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Trajectory Planning for Terminal Area Energy Management Phase of Reusable Launch Vehicles

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Abstract: A three-dimensional trajectory planning algorithm is proposed for the terminal area energy management (TAEM) phase of an unpowered reusable launch vehicle (RLV). Firstly, a reference dynamic pressure profile which characterizes the longitudinal motion is conceived on the basis of the maximum dive and maximum glide capabilities. Secondly, a reference ground-track path is developed, which is composed of four flight segments determined by the location, the size, and the turning mode of a heading alignment cone. Then, the RLV motion equations modeled by kernel extraction protocol (KEP) are numerically solved via secant iteration method, according to the knowledge of the pre-designed dynamical pressure profile and the ground-track path. Finally, a down-track correction scheme is designed to correct the down-track position along the runway centerline. Numerical simulations are conducted to illustrate the effectiveness of the proposed trajectory planning algorithm.

Keywords: Reusable launch vehicle (RLV), Terminal area energy management (TAEM), Trajectory planning, Kernel extraction protocol (KEP), Ground-track path

1. INTRODUCTION

The second-generation reusable launch vehicles (RLVs) have been designed to reduce the costs of space transportation and improve the safety. Advanced guidance and control technologies are recognized as effective means to achieve these objectives particularly during the re-entry phases (Schierman *et al.*, 2004). The atmospheric re-entry of a RLV usually starts with an initial re-entry (IRE) phase, followed by a terminal area energy management (TAEM) phase and an approach and landing (A&L) phase. As far as TAEM is concerned, it is characterized by the heading alignment, during which RLV performs a turn to align with the runway. This feature of lateral manoeuver makes the TAEM phase significantly different from the other two stages in three-dimensional space. The overall goal of the TAEM is to guide the unpowered RLV from the TAEM entry point (TEP) with a given energy state and initial position to an expected approach and landing interface (ALI) without violating the vehicle design constraints (e.g., the dynamic pressure and the load factor).

Due to the limited computer processing and storage capability, the earliest TAEM scheme adopted by US Space Shuttle uses the offline strategy with lateral and longitudinal channels decoupled (Moore, 1991), resulting in two limitations: 1) the accuracy of terminal guidance is reduced as a result of the decoupling between lateral and longitudinal channels, and 2) the capability of accommodating large dispersion is very limited because that only several pre-stored trajectories are tracked during real flight.

To address the aforementioned issues, extensive efforts have been devoted to improve the precision and adaptation of the TAEM flight. Two representative methods are the onboard two-dimensional and the offline three-dimensional trajectory planning. The first one is developed in (Horneman *et al.*, 2004; Kluever, 2007). The ground-track path is firstly designed, followed by an altitude profile conceived as a function of ground-track range. Then feasible trajectories are constructed by propagating the energy height from the TEP to the ALI. Finally the best one is selected according to the cost function. The adaptation to initial energy variations is improved by the above procedure. However, in this method the altitude profile is defined as a quadratic polynomial of ground-track range. The design basis is not clearly presented. Further investigation might be necessary. The offline three-dimensional trajectory planning algorithm is proposed in (Grubler, 2001; Barton *et al.*, 2002). The precision is considerably improved since the coupling feature between longitudinal and lateral channels has been considered. However, there exists a potential problem. The maximum turning capability of the vehicle is always utilized, therefore the vehicle has limited ability to adjust the trajectory to handle off-nominal conditions.

There are several other studies on the TAEM flight, for example, a trajectory shaping methodology is developed in (Hull *et al.*, 2005), where the trajectory planning problem is

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formulated as an optimization problem with a set of states and critical parameters to be solved. The adaptation to off-nominal vehicle aerodynamic characteristics can be achieved by continuously solving the optimization problem online. A non-linear programming (NLP) optimizer is exploited for trajectory planning, within the limits of mission profile and off-nominal conditions (Chartres *et al*., 2005). In (Grantham, 2003), an adaptive-critic based neural networks methodology is studied, where the cost function is formulated, maintaining a gradual glideslope and meeting specific terminal constraints. A novel trajectory optimization algorithm is presented based on interval analysis (Filipe *et al*., 2009). Moreover, the NLP based trajectory planning strategies using the theory of differential flatness are investigated in (Morio *et al*., 2008; Morio *et al*., 2010; Poustini *et al*., 2015). The trajectory shapes are relaxed and the guidance precision is improved in these three-dimensional trajectory planning algorithms. However, little attention has been paid to the particular feature of the gliding motion and the flight capability of the unpowered RLV.

As compared to the existing literature, the contributions of this paper lie in three aspects. 1) A dynamic pressure profile with an explicit physical interpretation is conceived using the kernel extraction protocol (KEP) equations. 2) A ground-track path is defined by several tuned parameters, so as to improve the adaptation of initial energy variation. 3) A new TAEM trajectory planning algorithm is proposed with integration of a down-track correction scheme, where the coupling character between lateral and longitudinal motion is accounted for.

The rest of the paper is as follows. Section 2 presents the unpowered RLV model, followed by the construction of a longitudinal profile. Section 3 proposes the ground-track path for the computation of lateral guidance commands. A new trajectory planning algorithm with integration of a down-track correction scheme is investigated in Section 4. The simulation results and assessment are illustrated in Section 5. Concluding remarks are drawn in Section 6.

2. DYNAMIC PRESSURE PROFILE

Motivated by the KEP (Barton *et al*., 2001), the unpowered RLV's gliding motion in three-dimensional space can be described as:

$$\frac{\mathrm{d}q}{\mathrm{d}h}=\left(\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}h}-\frac{\rho S_{ref}C_D}{m\sin\gamma}\right)q-\rho g\,, \tag{1}$$

$$\frac{\mathrm{d}\gamma}{\mathrm{d}h}=\frac{\rho}{2\sin\gamma}\left(\frac{S_{ref}C_L\cos\mu}{m}-\frac{g\cos\gamma}{q}\right), \tag{2}$$

$$\frac{\mathrm{d}\chi}{\mathrm{d}h}=\frac{\rho S_{ref}C_L\sin\mu}{m\sin 2\gamma}\,, \tag{3}$$

$$\frac{\mathrm{d}x}{\mathrm{d}h}=\frac{\cos\chi}{\tan\gamma}\,, \tag{4}$$

$$\frac{\mathrm{d}y}{\mathrm{d}h}=\frac{\sin\chi}{\tan\gamma}\,, \tag{5}$$

$$\frac{\mathrm{d}S}{\mathrm{d}h}=\frac{1}{\tan\gamma}\,, \tag{6}$$

with the C_L and C_D defined by:

$$C_L=\mathrm{f}_{\mathrm{Cl}}\left(\alpha,M\right), C_D=\mathrm{f}_{\mathrm{Cd}}\left(\alpha,M\right), \tag{7}$$

where h is the independent variable. q, γ, χ, x, y, and S are the state variables. μ and α are system inputs. Physical meanings of other variables are listed in Table 1.

Table 1. Physical meaning of system variables

S.V.	P. M.	S.V.	P. M.	S.V.	P. M.
h	Altitude	μ	Bank angle	m	Mass
γ	flight-path angle	α	Angle of attack	g	Gravitational acceleration
q	Dynamic pressure	C_L	Lift coefficient	S_{ref}	Reference area
χ	Heading angle	C_D	Drag coefficient	ρ	Atmospheric density
S	Ground range	M	Mach number	/	/
x	Down-track position along runway centerline				
y	Cross-track position from runway centerline				

S.V.: System Variable; P. M.: Physical Meaning.

Different from the traditional equations of motion, altitude and dynamic pressure in (1)-(6) are considered as independent variable and state variable, respectively. In fact, the KEP equations extract the main characters of RLV's gliding motion in three ways: 1) replacing velocity with dynamic pressure as a guidance state considering that the dynamic pressure can be imposed directly into many constraints during the TAEM flight; 2) as a much more slowly varying parameter, the dynamic pressure can provide a more robust iteration on the nonlinear equations of motion; and 3) employing altitude as an independent variable due to that one is usually interested in a successful gliding at a predetermined and fixed altitude rather than a fixed time in practical TAEM flight.

A dynamic pressure profile describing longitudinal features of a RLV should be defined before trajectory planning algorithm, within the following constraints:

1) The initial and final boundary constraints on dynamic pressure are $q_0\left(h_0\right)=q_{\mathrm{TEP}}$ and $q_f\left(h_f\right)=q_{\mathrm{ALI}}$, respectively.

2) The dynamic pressure varies as smoothly as possible throughout the TAEM glide phase. Moreover, The dynamic pressure keeps a small change rate in order for the approximate "Quasi-Equilibrium Glide (QEG)" (Kluever *et al*., 2015) during TAEM, and attains zero change rate at the end of TAEM, i.e., $\left(\mathrm{d}q/\mathrm{d}h\right)_{\mathrm{ALI}}=0$, to ensure a QEG at the A&L phase.

3) In addition, the dynamic pressure is bounded by the maximum value $q_{\max}$ and minimum value $q_{\min}$. Particularly, to avoid suffering from structure damage, the RLV should fly without violating the specific maximum value (i.e., $q_{\max}$),