for UAV autonomous flight control, effectively coping with the challenges of weak GNSS signals and high environmental complexity [8]. In riverbank inspection tasks, the integrated application of path planning and obstacle avoidance technology has greatly improved the efficiency of UAVs in detecting and cleaning riverbank garbage [14]. In the communication field, the trajectory design of UAV-assisted terahertz band energy harvesting relay networks provides a new solution for high-speed communication in the

Industrial Internet of Things (IIoT) [24]. Figure 3 shows the time division mechanism of the UAV-assisted terahertz relay network, clearly dividing the time slot into three parts: δT for energy harvesting from the power transmitter (PT) by the UAV, and two (1-δ)T/2 periods for information transmission between the IIoT device and the UAV, as well as between the UAV and the ground base station (gNB) through RF and THz links respectively (Source: [24]).![img](RF Link THz Link THz Link IIoT to UAV IIoT and UAV UAV to gNB information information energy harvesting from PT transmission transmission δT (1-δ)T/2 (1-δ)T/2)

3.3. Multi-UAV Collaboration and Swarm Intelligence

Multi-UAV collaboration technology is the key to improving the efficiency of complex task execution. Relevant research focuses on cooperative path planning, task allocation, and formation control. Shafiq et al. proposed a multi-colony social learning-based self-organization method, combining Max-Min Ant Colony Optimization (MMACO) with social learning mechanisms to realize optimal path planning of single swarms and optimal leader selection [21]. He et al. proposed a hybrid particle swarm optimization algorithm (HIPSO-MSOS), which simplifies the multi-UAV collaboration cost through a timestamp segmentation model and efficiently solves the cooperative path planning problem in 3D environments [22], laying a foundation for the application of multi-UAV systems in large-scale tasks.

4. Future Development Directions

Although remarkable progress has been made in UAV autonomous flight control technology, facing increasingly complex application scenarios and higher performance requirements, there are still many challenges to be overcome. Future research will focus on the following directions:

4.1. Enhancement of High Dynamic Environment Adaptability

Future UAVs need to have stable flight capabilities in extreme weather (strong winds, rain and snow, sand and dust), high-speed flight, and environments with high dynamic obstacles (such as low-altitude aircraft and moving vehicles). Research will focus on the design of robust control algorithms, sensor anti-interference technology, and the construction of dynamic environment prediction models to improve the adaptability of UAVs in complex and uncertain environments.

4.2. Optimization of Multi-UAV Intelligent Collaboration

With the expansion of the application scale of multi-UAVs, intelligent collaborative decision-making, dynamic task allocation, flexible formation flight, and distributed cooperative obstacle avoidance will become the core of research [10,21,22]. It is necessary to develop efficient communication protocols, distributed control algorithms, and conflict resolution mechanisms to realize the autonomous collaboration and swarm intelligence of multi-UAV systems, and improve the execution efficiency and fault tolerance of complex tasks.

4.3. Optimization of Computing Resources and Application of Edge Computing

The limitation of onboard computing resources is a key bottleneck restricting the deployment of complex algorithms [8,16]. In the future, edge computing technology will be used to realize the distributed deployment of computing tasks. Combined with lightweight model design (such as the PISCFF-LNet method [8]) and algorithm hardware acceleration, the computational complexity and energy consumption of algorithms will be reduced under the premise of ensuring control performance, to meet the deployment requirements of embedded devices.

4.4. Improvement of Autonomous Grasping and Manipulation Capabilities

In addition to flight and obstacle avoidance, the physical interaction capability of UAVs with the environment (such as autonomous grasping, precise delivery, and equipment maintenance) will become an important direction to expand application scenarios. It is necessary to integrate advanced technologies such as manipulator control, visual servoing, and force feedback perception to realize the precise manipulation of target objects by UAVs, and promote their in-depth application in logistics and distribution, emergency rescue, industrial maintenance and other fields.

4.5. Autonomous Exploration and Mapping Technology in Unknown Environments

The ability of autonomous exploration and real-time mapping in completely unknown environments is the core prerequisite for UAVs to perform tasks such as search and rescue and unknown area surveying and mapping [1,3,13]. Future research will focus on improving the integrated capability of autonomous positioning, environmental modeling, and path planning of UAVs in the absence of prior maps and GNSS signals, developing efficient exploration strategies and incremental mapping algorithms, and realizing rapid coverage and precise modeling of unknown environments.

5. Conclusion

UAV autonomous flight control in complex environments is a comprehensive research field integrating control theory, artificial intelligence, robotics, computer vision and other disciplines. Existing research has achieved remarkable progress in multi-sensor fusion for environmental perception, application of evolutionary computation and deep reinforcement learning in path planning, strategy optimization of obstacle avoidance technology, and innovation of robust control algorithms, providing solid technical support for the application of UAVs in various fields. However, facing key challenges such as high dynamic environment adaptability, multi-UAV intelligent collaboration, computing resource optimization, and autonomous physical interaction, this field still has broad research space. With the iterative upgrading of sensor technology, the continuous improvement of computing power, and the continuous innovation of intelligent algorithms, the autonomous flight control capability of UAVs will gradually break through existing bottlenecks, play a more important role in military national defense, agricultural plant protection, environmental monitoring, logistics and transportation and other fields, and provide new momentum for social and economic development and scientific and technological progress.

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