Chinese Journal of Aeronautics, (2016), **29**(1): 184–201

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Trajectory optimization of multiple quad-rotor UAVs in collaborative assembling task

Chen Yongbo, Yu Jianqiao *, Mei Yuesong, Zhang Siyu, Ai Xiaolin, Jia Zhenyue

School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

Received 3 June 2015; revised 18 August 2015; accepted 22 October 2015
Available online 22 December 2015

KEYWORDS

Hierarchic optimization strategy;
Parallel CFO-GA algorithm;
Path planning;
Six-degree-of-freedom rigid-body dynamic model;
Trajectory optimization;
Trajectory planning

Abstract A hierarchic optimization strategy based on the offline path planning process and online trajectory planning process is presented to solve the trajectory optimization problem of multiple quad-rotor unmanned aerial vehicles in the collaborative assembling task. Firstly, the path planning process is solved by a novel parallel intelligent optimization algorithm, the central force optimization-genetic algorithm (CFO-GA), which combines the central force optimization (CFO) algorithm with the genetic algorithm (GA). Because of the immaturity of the CFO, the convergence analysis of the CFO is completed by the stability theory of the linear time-variant discrete-time systems. The results show that the parallel CFO-GA algorithm converges faster than the parallel CFO and the central force optimization-sequential quadratic programming (CFO-SQP) algorithm. Then, the trajectory planning problem is established based on the path planning results. In order to limit the range of the attitude angle and guarantee the flight stability, the optimized object is changed from the ordinary six-degree-of-freedom rigid-body dynamic model to the dynamic model with an inner-loop attitude controller. The results show that the trajectory planning process can be solved by the mature SQP algorithm easily. Finally, the discussion and analysis of the real-time performance of the hierarchic optimization strategy are presented around the group number of the waypoints and the equal interval time.

1. Introduction

Unmanned aerial vehicles (UAVs) have become increasingly attractive for missions in which the human presence is dangerous or difficult. Among these UAVs, the unmanned quad-rotor helicopters have become increasingly popular platforms for the study of the UAVs from many viewpoints, such as the reconnaissance, the communications relay, the individual combat and so on.[1] The UAVs trajectory optimization that deals with the time evolution of the flight path is a very important part of the UAVs autonomous control system. Many researches about the quad-rotor helicopters focus on the

* Corresponding author. Tel.: +86 10 68912407.
E-mail addresses: bit_chenyongbo@163.com (Y. Chen), jianqiao@bit.edu.cn (J. Yu), mys001@bit.edu.cn (Y. Mei), ylww@bit.edu.cn (S. Zhang), bitaixiaolin@163.com (X. Ai), jiazhenyue@163.com (Z. Jia).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.12.008
1000-9361

controller design field, but the trajectory optimization process specifically aiming at the quad-rotor helicopters, is scarce.

In many references, the path planning and trajectory planning are similar. They can be collectively called the trajectory optimization. But in the strict sense, the UAVs trajectory planning process is different from the UAVs path planning process. The path planning is a process in which the UAV finds a three-dimensional (3D) space path from the starting point to the destination. The 3D space path is a static geometry path. It does not include the concept of time.[2] However, the results of the trajectory planning process are the time-varying flying paths. The results include the flying state of the vehicles. Generally speaking, the model and solution algorithm of the trajectory planning problem are more complicated than the ones of the path planning problem. However, many ideas from the path planning algorithms can help to solve the UAVs trajectory planning problem. For many simple scenarios, the simpler path planning algorithms can offer some sketchy and flyable flying results for the UAVs automatic control system quickly and efficiently. Both of them are very significant to the UAVs autonomous control system.

Because of the simpler model, the UAVs path planning problem has been solved by many methods, such as A^* algorithm,[3] artificial potential field (APF) method,[4,5] rapidly-exploring random tree (RRT) algorithm,[6,7] a large number of intelligent optimization algorithms[8,9] and so on. Recently, the intelligent optimization algorithms have drawn a lot of attention. For example, Duan et al. introduced many novel optimization algorithms to solve this problem without assuming kinematic and dynamic constraints, including the max–min adaptive ant colony optimization approach,[10] the chaotic predator–prey biogeography-based optimization (CPPBBO) algorithm,[11] the improved gravitational search algorithm[8] and the chaotic artificial bee colony (ABC) approach.[12] In order to use these algorithms, the original path planning problem which is an infinite dimensional problem is simplified to the finite dimensional optimization problem by the partition of the two-dimensional (2D) planning space. Although these methods can ensure the near-optimality of the path under some given objective functions, the dynamic and kinematic model of the UAVs is entirely ignored. These planning results are always unacceptable for the general UAVs, especially the fixed-wing aircraft. Even for the quad-rotor helicopters, these results will strongly limit the speed scheme of the UAVs.

Because through the trajectory planning algorithm the time-varying state variables can be obtained, the models of the trajectory planning problem need to be closer to the real aircraft model. Obviously, the high-fidelity model will help the control system to get the appropriate control commands that will maintain the actual flying vehicle on the obtained trajectories accurately. But the complicated model signifies the huge amount of calculation and the large difficulty of the planning process. So the suitable model of the planning object is very important for the computing processes and planning results.

Essentially, the trajectory planning problem is a multi-constraints optimal control problem. The most intuitive approach is to use the optimal control theory. Yao and Zhao[13] put forward the model predictive control (MPC) algorithm to solve the UAV trajectory planning problem in an uncertain environment. In Ref.[14], a novel finite horizon suboptimal controller is applied to solve the trajectory planning problems for the approach and landing (A&L) phase of the reusable launch vehicle (RLV). In this work, the model of the vehicle is a three-degree of freedom (3-DOF) longitudinal particle model. In addition to the optimal control theory, there are some other algorithms which can solve this problem. In Ref.[15], Zhang et al. applied a planning algorithm based on the inverse dynamics optimization to solve the ground attack trajectory planning problem of the unmanned combat aerial vehicle (UCAV) which is mathematically formulated as a receding horizon optimal control problem (RHC-OCP). In this work, the model of the UAV is described by the kinematic and dynamic model according to a full-blown 3-DOF particle model. In Ref.[16], Kamyar and Taheri used the differential evolution-sequential quadratic programming (DE-SQP) method and the particle swarm optimization-sequential quadratic programming (PSO-SQP) method to solve the trajectory planning problem based on the high-fidelity, 6-DOF dynamic model with the integration of accurate aerodynamic and propulsion models. In the existing literature, most of these papers focused on the fixed-wing UAV. There are only a small number of scholars researching the trajectory planning problem of the quad-rotor helicopters whose model is closer to the real UAV kinematic and dynamic model. Based on the commonly employed quad-rotor UAV model, Chamseddine et al.[17] used the Bézier polynomial function and the differential flatness method to solve the trajectory planning problem of the quad-rotor UAV.

The above references only show the single UAV path and trajectory planning method. Some multiple UAVs cooperative trajectory planning algorithms are proposed in some references. In the path planning area, Eva et al.[18] presented a path planner for multiple UAVs (multi-UAVs) based on the multiple coordinated agents co-evolution evolutionary algorithms (MCACEA) for the realistic scenarios. In Ref.[19], a path planning method based on the RRT was developed to generate paths for multi-UAVs in real time. In the trajectory planning area, Gu et al.[20] put forward a virtual motion camouflage (VMC) to solve the cooperative trajectory planning problem of the multi-UAVs, combining with the differential flatness theory, the Gauss pseudospectral method (GPM) and the nonlinear programming. In this work, the model of each UAV is described by the kinematic and dynamic model according to a full-blown 3-DOF particle model. The main difficulties of the multi-UAVs trajectory planning problem are the amount of calculation and the cooperative way. Of course, the amount of calculation of the problem increases with the size of the cluster and the complexity of the model. At the same time, the cooperative way is also very important.

The motivation of this paper is to solve the cooperative trajectory optimization problem of multiple quad-rotor unmanned aerial vehicles. Our concern is to find more efficient, more realistic and suboptimal trajectories for multiple quad-rotor UAVs without making too many simplifying assumptions on the trajectories. The existing references focusing on the similar problems have some shortcomings. The first problem is the lack of the reasonable systematic research about the overall solution frameworks. The other problem is that in order to simplify the problem, there are too many simplifying assumptions on the aircraft models. Faced with these problems, the hierarchic optimization strategy based on the offline path planning process and online trajectory planning process is put forward to solve this trajectory optimization problem. This