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Entry trajectory planning based on three-dimensional acceleration profile guidance

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ABSTRACT

A new entry trajectory generation approach based on rapid planning three-dimensional acceleration profile (TDAP) is proposed in this paper. The TDAP planner concept means extending the traditional drag planning approach into three dimensional drag space to accommodate much larger downrange or cross-range, and improve the maneuvering capability by utilizing both angle of attack and bank as primary control commands. To figure out this problem, firstly, the planner transforms the generation of TDAP into scheming two sub-profiles, longitudinal drag acceleration profile and lateral lift to drag acceleration profile in parallel. Each profile is generated in the corridor converted by all path constraints correspondingly. Secondly, a reduced order dynamics system is employed to extract all standard state variables and adjust the three-dimensional acceleration profile, ensuring the terminal position precision requirement to be met. Finally, a combined proportional derivative (PD) feedback law is designed to track the reference profile. Simulations with the Common Aero Vehicle (CAV) model show that the 3-D trajectories of both planned and generated by the guidance law can successfully satisfy all path constraints and flight task requirements.

1. Introduction

Atmospheric entry flight is a critical phase of operation for any reusable launch vehicle (RLV), crew return vehicle, or hypersonic glide vehicle (HGV). Entry guidance system determines the necessary command during entry and is significant to the development of entry vehicles. The Shuttle entry guidance [1], i.e. drag based guidance, is the benchmark of entry guidance and consists of two parts: longitudinal drag profile planning and tracking. The drag profile planner is based on the assumption that entry trajectory is a great arc, and the requirement of satisfying all path constraints. In order to track the drag profile, a guidance law is designed to adjust the magnitude of bank angle, balancing the gravitation with a fixed angle of attack profile. Besides tracking the drag profile, a bank-reversal logic, which changes the sign to the opposite when the heading angle error exceeds a velocity-dependent dead-band, is used to control the final cross-range accuracy. In addition, the reference drag profile will be updated according to the current state to null range error [2–4].

Although the Shuttle entry guidance has been very effective, there are still exist some drawbacks that may restrict the next generation of RLVs [5] and HGVs to obtain higher accuracy and improve maneuvering capability when comparing with the Shuttle. As the great arc assumption of entry trajectory ignores the curvature caused by lateral motion, the drag profile planned will not be able to guide large cross-range entries as well as the descent portion of aborts that require significant cross-range. To obtain more downrange, cross-range, or footprint [6], both the angle of attack and bank should be used as primary guidance commands during entry. Though the heating constraint at the initial entry dictates maximum angle of attack and it is required to be on the front side of the lift-to-ratio curve at the initiation of the terminal area energy management phase, there is still much freedom space left to design [7].

In order to improve the adaptive ability and autonomy of the Shuttle entry guidance, many scholars have devoted themselves to research more feasible entry guidance, especially reference trajectory planning methods [8] for future entry vehicles. Take generating more optimal drag profile quickly and improving its adaptive ability into account, Roenneke [9] proposed a new drag profile planning approach on the basis of downrange requirement for on-board implementation. However, the tracking law is the same as that of the Shuttle entry guidance. Seeking to maintain the strong attributes of the shuttle entry guidance, Mease et al. [10] developed a three dimensional trajectory generation approach with tak-

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ing simultaneous consideration both downrange and cross-range requirements for RLVs. The proposed scheme was to determine an optimal TDAP with which both the bank angle and angle of attack can be solved directly in the three dimensional corridor. As a feasible TDAP is relatively hard to obtain in the three dimensional entry corridor without any form of angle of attack assumption, it has to utilize a high performance computer to get the solution. Accordingly, Saraf [11,12] proposed an evolved acceleration guidance logic for entry (EAGLE) algorithm with a reference angle of attack profile. Differ from the Shuttle guidance, EAGLE employed an additional logic to adjust the reference angle of attack profile to manage the final bank reversal location. Although the rest is also the same as the drag based guidance, the angle of attack commanded by EAGLE is a secondary means of trajectory control. Later, Xie [13] extended Saraf's planner to meet waypoint and no-fly zone constraints. Based on the quasi-equilibrium glide condition (QEGC), Shen and Lu [14] proposed a new trajectory planning approach subject to all common inequality and equality constraints. This approach made a novel use of the QEGC and transformed the highly constrained nonlinear trajectory planning problem into two sequential one-parameter search problems. After that, Xue [15] modified the QEGC to allow enforcement of all path constraints expressible in the velocity–altitude space and developed a constrained predictor–corrector algorithm. It is applicable to medium-to-high lifting capability entry vehicles and has been demonstrated by the X-33 model. On the basis of Ref. [14] and [15], Ref. [16] recently proposed a unified entry guidance for a wide range of vehicles with varying lifting capabilities for orbital as well as suborbital entry missions on a single baseline predictor–corrector algorithm. By choosing appropriate augmentations of altitude-rate feedback, the long-standing challenge of enforcing common inequality trajectory constraints with a predictor–corrector algorithm is now satisfactorily overcome. With regard to autonomous and real-time or near real-time requirements, some scholars resorted to real-time planning reference trajectory based on analytical solutions [17]. In order to deduce the analytical solutions, they often had to make some assumption which limited its application. While others converted it into an optimal control problem and obtained the optimal trajectory [18,19] through solving the resulting Hamiltonian boundary-value problem. As for the optimal control problem, the biggest difficulty is that it is hard to obtain its solution. Consequently, some scholars resorted to direct numerical method, pseudospectral method in particular, to generate a feasible trajectory, because it can transform the complicated optimal control problem into a simple normal nonlinear problem [20,21].

Reentry reference trajectory planning [22] is a key component of the reentry guidance for HGVs. It can generate the guidance command by tracking the reference profile [23] and present a feasible solution that is guaranteed satisfaction of accuracy in meeting all the specified boundary conditions for the entry problem. Our objective of this paper is to develop a new approach of fast design a TDAP to accommodate much larger downrange or cross-range, and improve the maneuvering capability of by utilizing both angle of attack and bank as primary control commands. On the basis of Shuttle drag planning, there is only one lateral motion variable needed to expand the drag profile into three dimensional space. The ratio of the lateral and drag accelerations is a better variable to represent the lateral motion [10]. As the start and end energy can be determined by the given condition, it will be better to plan the reference profile as a function of energy rather than time. In this paper, a new approach to design the TDAP by scheming both the longitudinal drag profile and lateral command profile is presented. Based on the traditional entry corridor, the longitudinal drag acceleration entry corridor that is used to plan the longitudinal drag profile is developed without any assumption of angle of attack. Considering the coupling of longitudinal and lateral motion, a lateral entry corridor is developed by the QEGC and drag profile planned. Then the lateral profile is able to design in the corresponding lateral entry corridor. According to the reduced order dynamics, the initial longitudinal and lateral profile will be adjusted to accommodate all the path constraints and satisfy the terminal constrained requirements. And the trajectory states and control variables are also extracted by the TDAP planned. To verify the TDAP planning algorithm, a combined PD feedback law is designed. Further, some simulation scenarios are employed, and the feasibility and validity of this new approach are tested by a CAV-H model.

This paper is organized as follows. Section 2 describes the entry planning problem for trajectory generation, including equations of motion and constraints. Section 3 establishes a TDAP planner, which includes how to generate the feasible TDAP and tracking law. Section 4 demonstrates the validity of TDAP planning algorithm with the combined PD tracking law, examines the adaptive ability of the proposed approach under different terminal height, velocity and position constraints, and eventually contrasts the trajectory results between the traditional approach and ours. Finally, Section 5 summarizes the main contributions and also presents areas that merit further research.

2. Entry planning problem formulation

This section provides the necessary information, equations of motion and constraints, about the entry planning problem. The equations of motion follow from assuming that the Earth's rotation is negligible. During vehicle entry into the atmosphere, heating rate, dynamic pressure and total overload are the most important path constraints. If there are no-fly zones and waypoints, the path constraints should include how to avoid the no-fly zones and pass the waypoints. In addition, there are magnitude and rate constraints of the control variables that need be concerned. Also the terminal constraints, such as terminal altitude, velocity, and position constrains etc., should be taken into consideration.

2.1. Equations of motion

Because the vehicle is unpowered during the entry flight, the energy E is monotonic decreasing. Let μ dictate the gravitational constant, r be the distance from the vehicle to the planet's center, and V denote the Earth-relative velocity magnitude, then E can be expressed as

$$E = \frac{V^2}{2} - \frac{\mu}{r} \tag{1}$$

Assuming a spherical, non-rotating Earth and considering E as an independent variable, the vehicle's motion can be modeled by five state equations as in [10].

$$\frac{\mathrm{d}r}{\mathrm{d}E} = -\frac{\sin\theta}{D} \tag{2}$$

$$\frac{\mathrm{d}\lambda}{\mathrm{d}E} = -\frac{\cos\theta\sin\sigma}{rD\cos\phi} \tag{3}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}E} = -\frac{\cos\theta\cos\sigma}{r}D \tag{4}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}E} = -\frac{L}{V^2D}\cos\upsilon + \left(g - \frac{V^2}{r}\right)\frac{\cos\theta}{V^2D} \tag{5}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = -\frac{\tan\phi\cos\theta\sin\sigma}{r}\frac{1}{D} - \frac{1}{V^2\cos\theta}\frac{L\sin\upsilon}{D} \tag{6}$$

In equations (2)–(6), the state vector $\boldsymbol{X} = (r, \lambda, \phi, \theta, \sigma)^{\mathrm{T}}$, where λ is the longitude, ϕ is the latitude, θ is the flight path angle and