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Overview of Research on 3D Path Planning Methods for Rotor UAV

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***Abstract*—With the continuous development of UAV technology, autonomous path planning methods suitable for UAVs are also evolving. In complex environments, UAVs not only need to consider the dynamics and time constraints, but also find the best and collision-free path. Although many researchers have conducted research on UAV path planning, there is a lack of comprehensive investigation and intuitive display of UAV path planning in a three-dimensional complex unknown environment. This article comprehensively analysis the path search algorithm and trajectory optimization method for UAVs in a three-dimensional environment, classifies them and compares them for each category, analyses the advantages and disadvantages of these methods.**

Keywords-UAV; path planning; path search algorithm; trajectory optimization method.

I. INTRODUCTION

As the application fields of drones become more and more extensive, the requirements for drones are getting higher and higher. Especially for drones flying in some high-dimensional, complex and unknown environments, safety has become crucial. As a key technology of UAV flight, path planning is becoming more and more attractive for researchers. However, at this stage, researchers have entered in-depth research to solve specific problems in a single method, but have not integrated the existing suitable UAVs to make a clear classification of the method of flying in three-dimensional environment. The paper classifies existing path search algorithms and path optimization methods suitable for UAVs. As shown in Figure1. Commonly used search algorithms mainly include heuristic-based path search algorithm, sampling-based search algorithm, potential field method, biological heuristic algorithm and continuous improvement of single algorithm and fusion of multiple algorithms. In recent years, trajectory optimization methods are mainly divided into three categories, minimum trajectory optimization, hard constraints optimization and soft constraints optimization. Minimum trajectory optimization is unconstrained optimization. Hard constraints optimization sets boundary values and soft constraints optimization uses binding force to ensure that the drone escapes from obstacles. With the continuous development of artificial intelligence technology, current methods tend to combine path search and trajectory optimization to generate a safe, smooth and dynamically feasible trajectory suitable for UAV flight. In the future, UAVs will be increasingly used in complex and unknown dynamic environments, and high-speed and safe flight will be the norm.

II. PATH SEARCH ALGORITHM

This article mainly divides the path search algorithm into five categories, and describes its characteristics in sections.

A. *Heuristic-based Path Search Algorithm*

Heuristic-based path search algorithm mainly include Dijkstra's algorithm, A* algorithm, Lifetime Plan A*(LPA), D*-Lite, Theta*, Lazy Theta*, dynamic A*(D*). It constructs its own cost evaluation function and finds the optimal path through the smallest cost point. Dynamic A * (D *) was first proposed by A Stentz. It is a sensor-based algorithm that can change the weight of its edges to form a time map. There are many optimizations and improvements to the A*algorithm in the three-dimensional scene, include increasing search space and improving path smoothness. In 2019, three-dimensional path planning was carried out through variable step size search and newly designed variable weight path evaluation function [1].

B. *Sample-based Search Algorithm*

Sample-based search algorithms mainly include PRM and RRT. Compared with other algorithms, RRT has an advantage in that it can effectively consider non-holonomic constraints within the algorithm to avoid the consideration of complex kinematics constraints and simplify the path planning problem. Yang proposed a conflict-free path using RRT, but RRT did not have the ability to re-plan the program and optimize. Therefore, improved versions (such as RRT*, DDRRT and RRG) have been proposed to solve this problem. The kino-dynamic RRT* changed the Steer function to suit constraint navigation [2]. Anytime-RRT* updated the current trajectory at any time [3]. Informed RRT* improved convergence rate [4]. PRM converts continuous space into discrete space. Paper [5] used search

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algorithms such as A* to find paths on the road map to improve search efficiency.

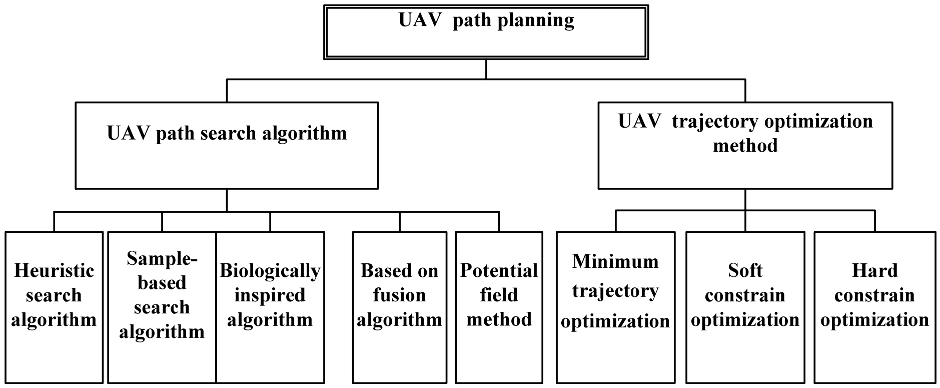

Figure 1. UAV path planning.

C. *Potential Field Method*

The artificial potential field method forms a virtual artificial potential field through the repulsive force field of the obstacle and the gravitational field of the target position, and then searches for a downward direction of the potential function, and finds an optimal path without collision in this way. But when multiple obstacles appear in the potential field space at the same time, it is easy to fall into a local minimum. In order to avoid obstacles, based on the traditional artificial potential field method [6,7,8] have improved the potential field method, Chen [6] set waypoints to make the aircraft avoid obstacles, Paper [7] changed the repulsion force Field function. Tian [8] set the velocity vectors of the target and obstacles in the relative position gravitational field and repulsive field functions.

D. *Biologically Inspired Algorithm*

Algorithms inspired by biology are derived from imitating biological behavior to solve problems. This path planning method saves the process of building a complex environment model, and proposes a powerful search method to stably converge to the target. Mainly divided into two categories, evolutionary algorithms and neural networks. Evolutionary algorithms include ant colony algorithm and particle swarm optimization algorithm. Evolutionary algorithm [9] was propounded to solve the problem that traditional Linear Programming. But because of the crossover operator is chose partly random, this kind of algorithms sometimes suffer the problem of premature convergence. Yu [10] implemented in robots to achieve global optimal path with the help of neural network algorithm.

E. *Based on Fusion Algorithm*

Fusion algorithm can be divided into two categories. One algorithm is to combine several Path planning algorithms are integrated together to work together to find the best path. The other algorithm consists of several path planning algorithms, when one algorithm completes its part, the other algorithm immediately starts working. Xiao [11] used a 3D grid to represent the environment, and uses 3D PRM to form a road map in an obstacle-free space, and finally combines the best algorithm based on A* nodes to obtain the best path. An improved algorithm combining the artificial potential field method with the A-star algorithm was proposed [12]. The artificial potential field method is used to guide the global path planning, and the A-star algorithm guides the local path planning.

III. UAV TRAJECTORY OPTIMIZATION ALGORITHM

Trajectory optimization ensures that the UAV path is smooth and safe and the dynamics is feasible. It is mainly divided into three categories, minimum trajectory optimization, hard constraint optimization, and soft constraint optimization.

A. *Minimum Trajectory Optimization*

The minimum trajectory optimization only ensures that the generated trajectory is smooth and dynamics feasible, but there is no restriction on the trajectory itself, and it is suitable for unobstructed flight between two points. Mellinger [13] proposed an algorithm that enables the real-time generation of optimal trajectories through a sequence of 3-D positions and yaw angles, while ensuring safe passage through specified corridors and satisfying constraints on velocities, accelerations and inputs. A nonlinear controller ensures the faithful tracking of these trajectories. Paper [14] adopted joint optimization of polynomial path segments in the unconstrained quadratic program, speeding up the generation of high-quality trajectories.

B. *Constrain Optimization*

Increase safety constraints for flight safety. Mainly divided into two categories, hard constraints that increase the boundary value and soft constraints that increase the binding force. The hard constraint method considers all safe areas to be equivalent. Chen [15] used a free-space flight corridor to constrain the trajectory between the corresponding grid points. Gao [16] replaced the previous polynomial with a Bessel polynomial, and used a matrix to represent the mapping relationship. Paper [17] used dense constraints to add a large number of constraints at discrete time periods, the acceleration at each time period is constant. The disadvantage of hard constraints is that some parts of the trajectory will be close to the obstacle. If the control part cannot follow the trajectory completely, it will cause a collision. The soft constraint method is to apply a "push force" to push the trajectory away from the obstacle. Ruder [18] reviewed the gradient descent optimization algorithm. Paper [19] proposed a complete formula using environmental gradients to optimize the trajectory coefficients of piecewise polynomials. The core problem of soft constraints is how to design a good objective function, so when the objective function is set unreasonably, the path may encounter obstacles.

IV. NEW UAV PATH PLANNING

The hard constraint method can ensure the global optimal trajectory, but it is easy to approach obstacles in free space, the dynamic constraints are too conservative, and the flight speed is slow. The soft constraint method uses gradient information to push the trajectory away from the obstacle, but there is a local minimum, which cannot successfully guarantee the success rate and kinematic feasibility. The new method combines the advantages of both. A dynamic-based hybrid A* search algorithm is used by Zhou [20] to find the initial trajectory with the shortest safe and feasible time, and the convex hull properties of B-splines are used to improve the efficiency and convergence speed of optimization. Adjust the time distribution to represent the trajectory as an uneven B-spline curve. Zhou [21] used PGO (Path Guidance Optimization) method to solve the problem of drones falling into local minimums in gradient-based trajectory optimization. Paper [22] designed a framework that not only includes the path guided optimization method of multiple topological paths, but also introduces a perceptual planning strategy to actively observe and avoid unknown obstacle risks.

V. RESULTS

A lot of UAV 3D path planning algorithms have been proposed in recent years. This paper lists the algorithms in each category that synthesized among almost all the works reported during recent years, A detailed analyzes on advantage and disadvantage of methods in each category is given in Table 1.

TABLE 1. PATH PLANNING ALGORITHM COMPARISON.

	Elements	Disadvantage	Advantage
Sample-based search	PRM, RRT, variants	Need pre-known information of Environment, optimal path is random	Avoiding complex kinematics constraints.
Heuristic search	A*, D*, variants	Large amount of node calculation and poor real-time performance, not suitable for dynamic trajectory planning	Good overall
Biologically inspired	evolutionary algorithms and neural networks.	deal with complex unstructured constrains	Long application time and wide search range
Potential field method	APF, variants	Easy to fall into a local minimum.	Good real-time
Based on fusion	Fusion of two or more algorithms	The fusion algorithm increases the amount of calculation, and the actual effect after fusion is not as good as the theoretical effect	Make up for the shortcomings of a single algorithm
Minimum trajectory	[13],[14]	The trajectory cannot avoid obstacles.	Smooth trajectory dynamics feasible
Hard constrain	[15],[16],[17]	Trajectories close to obstacles and speed deficient.	Hard-constrained methods ensure global optimality by the convex formulation.
Soft constrain	[18],[19]	There is a local minimum, the success rate and kinematic feasibility low	push trajectory far from obstacles
New path planning	[20],[21],[22]	Not mature	improves the computation efficiency as well as the convergent rate. high speed fly

VI. CONCLUSIONS

Summarization of each category will be given below. Sampling-based algorithms must first sample the environmental information. The generated path is random and cannot guarantee optimality, but its structure is simple and can avoid complex kinematic constraints. Heuristic search can directly find the global optimal path, but Large amount of node calculation and poor real-time performance, not suitable for dynamic trajectory planning. Biologically inspired algorithm can deal with complex unstructured constrains as well as other NP problem. This kind of algorithms optimizes the path by mutation, but mutation process requires a long iteration time. Potential field method has good real-time performance but easy to fall into local minimum. Based on fusion algorithm can make up for the shortcomings of a single algorithm, but increase the amount of calculation, and the actual effect after fusion is not as good as the theoretical effect. Minimum trajectory optimization can ensure smooth trajectory and dynamic feasible, but it cannot avoid obstacles. Hard constrain optimization ensure global optimality by the convex formulation. The disadvantage of hard constraints is that some parts of the trajectory will be close to the obstacle. Soft constrain optimization can push trajectory far from obstacles, but local minimum and kinematic feasible low cannot be ignored. New path planning improves the computation efficiency as well as the convergent rate, it can ensure UAV high speed fly. In the future, UAVs will be widely used in the military field. In unknown and complex environments, they can not only perceive the surrounding environment information in depth, but also achieve safe and fast flight under increasingly mature path planning algorithms.

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