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Real-time trajectory planning for UCAV air-to-surface attack using inverse dynamics optimization method and receding horizon control

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Abstract This paper presents a computationally efficient real-time trajectory planning framework for typical unmanned combat aerial vehicle (UCAV) performing autonomous air-to-surface (A/S) attack. It combines the benefits of inverse dynamics optimization method and receding horizon optimal control technique. Firstly, the ground attack trajectory planning problem is mathematically formulated as a receding horizon optimal control problem (RHC-OCP). In particular, an approximate elliptic launch acceptable region (LAR) model is proposed to model the critical weapon delivery constraints. Secondly, a planning algorithm based on inverse dynamics optimization, which has high computational efficiency and good convergence properties, is developed to solve the RHC-OCP in real-time. Thirdly, in order to improve robustness and adaptivity in a dynamic and uncertain environment, a two-degree-of-freedom (2-DOF) receding horizon control architecture is introduced and a regular real-time update strategy is proposed as well, and the real-time feedback can be achieved and the not-converged situations can be handled. Finally, numerical simulations demonstrate the efficiency of this framework, and the results also show that the presented technique is well suited for real-time implementation in dynamic and uncertain environment.

1. Introduction

Unmanned combat aerial vehicles (UCAVs) are predicted to be the next generation front line fighter aircraft.[1] They are equipped with missiles or guided bombs, and can launch an attack and return to base or land on aircraft carriers. These vehicles will provide more tactical flexibility than a cruise missile because they will be able to loiter in the area and search for a moving target, and then strike it with their weapons.

Compared with a reconnaissance flight, during the course of an air-to-surface (A/S) attack, UCAVs will autonomously fly with highly aggressive maneuvers and fly frequently on the fringe of the flight envelope, to meet the pre-weapon-launch targeting conditions as quickly as possible, while avoiding the detection and engagement of surface-based air defenses. The idea of directly commanding the UCAV to track and attack a target, especially moving target, would be

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impractical, considering the fast and complicated dynamics of a typical UCAV. Therefore, one of the key technologies of UCAV is the autonomous, on-board, real-time trajectory planning.

The objective of this paper is to develop an efficient real-time trajectory planning framework for the typical UCAV platform, which can construct, in real time, a solution that optimizes the system objective while satisfying the boundary, path and platform kinematic and dynamic constraints, as well as sensor and weapon employment constraints.

2. Related work and contributions

Several trajectory planning methods for aircraft have been developed, particularly in recent years, with the development of computational capabilities, and the real-time trajectory planners are becoming feasible. Detailed descriptions and analysis of the various methods are included in Refs.[2–4] These methods include artificial potential field methods[5–8], sample-based planning methods[9–11], maneuver automation (MA)[12–14] and optimal control methods.

There is no doubt that optimal control theory[4,15,16] is the most natural framework for solving trajectory planning problems[17]; however, the rapid solution of optimal control problems (OCPs) for complicated nonlinear systems, such as aerial vehicles, is a challenging task. Analytical solutions are seldom available or even possible. As a result, more often than not, one resorts to numerical techniques. Available numerical methods can be classified into two general approaches[4]: direct and indirect methods. Indirect methods[18] solve the optimal control problem by formulating the first-order optimality conditions, applying Pontryagin's maximum principle and using nonlinear programming (NLP) to solve the resulting two-point boundary value problem numerically. They are not currently feasible for real-time implementation by on-board aircraft systems for the reasons given by Betts.[4] Direct methods[16,19,20], on the other hand, are widely accepted as a promising method suitable for real-time implementation. The main idea of direct methods is to reduce the OCP to a finite-dimensional nonlinear NLP problem by discretization and parameterization of a subset of the state and control vectors, and then solved using developed optimizers. Compared to indirect methods, though this type of method is not guaranteed to result in an optimal solution, it will usually generate a near-optimal solution more robustly and have a larger convergence radius. For in-flight real-time trajectory generation when the overall system accuracy is limited by atmospheric conditions, uncertainty, and noise, the priority is to generate near-optimal solutions within the required time intervals, so the fast direct methods are well suited.

Direct methods can be further classified by the subset of state and control variables that are parameterized[21]: if only control and some of the state variables are parameterized then numerical integration of the remaining state equations is required (e.g. direct shooting or direct multiple shooting[22]), but if all state variables are parameterized, then explicit numerical integration is not required (e.g. pseudospectral[15,23] and inverse dynamics methods[24–30]) and tends to be significantly faster than integration methods.[31]

The algorithm proposed in this paper belongs to the latter category. Numerous researchers have recently explored using pseudospectral methods for aerial vehicles trajectory optimization problems.[32–34] The main drawbacks of pseudospectral methods are the intensive computation for optimization and the indeterministic computation time for a converged solution, which are important considerations for real-time implementation. Inverse dynamics was originally used for flight control to generate the controls that drive a system to follow a desired state trajectory. Subsequently, several researchers[24,25] introduced this concept into the trajectory generation problem domain. Recently, inverse dynamics methods have been used for real-time on-board calculation of near-optimal trajectories.[27–29] Compared to pseudospectral methods, inverse dynamics method has many potential advantages. Firstly, it can use any model and any performance index[30] (i.e. it is not subject to the "curse of dimensionality" and does not require differentiability of the performance index as many other direct methods do). Secondly, it can transform the OCP into an NLP problem of very low dimension (typically < 20). Some numerical simulations[19] suggest that its computational speed could be more than an order of magnitude faster than the pseudospectral methods, with small loss of optimality, and its robustness and convergence properties are also better. Motivated by these advantages, this paper employs inverse dynamics method to develop real-time trajectory planning algorithms.

Furthermore, in order to deal with the uncertainty associated with unknown obstacles, pop-up threats or moving target in battlefield environment, the trajectory planning algorithm needs to continually account for the changes in situational awareness (SA), and rapidly adjust the flight trajectory being executed. Using receding horizon control (RHC)[35] strategy is well-known to be an effective mean to compensate for the uncertainty. RHC is based on iteratively solving the short term planning problem so that the computation time is dramatically reduced. Besides, RHC avoids "wasting" detailed computation on the uncertain far future, thus, the computational efficiency is improved, especially for the problems in a dynamic and uncertain environment.

In this paper, we present a computationally efficient real-time trajectory planning framework, which attempts to combine the high computational efficiency and good convergence properties of inverse dynamics optimization methods and the robustness and adaptivity of receding horizon optimal control techniques.

The rest of the paper is organized as follows: Section 3 describes a proper problem formulation for the A/S attack trajectory planning problem. Section 4 describes the real-time trajectory planning algorithm based on the inverse dynamics optimization method. Section 5 describes the proposed two-degree-of-freedom (2-DOF) RHC architecture. Finally, we provide several numerical experiments in Section 6 and conclude in Section 7.

3. Problem formulation

3.1. Aircraft dynamical model

Usually in a real-time trajectory planning context, a method requires an aircraft dynamical model that is simple enough to meet the computational time limitations, and produces feasible trajectories and controls accurate enough to be used as inputs to a flight control system. For an A/S attack mission, the