International Core Journal of Engineering Volume 10 Issue 3, 2024
ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0006

A Review of Research on Aircraft Trajectory Planning

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Abstract

This paper first describes the concept and purpose of trajectory planning. Then the physical limits, mission requirements, real-time requirements and collaboration requirements of route planning are introduced respectively. what's more the methods of route planning are divided into trajectory optimization, path planning and route planning based on analogy which are described in detail. Finally, it makes a summary of the use of route planning methods and prospects the direction of future research of route planning.

Keywords

Route Planning; Trajectory Optimization; Planning Method.

1. Introduction

With the development of computers, automation, and information technology, modern aircraft technology has undergone tremendous changes. There are more and more types of aircraft with higher performance, higher technology density, complex structure, and strong coordination, making the operation of aircraft increasingly complex. At the same time, with the increasing difficulty, danger, and intensity of modern flight tasks, it becomes more and more difficult to complete complex flight tasks solely by manual operation of pilots due to their limitations in physiology and psychology. Therefore, the concept of aircraft trajectory planning emerged. Aircraft trajectory planning refers to finding an optimal or feasible flight trajectory from the starting point to the target point under the constraints of aircraft maneuverability, penetration probability, ground collision probability, and flight time.

The purpose of aircraft trajectory planning is to plan the optimal or satisfactory flight trajectory for the aircraft by comprehensively considering factors such as arrival time, fuel consumption, threats, and flight areas, so as to ensure the successful completion of the flight mission and safe return to the base.

2. Basic Limitations and Requirements of Aircraft Trajectory Planning

In the process of trajectory planning, many factors need to be considered, and these factors are often intertwined. Changing one factor usually causes changes in other factors, so it is necessary to coordinate the relationships between multiple factors during the trajectory planning process. The trajectory planning of aircraft needs to meet some basic constraints and requirements as follows:

2.1 The Physical Limitations of Aircraft

In trajectory planning, the physical limitations of the aircraft must be considered; otherwise, the aircraft will not be able to fly according to the generated trajectory. The physical limitations of the aircraft mainly constrain the trajectory in the following aspects.

(1) Maximum Turning Angle: The maximum turning angle depends on the physical performance of the specific aircraft. It restricts the generated flight path to turn within a maximum angle that is less than or equal to the pre-determined value. In addition, some missions also limit the sharp turns of the

aircraft. For example, the sharp turns of an aircraft in dense formation flying will greatly increase the probability of collision between the aircraft.

(2) Maximum Climb/Dive Angle: The maximum climb/dive angle is determined by the maneuverability of the aircraft itself, which limits the maximum angle of ascent and descent of the flight path in the vertical plane.

(3) Minimum Track Segment Length: It is the shortest distance that an aircraft must fly straight before it begins to change its flight attitude. In order to reduce navigation errors, aircraft generally do not want to make detours and frequent turns when flying at long distances.

(4) Minimum Flight Altitude: If a flying vehicle flies too low, it often increases the probability of crashing into the ground due to collision. Therefore, the minimum flight altitude needs to be set according to the maneuverability of the aircraft.

2.2 Flight Mission Requirements

The purpose of every flight of an aircraft is to accomplish specific missions. Based on the requirements of these missions, constraints are often placed on factors such as the aircraft's arrival time and direction of entry into the target area.

(1) Flight Path Distance Constraint: Urgent flight missions often require that the aircraft must arrive at a designated destination point before a certain time. Due to the limited maximum speed of the aircraft, it is required that the length of the flight path must not exceed a pre-set maximum distance.
(2) The flight path distance ultimately depends on the amount of fuel supply of the aircraft.

The fixed direction of approach: Some flight missions require the aircraft to approach the target from a specific direction. For example, in military applications, it is often required that the aircraft approaches the target from the weakest anti-aircraft direction.

(3) The Stealth of Flight Path: The stealth of flight path is the first factor to be considered in military aircraft flight path planning. In a wartime environment, stealth means safety. In the design process of modern aircraft, the radar cross section (Radar Cross Section, RCS) of the aircraft is generally made as small as possible to reduce the probability of being detected by enemy early warning radar and interception radar. However, even if the aircraft adopts various stealth technologies during design, there will still be some radar signals reflected back at high altitudes, so designing a flight path with good stealth is crucial. There are usually two ways to hide a flight path: one is to keep the flight path away from the threat source; the other is to lower the flight altitude, using the effect of terrain occlusion and reflected ground clutter to reduce the probability of being detected by radar.

2.3 Real-time Requirements

When complete and accurate environmental information is pre-prepared, people can usually plan an optimal trajectory from the starting point to the destination in one go.However, in practical applications: on one hand, due to the constant changes in flight environment, it is difficult to ensure that the obtained environmental information does not change; on the other hand, due to the uncertainty of tasks, aircrafts often need to temporarily change their flight tasks. For example, aircrafts need to perform emergency rescue missions, etc. In these situations, it is impossible to pre-plan a satisfactory trajectory on the ground. For the first scenario mentioned above, when the change area of the environment is not very large, online re-planning of the trajectory can be carried out through local updating methods. For the second scenario or when the change area of the environment is larger, real-time online planning capabilities must be possessed.

2.4 Collaborative Requirements

The joint execution of multiple aircraft for a specific task is the basic characteristic of current flight missions. Therefore, the cooperative performance of aircraft is also one of the factors that must be considered in trajectory planning. Cooperativeness requires trajectory planning to consider various factors, for example, a specific task requires multiple aircraft to arrive at the designated location from different directions simultaneously. During the execution of this task, if an aircraft encounters a threat and needs to change its arrival time, other aircraft must make corresponding adjustments. Therefore, the expected arrival time of the entire flight formation may not necessarily be completely in accordance with the originally scheduled time, but rather a dynamic result of mutual coordination during the planning process. In this situation, how to generate effective trajectories for each aircraft and coordinate the arrival time of the aircraft is the key to completing the flight mission.

3. Common Methods of Trajectory Planning

After extensive research by numerous domestic and international experts and scholars, it has been proven that trajectory planning is an NP problem, and direct solution often leads to combinatorial explosion. To accelerate the planning process, many different planning algorithms have been proposed by domestic and international scholars, which can be divided into three categories based on usage: trajectory optimization, path planning, and analog-based trajectory planning [1].

3.1 Trajectory Optimization

Trajectory optimization is to determine the state and control variables in the dynamic model so that the cost function or performance index reaches optimal. In a sense, it is actually an optimal control problem. Since the analytical solution of such problems is difficult to obtain directly, numerical methods are often used. The main methods include the steepest descent method, dynamic programming method, nonlinear programming method, optimal control method, and singular perturbation method.

Asseo uses the variational method combined with the steepest descent method to solve the TF/TA2 problem[2]. First, the lateral constraints of the aircraft are considered and a two-dimensional path in the horizontal plane is generated. Then, the vertical path of the horizontal path is calculated using a parabolic fitting method. This method is based on the gradient of the objective function and requires a large number of iterations. The algorithm is relatively simple, has fast convergence, and requires continuous first-order partial derivatives of the terrain, which makes it less demanding on the terrain compared to optimal control methods. However, due to its inherent limitations, gradient methods may converge to local optima rather than global optima.

The model of dynamic programming method is simple, has low requirements for terrain, does not rely on the continuity of threat fields, is easy to implement, and is suitable for small-scale trajectory optimization. Waller used a dynamic programming method that takes flight altitude and speed as state variables, divides time into segments, and uses thrust and heading as control variables to perform a two-dimensional simulation of terrain tracking in the vertical plane [3] . For larger areas, due to the limitations of its own state space, dynamic programming method may suffer from combinatorial explosion and fail to achieve the goal of trajectory optimization.

Cui Guotao et al. first discretized the dynamics model of cruise missiles, directly converting TF/TA trajectory optimization into a nonlinear programming problem[4]. Then, by solving the nonlinear programming problem, they generated the globally optimal flight trajectory. However, at this time, the number of variables is very large, and only sequential quadratic programming can be used to solve it, utilizing special sparse block structures.

The optimal control method model is relatively complex. When dealing with TF/TA2 problems, it is common to decompose the problem. Wilber proposed using the angle between the speed direction and the tangent plane coordinate axis of the terrain as the control variable [5]. The position coordinates of the aircraft are used as state variables. This transforms the trajectory optimization problem into an optimal control problem with a fixed starting point, free terminal, and free time for solution. However, the optimal control method can lead to deadlock in complex terrains, easy divergence, and strict requirements for terrains. Generally, it requires continuous second-order partial derivatives of the terrain. The initial heading of the end point position and its complex relationship with the terrain are generally difficult to determine. It often takes repeated calculations to reach the termination condition, resulting in a longer computation time.

The main idea of the singular perturbation theory is to use an asymptotic approximation containing one or more small quantities to represent nonlinear, high-dimensional problems and simplify them into linear, low-dimensional problems. In the late 1980s, the singular perturbation method was combined with Pontryagin's minimum principle to optimize the simplified model, and the tactical flight trajectory generation technology for military aircraft under the presence of ground threat sources was studied [6]. However, the accuracy of the singular perturbation method depends on the degree of time scale separation, and there is no standard method in nonlinear systems to determine the time scale separation point.

3.2 Path Planning

Most of the literature focuses on path planning rather than trajectory optimization problems. A path is formed by connecting multiple line segments or path points in sequence. This type of problem is typically described as follows: In the planning space of an aircraft, one needs to determine a sequence of line segments or path points as the flight route, such that the cost function reaches optimality. From a geometric perspective, there are two types of methods: those based on graphs and those based on grids.

(1) Graph-based Planning Method

In the graph-based path planning method, firstly, the free C space (Configuration Space) is represented as a network graph composed of one-dimensional line segments according to certain rules. Then, a certain search algorithm is used to perform trajectory search on this network graph. In this way, the path planning problem is transformed into a network graph search problem. The main methods include Voronoi diagram method and PRM method.

The Voronoi diagram is formed by making the perpendicular bisector of each pair of adjacent radar and missile positions according to their arrangement, thus creating a polygon surrounding each radar and missile position[7]. The boundaries of this polygon are all possible flight paths, then weights are assigned to these boundaries, and finally some algorithm is used to search for the optimal flight path. The number of edges in the Voronoi diagram is only of order O(n), and the time required to construct the Voronoi diagram is of order O(nlogn), but it is generally only suitable for two-dimensional path planning.

The PRM (Probabilistic Roadmap Method) was first proposed by Overmars et al. in 1992 [8]. This method generates a roadmap by randomly sampling in the planning space, and then searches for a path in this roadmap. One of the advantages of this method is that it allows for a trade-off between planning time and path quality. The longer the time spent constructing the random roadmap, the greater the likelihood of finding an optimal path. In a fixed environment, the random roadmap can usually be constructed in advance. However, if the planning environment changes, the random roadmap cannot be updated locally to adapt to the new environment. Therefore, this algorithm is generally not suitable for online real-time applications.

(2) Raster-based planning method

Raster-based planning methods primarily involve dividing the continuous C space into simple units. The subsequent steps include identifying the unit that encompasses both the starting point and the target point, followed by finding a series of connected units to link the starting unit to the target unit. Dynamic programming and A* algorithms are among the primary techniques employed in this approach.

The fundamental idea of dynamic programming is to transform a multi-step optimal decision-making problem into multiple one-step optimal decision-making problems. When Denton et al. used dynamic programming to calculate the three-dimensional optimal path, they decomposed the three-dimensional path into horizontal and vertical directions for calculation, resulting in a dynamic search trajectory tree [9]. During the processing, by categorizing nodes, the increase in the number of nodes was limited, effectively reducing the branching number of planning and thus improving computational efficiency. Min Changwan et al. also proposed a dynamic programming method to determine safe corridors and reference trajectories[10]. Considering factors such as navigation system accuracy and digital map error, they divided the search space into grids, using grids as path points for dynamic programming search. The optimal solution obtained in this way is a set of path points composed of a series of grid points. However, its disadvantage is that it is prone to combinatorial explosion problems in large-scale searches.

The A* algorithm is a classic optimal heuristic search algorithm. Rouse divides the entire region into several square grids, taking the center point of the grid as the path point, and implements the optimal path planning through the heuristic A* algorithm[11]. Szczerba et al. use a technique called sparse A* search (SAS) for trajectory planning[12]. This algorithm effectively reduces the search space to real-time convergence and obtains satisfactory solutions by combining path constraints, but it only performs trajectory search in two-dimensional planes. Li Chunhua et al. propose a real-time three-dimensional trajectory planning method based on SAS[13]. This method makes full use of the elevation information of the terrain, which can effectively avoid terrain and threat avoidance. The A* algorithm significantly improves search efficiency due to intelligent search, but the degree to which the algorithm ultimately approaches optimality depends on the expression of the heuristic function. When the search space is large, the computational load will also be large.

3.3 Analogical-based Trajectory Planning

Analogical-based trajectory planning is a method that utilizes concepts from physics or biology to transform and solve the trajectory planning problem. This includes methods such as artificial potential field, genetic algorithm, neural network, simulated annealing, and ant colony algorithm.

The main idea of the Artificial Potential Field Method is to utilize the relevant laws of attraction and repulsion in physics about magnetic fields. It treats the target as an attractive field, threats and obstacles as a repulsive field, and the aircraft flies in the potential field generated by the combination of both. Bortoff provided an example of trajectory planning for unmanned aerial vehicles passing through radar threat areas using the Artificial Potential Field Method[14]. The trajectory is represented by the state of a spring chain in the potential field, with the potential energy of the spring chain defined as the weighted sum of spring length and distance from the radar. After initialization, under the influence of the field, the spring chain eventually reaches its lowest potential energy state, which is the optimal trajectory. One notable advantage of this method is its fast planning speed, but it may fail to find a path, resulting in planning failure due to local minimum where attraction and repulsion forces are equal.

Genetic algorithm provides a general framework for solving complex problems. It imitates the inheritance and evolution of biology, and according to the principle of "survival of the fittest", it uses operations such as replication, crossover, and mutation to gradually approximate the optimal solution from the initial solution. Its five elements include: chromosome encoding, initial population, fitness function, genetic operation, and control parameters. Some scholars have used genetic algorithms for trajectory planning of aircraft[15]. Genetic algorithm uses simple coding techniques and reproduction mechanisms to represent complex phenomena, thus solving very difficult problems. In particular, it has advantages that traditional optimization methods cannot match because it is not constrained by restrictive assumptions about the search space, does not require assumptions such as continuity, derivative existence, and unimodality, and has inherent parallelism. It should be noted that as a global optimal algorithm, genetic algorithm can generally converge quickly to the vicinity of the optimal solution, but after approaching the optimal solution, the convergence speed may become very slow. Other search techniques can be considered after converging to the suboptimal solution.

Neural network is a computational method established under the inspiration of biological functions. Glmore gives a case of using Hopfield network for trajectory planning[16]. Firstly, the terrain information of digital map is mapped onto a Hopfield neural network, then a suitable energy function is constructed based on constraint conditions, and finally the desired trajectory is obtained by minimizing the energy through network convergence. Its disadvantage is also that the amount of computation is too large.

Simulated annealing algorithm is a heuristic random search algorithm based on Monte Carlo iteration proposed by Kirkpatrick et al. in 1982[17]. This algorithm simulates the annealing process of solid materials, accepts new solutions according to the Metropolis criterion, and accepts deteriorated solutions with a certain probability, thus obtaining the global optimal solution. An adaptive cooling method is proposed to obtain satisfactory results.

Ant colony algorithm is a new biomimetic algorithm that imitates the foraging behavior of ants[18]. As a stochastic optimization method, it absorbs the behavioral characteristics of ants and has achieved good results in solving a series of difficult combinatorial optimization problems through its inherent search mechanism. Similarly, ant colony algorithm is not constrained by restrictive assumptions about the search space, and does not require assumptions such as continuity, derivative existence, and unimodality, but its convergence speed is not very fast.

4. Conclusion

In the practical application of trajectory planning algorithms, it is often not a single algorithm that is used, but different planning algorithms are used at different stages. This can not only ensure that the overall trajectory is optimal under certain performance indicators, but also facilitate real-time planning in complex environments.With the rapid development of high and new technologies today, trajectory planning technology has become an indispensable part of developing cruise missiles, unmanned aerial vehicles, and civil aircraft. The focus of future research will further develop towards intelligence, real-time performance, and feasibility.

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