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Onboard guidance system design for reusable launch vehicles in the terminal area energy management phase

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ABSTRACT

A terminal area energy management (TAEM) guidance system for an unpowered reusable launch vehicle (RLV) is proposed in this paper. The mathematical model representing the RLV gliding motion is provided, followed by a transformation of extracting the required dynamics for reference profile generation. Reference longitudinal profiles are conceived based on the capability of maximum dive and maximum glide that a RLV can perform. The trajectory is obtained by iterating the motion equations at each node of altitude, where the angle of attack and the flight-path angle are regarded as regulating variables. An onboard ground-track predictor is constructed to generate the current range-to-go and lateral commands online. Although the longitudinal profile generation requires pre-processing using the RLV aerodynamics, the ground-track prediction can be executed online. This makes the guidance scheme adaptable to abnormal conditions. Finally, the guidance law is designed to track the reference commands. Numerical simulations demonstrate that the proposed guidance scheme is capable of guiding the RLV to the desired touchdown conditions.

1. Introduction

The second-generation reusable launch vehicles (RLVs) have been designed, aiming at reducing the costs of space transportation while improving the safety and reliability of the vehicles [1,2]. Advanced guidance and control (G&C) technologies are well recognized as an effective means to achieve these objectives particularly during reentry flight [3]. The atmospheric reentry of a RLV usually starts with an initial reentry (IRE) phase, followed by a terminal area energy management (TAEM) phase as well as an approach and landing (A&L) phase.

As far as the TAEM guidance is concerned, the objective is to guide the unpowered RLV from a terminal entry point (TEP) with a given energy state to an expected approach and landing interface (ALI) without violating the vehicle's design constraints (e.g., the dynamic pressure and the load factor). It is characterized by a heading alignment cylinder (HAC), during which the RLV performs a turn around the cylinder to align with the runway. This feature of lateral manoeuver makes the TAEM phase significantly different from the IRE phase and A&L phase in three dimensional motions. Recently, extensive studies focus on guidance scheme for vertical motion in IRE and A&L phases, such as [4–9], nevertheless fewer efforts have been placed on the TAEM guidance scheme.

The preliminary TAEM guidance system in the US space shuttle relies on reference trajectories that are calculated and stored in the onboard computer before flight [10]. This strategy works well in nominal cases. However, the offline trajectories with decoupled lateral and longitudinal channels can result in some limitations. 1) The capability of accommodating large uncertainties is limited due to fixed reference trajectories. 2) The accuracy of terminal guidance is decreased as a consequence of the decoupling between lateral and longitudinal motions.

To address the aforementioned issues, several efforts have been devoted to online guidance systems for the TAEM phase. An onboard two-dimensional trajectory planning algorithm is developed in Refs. [11] and [12]. The main idea is to generate a feasible path by iterating three geometric parameters. The ground-track path is firstly designed, followed by an altitude profile conceived as a function of ground-track range. Feasible trajectories are therefore constructed by propagating the energy from the TEP to the ALI. Finally the best one is selected according to the cost function. In Refs. [13] and [14], the energy-tube concept is introduced to analyze the maximum and minimum required energies for a specific target point. Afterwards this concept is integrated into a planning and estimation algorithm to calculate the best HAC position, as well as its deviation in response to abnormal conditions [15].

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In Ref. [16], a long-term and short-term online trajectory generation scheme is proposed, accounting for the most relevant vehicle and trajectory constraints. In Ref. [17], an online trajectory planning and guidance approach is proposed, where the reference path can be adjusted online. The guidance adaptation capability is improved by these strategies to some extent. The reference longitudinal profile in these methods is usually defined by an altitude profile as a quadratic polynomial of ground-track range or a Mach profile as a cubic polynomial of altitude. However, the physical interpretation of such a longitudinal profile requires more explanations, taking [16] as example. On the other hand, it might be impossible to use a single fixed longitudinal profile in the event of off-nominal conditions, which is also concluded in Refs. [13] and [17]. Hence, further investigation is needed for reference longitudinal profile design.

On the other hand, three-dimensional trajectory planning methods are discussed by considering the coupling between longitudinal and lateral motions. Offline three-dimensional trajectory planning algorithms are presented in Refs. [18] and [19]. However, a possible problem is that the maximum turning capability of the vehicle is always utilized, which limits the capability of adjusting the trajectory under abnormal conditions. Other studies have focused on applying direct non-linear programming (NLP) method to the TAEM guidance problem. For example, a NLP optimizer is exploited for trajectory planning, allowing for the restrictions of mission profile and off-nominal conditions [20]. A three-dimensional TAEM trajectory planning algorithm combined with a down-track correction scheme is proposed in Ref. [21]. In Ref. [22], an adaptive neural network-based methodology is studied to maintain a gradual glideslope and meet specific constraints, where the cost function is formulated. A new trajectory optimization algorithm is presented based on interval analysis in Ref. [23]. An optimization algorithm with dynamic pressure as the cost function is used to obtain the optimal trajectory for TAEM phase [24]. The NLP-based trajectory planning strategies using the theory of differential flatness are investigated in Refs. [25] and [26]. These NLP-based three-dimensional trajectory planning algorithms can generate trajectories precisely. However, they are usually time-consuming for onboard applications. In addition, little attention has been paid on the unique feature of the unpowered gliding motion in these algorithms.

Motivated by the discussed facts, this paper focuses on an onboard TAEM guidance system design. The developed scheme generates longitudinal profiles by taking into consideration of the vehicle dynamic constraints. Meanwhile, the ground-track path is adjusted in real-time, and the guidance commands are generated online. In such a way, this scheme is adaptable in the event of variations in initial conditions, and might potentially serve as an onboard guidance scheme. Compared with the existing literature, the contributions of this paper lie in four aspects. 1) A dynamic pressure profile with explicit physical interpretation is conceived by iterating the kernel extraction protocol (KEP) equations; 2) An onboard task management scheme is constructed to predict ground-track range online. Guidance commands are generated subsequently by comparing the predicted range with the reference one. In this way, the longitudinal and lateral motions are combined together; 3) A guidance law with consideration of real flight situations is developed for trajectory tracking; 4) Simulations with consideration of not only initial condition variations but also model uncertainties are conducted to verify the feasibility and robustness of the proposed method.

The rest of the paper is arranged as follows. Section 2 presents the mathematical model and KEP equations, as well as the idea of energy management and TAEM guidance objectives. In Section 3, the dynamic pressure profiles bounded by maximum dive and maximum glide capability is proposed. In Section 4, an onboard ground-track predictor (GTP) is developed. In Section 5, the guidance laws for both longitudinal and lateral motions are investigated. In Section 6, the effectiveness of the proposed guidance scheme is demonstrated by simulating different TAEM scenarios in the presence of abnormal conditions. Concluding remarks are drawn in Section 7.

2. Preliminaries

2.1. Mathematical model

By assuming a flat Earth, three-dimensional gliding dynamics of an unpowered RLV during the TAEM phase can be described as:

$$\frac{dV}{dt} = -\frac{D}{m} - g\sin\gamma, \tag{1}$$

$$\frac{d\gamma}{dt} = \frac{L\cos\mu}{mV} - \frac{g}{V}\cos\gamma, \tag{2}$$

$$\frac{d\psi}{dt} = \frac{L\sin\mu}{mV\cos\gamma}, \tag{3}$$

$$\frac{dx}{dt} = V\cos\gamma\cos\psi, \tag{4}$$

$$\frac{dy}{dt} = V\cos\gamma\sin\psi, \tag{5}$$

$$\frac{dh}{dt} = V\sin\gamma, \tag{6}$$

where V is the velocity, γ is the flight-path angle, ψ is the heading angle, x is the down-track position along runway centerline, y is the cross-track position from runway centerline, h is the altitude, μ is the bank angle, m is the mass, and g is the constant gravitational acceleration. The lift force L and drag force D are calculated as:

$$L = \overline{q}S_{ref}C_L, \tag{7}$$

$$D = \overline{q}S_{ref}C_D, \tag{8}$$

with the dynamic pressure $\overline{q}$ defined by:

$$\overline{q} = 0.5\rho V^2, \tag{9}$$

where S_{ref} is the reference area, and ρ is the atmospheric density. The lift coefficient C_L and the drag coefficient C_D are depended on angle of attack α, Mach number M, and speedbrake deflection δ_{sb}. Note that a speedbrake is modeled as an aerodynamic drag increment, which is initiated during subsonic flight in this work. Moreover, control surface positions (i.e., aileron, body-flap, elevator, and rudder) have impacts on C_L and C_D, as a matter of fact. They are ignored nevertheless for the sake of simplicity, since the neglected terms affect primarily rotational motion rather than point-mass motion.

2.2. KEP equations

It is a traditional way for trajectory planning to integrate the motion Eq. (1)–(6) in the time domain. However, motivated by Ref. [18], the KEP motion equations are derived in this section and used to generate reference trajectory hereafter. The KEP equations are essentially rearrangements of the motion equations into a form involving dynamic pressure and altitude. To this end, by taking the derivative of Eq. (9) with respect to time, and recalling Eq. (6), one can get:

$$\frac{d\overline{q}}{dt} = \rho V\dot{V} + 0.5\dot{\rho}V^2 = \frac{\rho}{\sin\gamma}\frac{dh}{dt}\frac{dV}{dt} + \frac{d\rho}{dt}\frac{\overline{q}}{\rho}. \tag{10}$$

Then, in order to replace time with altitude as the independent variable, dividing Eq. (10) by Eq. (6) yields an expression for change rate of dynamic pressure with respect to altitude:

$$\frac{d\overline{q}}{dh} = \frac{\rho}{\sin\gamma}\frac{dV}{dt} + \frac{d\rho}{dh}\frac{\overline{q}}{\rho}. \tag{11}$$