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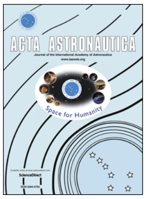

Online trajectory planning and guidance for reusable launch vehicles in the terminal area

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ABSTRACT

A guidance scheme has been proposed based on a new online trajectory planning algorithm for an unpowered reusable launch vehicle (RLV) in the terminal area energy management (TAEM) phase. The trajectory planning algorithm is able to rapidly generate a feasible path from the current state to a desired state at approach and landing interface (ALI) based on the dynamic pressure profile and new ground track geometry. Simple guidance laws are used to keep the RLV flying along the reference path which can be adjusted online by five related parameters. Then, the effectiveness and adaptability of the proposed TAEM guidance scheme is demonstrated by numerical trials with variations in the initial energy, position and aerodynamic performance.

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1. Introduction

Recently, advanced reusable launch vehicles (RLV) have been developed to reduce the costs of the space transportation and make significant improvement of vehicle flexibility and reliability [1,2]. In addition, the future space transportation systems will likely emphasize the robustness in terms of variations in mission objectives, dispersions and other uncertainties. Therefore, it is necessary and important to develop an automated mission-planning algorithm which can potentially serve as an onboard guidance scheme with the ability to rapidly generate the various trajectories and guidance commands by re-planning the trajectory from the current vehicle state to a desired target state.

The descent flight of the RLV commonly consists of the entry phase, the terminal area energy management (TAEM) phase and the approach and landing (A&L) phase. The TAEM is a critical flight phase that brings the unpowered vehicle from the terminal entry point (TEP) to the approach and landing interface (ALI) and it is mainly responsible for aligning the vehicle with the runway while dissipating the vehicle's surplus energy. The traditional TAEM guidance strategy is based on the space shuttle and consists of several segments: energy dissipation S-turn phase (exists only when the energy surplus at TEP), acquisition phase, heading alignment phase, and pre-final phase [3]. In spite of that the space shuttle TAEM guidance strategy has been demonstrated to be effective, it nevertheless mainly depends on a set of fixed, pre-determined reference trajectories which only account for a limited number of off-nominal scenarios. Therefore, some improvements have been made in the TAEM trajectory guidance scheme.

A great effort has been made with the aim of developing advanced guidance algorithms capable to deal with drastic off-nominal conditions. Hanson had argued that advanced guidance and control technologies can successfully return an RLV suffered from aero-surface failures, poor vehicle performance and larger-than-expected flight dispersions [4,5]. Grantham presented an adaptive critic neural network based guidance methodology that can

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generate TAEM trajectories in a wide range of vehicle states during landing [6]. Burchett developed a TAEM trajectory guidance method based on fuzzy logic which is capable of compensating for control surface failures by restricting the allowable bank angle [7]. Hall presented the first application of sliding mode disturbance observer driven sliding mode control to improve RLV flight control performance [8]. Kluever proposed a TAEM guidance method for a scenario with bank constrains, which determines the best feasible path by iterating on the bank reversal switch time and downrange location of the heading alignment circle (HAC) [9]. Morio et al. designed a robust TAEM guidance scheme based on a non-linear dynamic inversion technique so as to circumvent off-nominal flight conditions [10].

The online trajectory planning algorithm has been newly investigated as an effective way to fundamentally compensate for the defect of the pre-determined reference trajectories. Horneman and Kluever determined an optimal TAEM trajectory among a set of feasible trajectories that were propagated according to different geometric parameters [11,12]. Hull et al. described an online trajectory generator for both the TAEM and A&L phase by periodically updating six parameters online in response to changes of the aerodynamic characteristics of the vehicle [13]. Mayanna et al. developed a TAEM guidance method with vertical guidance relying on a pre-specified dynamic pressure profile and lateral guidance relying on the new proposed ground track geometry [14]. Kluever proposed an algorithm capable of rapidly generating a feasible TAEM trajectory by iterating on the downrange location of the HAC and its radius [15]. Ridder and Mooij presented a planning algorithm based on the energy-tube concept, which can be used in an on-board planner [16,17]. Jiang and Yang proposed a TAEM trajectory planning algorithm by energy-to-range ratio with a new lateral approaching strategy method in the situation of energy surplus [18].

In this paper, a TAEM trajectory guidance strategy is proposed based on an online trajectory planning algorithm with the ability to rapidly generate a feasible path from the current state to the desired ALI state. Unlike the existing way of fixing the vertical profile [12,14,15,18,19], the dynamic pressure profile used to determine the vertical profile in this paper is adjustable online, which greatly increases the design freedom. The proposed lateral design approach based on a new ground track geometry makes it unnecessary to execute the energy dissipation S-turn phase and choose the approaching mode (direct mode or overhead mode) [9,12,15,16], which reduces the design complexity, and similarly, this ground track geometry can be adjusted online. In addition, as the ground track distance predicted along fixed geometric segments is inaccurate because of the existence of coupling between vertical and lateral motion, this online trajectory planning algorithm can obtain the actual ground track distance by numerically propagating the trajectory rather than adjusting the downrange according to a table with correction information stored in advance [14].

2. System model

The earth is assumed to be flat, nonrotating, and inertial during the derivation of the equations of motion for an unpowered RLV in the TAEM phase. The RLV is considered as a point mass, so its motion is defined as:

$$\dot{V} = -\frac{D}{m} - g\sin\gamma \tag{1}$$

$$\dot{\gamma} = \frac{L\cos\sigma}{mV} - \frac{g\cos\gamma}{V} \tag{2}$$

$$\dot{\chi} = \frac{L\sin\sigma}{mV\cos\gamma} \tag{3}$$

$$\dot{h} = V\sin\gamma \tag{4}$$

$$\dot{x} = V\cos\gamma\cos\chi \tag{5}$$

$$\dot{y} = V\cos\gamma\sin\chi \tag{6}$$

where $+x$ axis points along the runway centerline in the direction of approach and the $+y$ axis points right of the runway on approach, the $+z$ axis points downward along the local vertical, and the origin is at the runway threshold. V is the velocity magnitude, and γ is the flight path angle measured from the horizonal plane to the velocity. The runway-relative heading angle χ is measured clockwise in the horizontal plane from the runway centerline to the velocity. h represents the altitude, and x and y are the horizontal position coordinates of the RLV. σ is the bank angle, m is the vehicle's mass, and g is the gravitational acceleration.

The simplified aerodynamic model is used in the formulation as follows:

$$L = qSC_L \tag{7}$$

$$D = qSC_D \tag{8}$$

where L is the aerodynamic lift force, D is the aerodynamic drag force, q is the dynamic pressure, and S is the reference area of the RLV. The aerodynamic lift coefficient C_L and drag coefficient C_D are computed by a two-dimensional table look-up with angle-of-attack α and Mach number M as the independent variables.

3. Vertical guidance

3.1. Dynamic pressure profile

Generally, the linear, quadratic or cubic curve will be used to parameterize the dynamic pressure profile [20,21]. As Ridder and Mooij have concluded that it is not possible to use a single fixed dynamic pressure profile in the case of abnormal conditions [17], in this paper, we design the dynamic pressure profile with respect to altitude as a straight line combined with two third order polynomials to make it easier to modify the profile. The dynamic pressure

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