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Advances in Space Research xxx (2015) xxx–xxx

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Advances in Space Research
(a COSPAR publication)

www.elsevier.com/locate/asr

Onboard planning of constrained longitudinal trajectory for reusable launch vehicles in terminal area

Zixuan Liang, Qingdong Li *, Zhang Ren

Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing 100191, China

Received 9 June 2015; received in revised form 16 November 2015; accepted 23 November 2015

Abstract

A rapid planning algorithm is developed to generate a constrained longitudinal trajectory onboard for reusable launch vehicles (RLVs) in the terminal area energy management (TAEM) phase. The longitudinal trajectory is planned in the flight-path angle vs. altitude space. This flight-path angle profile is designed with required altitude, flight-path angle and range-to-go, and then optimized as a one-parameter search problem to meet the velocity constraint. Considering the dynamic pressure constraint, a dynamic pressure protection (DPP) method is designed. With the DPP, the highly constrained longitudinal trajectory is generated by tracking the planned flight-path angle profile. Finally, the TAEM trajectory planning algorithm is tested on the X-33 vehicle model in different cases. The algorithm is shown to be effective and robust to generate longitudinal flight trajectories with all constraints satisfied in high precision. In each case, the constrained trajectory is planned within 1 s on a PC, which indicates that the algorithm is feasible to be employed onboard.

Keywords: Reusable launch vehicle; Terminal area energy management; Onboard planning; Trajectory optimization; Flight constraint

1. Introduction

The reusable launch vehicle (RLV) is a type of reliable and economical space transportation which may be a replacement for the previous Space Shuttle in the future (Freeman et al., 1997; Rasky et al., 2006). When a RLV descents from an orbit or a sub-orbit, it would commonly fly through three phases: the entry phase (Harpold, 1979; Lu, 2014) which starts at an altitude of 120 km with approximately Mach 25, the terminal area energy management (TAEM) phase (Burchett, 2004) which starts at an altitude between 25 and 30 km with approximately Mach 3, and the approach and landing (A&L) phase (Kluever, 2004; Kluever and Neal, 2015) which starts at an altitude between 3 and 5 km with approximately Mach 0.5. As the vehicle glides without any propulsion during the entry phase and multiple dispersions exist throughout the atmospheric entry, large errors would appear for the initial condition of the TAEM phase. The main task for the TAEM phase is to reduce errors caused in the previous entry phase and offer a good condition for the upcoming A&L phase. The terminal condition of the TAEM phase is under multiple constraints, especially in the longitudinal plane, including the altitude constraint, the velocity constraint, the range-to-go constraint, and the flight-path angle constraint. Additionally, the TAEM phase trajectory is constrained with the dynamic pressure limit. Hence, a reliable TAEM guidance system is essential for a safe flight of the RLV.

Generally, the TAEM guidance strategy is developed in two steps: first, optimize a constrained flight trajectory on the ground; then, track this trajectory onboard via an advanced control algorithm. Plenty of excellent research has been conducted for the trajectory optimization and

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* Corresponding author. Tel.: +86 10 82314573x13.
E-mail addresses: aliang@buaa.edu.cn (Z. Liang), buaa.gnc@gmail.com (Q. Li), renzhang@buaa.edu.cn (Z. Ren).

http://dx.doi.org/10.1016/j.asr.2015.11.027

Please cite this article in press as: Liang, Z., et al. Onboard planning of constrained longitudinal trajectory for reusable launch vehicles in terminal area. Adv. Space Res. (2015), http://dx.doi.org/10.1016/j.asr.2015.11.027

the tracking law (Morio et al., 2007, 2010; Kluever, 2007; Ridder and Mooij, 2011a,b). Though this strategy is simple to be employed, it cannot meet the request of the next generation of RLV which should be more reliable and adaptive. For example, the vehicle should own the capability to plan a feasible trajectory onboard when the initial flight condition is dispersed and the pre-designed one is no longer effective.

With this purpose, Barton et al. (2002) planned the longitudinal trajectory based on a dynamic pressure profile, and generate the lateral trajectory via the Sub-optimal Nodal Application of the Kernel Extraction (SNAKE) method. The dynamic pressure profile has been widely used in longitudinal trajectory planning approaches and shown effective (Barton et al., 2002; Da Costa, 2003; Mayanna et al., 2006). However, the flight-path angle constraint which is important for a safe landing is usually not focused on, which means these approaches may fail when the required terminal flight-path angle is changed. Horneman and Kluever (2004) designed a quadratic polynomial altitude profile with respect to the ground track length. The profile can meet the flight-path angle constraint, but it leaves the terminal velocity uncontrolled. In their research, the terminal velocity corresponding to the energy is achieved by adjusting the lateral trajectory. Morani et al. (2011) and Corraro et al. (2011) planned the longitudinal trajectory based on a Mach number profile which can take the terminal flight-path angle and velocity into consideration. Similarly in their study, the range-to-go constraint is not considered in the longitudinal profile, thus it has to be modified by the lateral guidance logic.

Actually, the vehicle's energy can be managed by either an adaptive lateral maneuver or an onboard-planned longitudinal trajectory. Take the flight with higher initial energy as an example. A longer trajectory with stronger lateral maneuver can be flown to dissipate the energy. Moreover, the high initial energy is able to be dissipated as well by flying a lower trajectory in the longitudinal plane. Because the velocity can be reduced by larger drag at lower altitude. In this study, the onboard planning algorithm for the constrained longitudinal trajectory is focused on.

An onboard trajectory planning method should be designed under two principles: first, all typical flight constraints are considered; second, the algorithm is simple enough to be employed onboard. Furthermore, constraints for longitudinal variables are better to be satisfied in the longitudinal profile so that enough control authority is saved for the lateral guidance. The authors proposed an onboard longitudinal trajectory planning method for the TAEM phase of RLVs (Liang et al., 2014). Actually, in that method, the dynamic pressure constraint was simply considered instead of accurately limited. In this paper, an improved trajectory planning algorithm with the dynamic pressure protection (DPP) and the profile tracking is designed. Hence, the terminal constraints (such as constraints for the altitude, the velocity, the range-to-go, and the flight-path angle), the angle of attack constraint, and the dynamic pressure constraint are all well satisfied in this study.

The outline of this paper is as follows. Section 2 introduces flight dynamics and constraints for the TAEM phase. Section 3 presents a rapid trajectory planning algorithm including methods for the flight-path angle profile planning, the DPP, and the constrained trajectory generation. In Section 4, the proposed trajectory planning algorithm is tested on the X-33 vehicle model in different cases. Finally, Section 5 gives the conclusion.

2. Fundamentals

2.1. Flight dynamics

The three dimensional point-mass equations for a RLV over a flat and non-rotating Earth are described by Ridder and Mooij (2011b)

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -D - g\sin\gamma \tag{1}$$

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{1}{v}(L\cos\sigma - g\cos\gamma) \tag{2}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{L\sin\sigma}{v\cos\gamma} \tag{3}$$

$$\frac{\mathrm{d}h}{\mathrm{d}t} = v\sin\gamma \tag{4}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v\cos\gamma\sin\psi \tag{5}$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = v\cos\gamma\cos\psi \tag{6}$$

where v is the Earth-relative velocity, γ is the flight-path angle, ψ is the velocity heading angle, and h is the altitude of the vehicle. (x, y) describes the vehicle's location with the positive x-axis and the positive y-axis pointing along and right of the runway centerline on approach, respectively. g is the gravitational acceleration. σ is the bank angle. L and D are the aerodynamic lift and drag accelerations given by

$$L = \frac{qC_L(\alpha, Ma)S_A}{m}, \quad D = \frac{qC_D(\alpha, Ma)S_A}{m} \tag{7}$$

where S_A is the vehicle's reference area, and m is the mass. $q = \rho v^2/2$ is the dynamic pressure, with the atmospheric density ρ given by the International Standard Atmospheric (ISO 2533, 1975). C_L and C_D are the lift and drag coefficients that depend on the angle of attack α and the Mach number Ma. For the X-33 vehicle at Mach numbers from 0.5 to 3, the lift and drag coefficients (Kluever, 2007; Chen, 2011) are shown in Figs. 1 and 2, respectively.

Considering that the flight time is not limited in the TAEM phase, the altitude which monotonically decreases during this phase can be used as the independent variable (Da Costa, 2003). Then, differential equations are given by

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