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Hybrid Re-entry Guidance for Reusable Launch Vehicle

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Abstract

A hybrid re-entry guidance approach, based on the nominal trajectory guidance method and predictor-corrector guidance, is proposed for the reusable launch vehicle (RLV). This approach generates a feasible re-entry trajectory which consists of pre-entry phase, optimized bank angle phase and predictor-corrector phase. With the help of quasi-equilibrium glide condition (QEGC), the angle's constraints are transformed from re-entry constraints in optimized bank angle phase, and then guidance command is optimized using sequential quadratic program (SQP). In predictor-corrector phase, downrange errors are repeatedly calculated to update constant bank angle profiles. A bank reversal strategy based upon an azimuth error deadband is designed to control crossrange. Simulations with nominal and dispersion conditions demonstrate good performance of the guidance method.

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Keywords: hybrid re-entry guidance; RLV; QEGC; SQP

1. Introduction

It is well known that the atmospheric re-entry is the most critical part of the overall return mission of a RLV and entry guidance approach plays an important role in steering the vehicle safely from initial penetration of the Earth's atmosphere (altitude of 120km) until activation of the terminal area guidance at Mach 2-3. In general, the re-entry guidance can be divided into two categories: the nominal trajectory guidance method and predictor-corrector guidance. The guidance using a nominal trajectory is successfully implemented for the Shuttle entry guidance. This method is easy to actualize and has less requirements of computer capability. However, intense analysis is required whenever any change occurs in the vehicle or the mission and that will prolong the design cycle. Predictor-corrector

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guidance has high-precision landing site, and it is insensitive to the initial error and has robustness for disturbances. However, it has higher requirements of computer performance.

Wang Qing et al. [2] have presented a predictor-corrector entry guidance algorithm for hypersonic vehicle based on energy. Li and Xie [3] have developed a guidance scheme combined numerical predictor-corrector method and QEGC, to meet path constraints and terminal conditions with the specified accuracy. To be robust to stochastic parameter variations, the error compensation strategy, developed by Wang et al. [4], adopts predictor-corrector guidance algorithm at some mission characteristic points. Ashok Joshi and K. Sivan [5] have presented the numerical predictor-corrector approach and an algorithm based on real-time trajectory planning. In another guidance scheme for the Orion Crew Exploration Vehicle (CEV) [6], a numerical predictor-corrector methodology for adaptive and accurate entry guidance is adopted to meet the required terminal conditions at Terminal Area Energy Management (TAEM) interface. Chen [7] has developed a nominal trajectory method based on a new drag acceleration profile, and provided detail guidance program process.

In this paper, we propose a hybrid re-entry guidance approach based on the nominal trajectory guidance method and the predictor-corrector guidance. This could bring a remarkable advantage to the design of a reference profile: not only calculating time and difficulty of the predictor are reduced, but the terminal precision can also be enhanced. The 3DOF re-entry kinematic and dynamic equations are conducted and the constraints for re-entry trajectory are included in Sec.2. The hybrid guidance which is divided into two parts is described in Sec. 3. Section 4 contains simulations with nominal and dispersion conditions. Section 5 concludes the study.

2. Entry Guidance Problem Formulation

2.1 Dynamics

The dimensionless 3DOF equations [8] of motion of a RLV over a spherical, rotating Earth are given by

$$\dot{r} = V\sin\gamma \tag{1}$$

$$\dot{\theta} = V\cos\gamma\sin\psi / r\cos\phi \tag{2}$$

$$\dot{\phi} = V\cos\gamma\cos\psi / r \tag{3}$$

$$\dot{V} = -D - \sin\gamma / r^2 + \Omega^2 r\cos\phi(\sin\gamma\cos\phi - \cos\gamma\sin\phi\cos\psi) \tag{4}$$

$$\dot{\gamma} = \frac{1}{V}[L\cos\sigma + \left(V^2 - \frac{1}{r}\right)\frac{\cos\gamma}{r} + 2\Omega V\sin\psi\cos\phi + \Omega^2 r\cos\phi(\cos\gamma\cos\phi + \sin\gamma\sin\phi\cos\psi)] \tag{5}$$

$$\dot{\psi} = \frac{1}{V}[\frac{L\sin\sigma}{\cos\gamma} + \frac{V^2\cos\gamma\sin\psi\tan\phi}{r} - 2\Omega V(\tan\gamma\cos\psi\cos\phi - \sin\phi) + \frac{\Omega^2 r\cos\phi\sin\psi\sin\phi}{\cos\gamma}] \tag{6}$$

where r is the radial distance from the Earth's centre to the vehicle, normalized by the radius of the Earth. The longitude and latitude are θ and ϕ, respectively. The Earth-relative velocity V is normalized by $\sqrt{g_0 R_0}$ with $g_0 = 9.81 m/s^2, R_0 = 6{,}378{,}135 m$. The flight path angle is γ and the relative-velocity azimuth angle ψ is measured from the north in a clockwise direction. σ is the bank angle and Ω is self-rotation rate of the Earth, normalized by $\sqrt{g_0 / R_0}$. The terms D and L are the aerodynamic drag and lift accelerations in g; that is,

$$L = \frac{\rho V^2 C_L S_{ref}}{2mg_0}, \quad D = \frac{\rho V^2 C_D S_{ref}}{2mg_0} \tag{7}$$

where S_{ref} is the reference area of the vehicle, and ρ atmospheric density, and m the mass of the vehicle. Note that C_L and C_D are functions of α, the angle of attack. The differentiation is with respect to the time t, normalized by $\sqrt{R_0 / g_0}$.

2.2 Entry guidance path constraints

The entry trajectory is constrained by path constraints for thermal protection, load, and vehicle integrity considerations. Examples of the path constraints are heat rate, dynamic pressure, and normal aerodynamic-load factor as expressed in the following:

$$\dot{Q} = k_Q \sqrt{\rho} V^{3.15} \le \dot{Q}_{\max} \tag{8}$$

$$q = \frac{1}{2} \rho V^2 \le q_{\max} \tag{9}$$

$$n = \sqrt{\left(L^2 + D^2\right)} \le n_{\max} \tag{10}$$

k_Q is a constant, and the values of $\dot{Q}_{\max}$, $q_{\max}$, $n_{\max}$ are all specified.

3. Hybrid re-entry guidance approach

The hybrid re-entry guidance approach presented in this paper divides a trajectory into three phases: pre-entry phase, optimized bank angle phase and predictor-corrector phase. In pre-entry phase, the vehicle usually enters the next phase uncontrollably because of low dynamic pressure. We choose the terminal position of this phase by

$$\left| \frac{dr}{dV} - \left(\frac{dr}{dV} \right)_Q \right| < \varepsilon \tag{11}$$

where ε is a tiny constant. We could get $\dfrac{dr}{dV}$ from Equation (1), (4), and calculate the partial derivative of Equation (8) to V :

$$\left(\frac{dr}{dV} \right)_Q = \frac{6.3Rh}{R_0 V} \tag{12}$$

Then we could get the transition point 1 given in Fig.1 Keeping optimized bank angle phase until the height down to 40km can let the vehicle keep off blackout range. So the transition point 2 is given. Fig 2 presents the different constant bank angles in pre-entry phase, then we choose $\sigma = 20^\circ$ to design pre-entry trajectory.

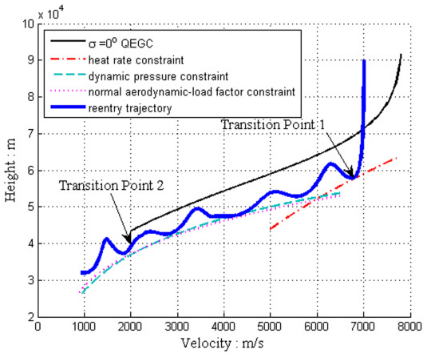

Fig 1 Entry trajectory partitioning strategies

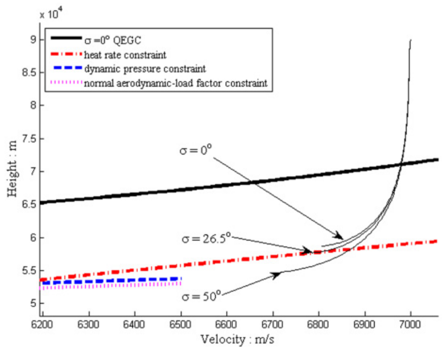

Fig 2 Pre-entry trajectories in different bank angles

3.1 The optimized bank angle phase

It is necessary for the trajectory planning, which meets all the terminal constraints simultaneously, to be carried out with some control parameters. We optimize bank angle command transformed entry constraints—dynamic pressure, normal aerodynamic-load and heat rate constraints to bank angle's constraints by using QEGC. The bank angle guidance command is optimized using SQP algorithm and the performance index function is chosen based on range and heat in the optimized bank angle phase, are given in Fig 3, 4.

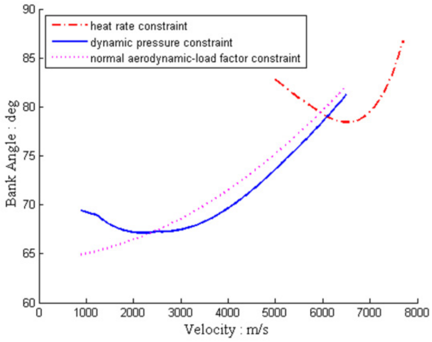

Fig 3 Bank angle constraints corridors

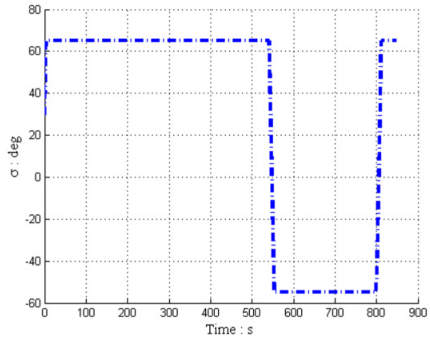

Fig 4 Optimized bank angle curve

3.2 Predictor-corrector phase

To enhance the accuracy of the solution onboard, the guidance system has to predict the error of range-to-go to update bank angle steering profile. The longitudinal and lateral guidance are designed for predictor-corrector guidance. Range errors are repeatedly calculated to update amplitudes of the bank angles. The formulae are given in Eq. (13), (14)

$$\begin{aligned} \sigma_{i+1} &= \sigma_i - \frac{\sigma_i - \sigma_{i-1}}{f_i - f_{i-1}} f_i \\ f_i &= S_i - S_c \end{aligned} \tag{13}$$

$$S = R_0 \arccos(\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(\theta_2 - \theta_1)) \tag{14}$$

where S_c is the distance of range-to-go, and S the distance from (θ_1, ϕ_1) to (θ_2, ϕ_2), f_i the ranging. For the lateral guidance, a bank reversal strategy based on azimuth angle error is designed to improve precision, and the result is given in Fig 5.

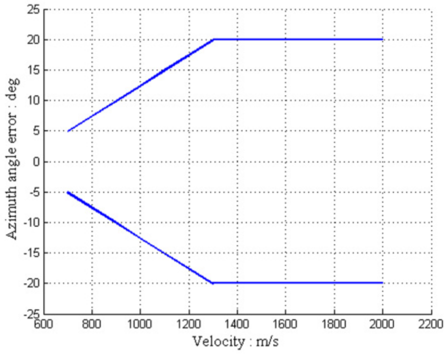

Fig 5 Azimuth error deadband

4. Simulation results and analysis

The input data used during re-entry guidance is

$$m = 500kg\ ,\ S_{ref} = 0.8m^2\ ,\ \dot{Q}_{\max} = 8000kW / m^2\ ,\ n_{\max} = 2.5g\ ,\ q_{\max} = 14kPa$$

The re-entry conditions and the terminal parameters in nominal condition are given in Table 1.

Table 1 The parameters of entry guidance simulation and in nominal condition

Parameter	Value	Parameter	Value
Initial height(km)	90	Initial velocity(m/s)	7000
Initial longitude(deg)	-133.5	Initial flight path angle(deg)	0
Initial latitude(deg)	33.4	Initial azimuth angle(deg)	-140
Terminal longitude(deg)	-174.5	Terminal latitude(deg)	8.2
Terminal velocity(m/s)	922	Peak value of heat rate(kw/m^2)	7779.6
Longitude in nominal condition(deg)	-174.4943	Peak value of dynamic pressure(kPa)	13.89
Latitude in nominal condition (deg)	8.1751	Peak value of load(g)	2.2506

An entry sub-satellite track for RLV is shown in Fig 6. Fig 7 illustrates azimuth angle curve and azimuth angle error variations.

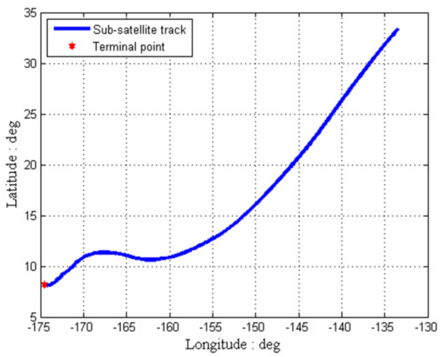

Fig 6 Entry sub-satellite track

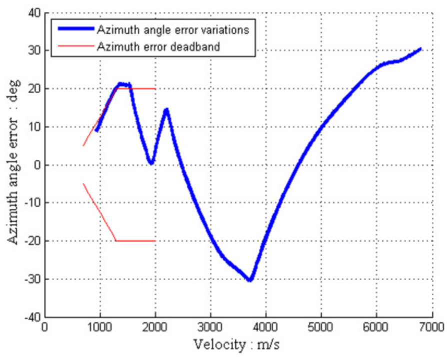

Fig 7 Azimuth angle curve

Because of the stochastic variations of atmospheric parameters and aerodynamic parameters during re-entry flight, RLV could not arrive the terminal point as planning. To verify the feasibility and stability, the hybrid re-entry guidance approach is implemented in dispersion conditions; that is atmospheric density deviation $\pm 20\%$, mass deviation $\pm 3\%$, aerodynamic coefficient deviation $\pm 10\%$. Fig 8 and Fig 9 depict the results. It is seen that the hybrid re-entry guidance approach is also effective and feasible in dispersion conditions from Table 2.

Table 2 Simulation results in different parameter deviations

Deviations	Deviation value	Longitude(deg)	Latitude(deg)	Peak value of heat rate(kw/m2)	Peak value of dynamic pressure(kPa)	Peak value of load(g)
Atmospheric density deviation	±20%	-174.3868	8.1366	7679.7	13.785	2.2380
Mass deviation	±3%	-174.3811	8.1538	7680.8	13.590	2.2478
Aerodynamic coefficient deviation	±10%	-174.2264	8.0793	7321.4	12.532	2.2380
Stochastic deviations	——	-174.5301	8.3429	7666.4	13.549	2.2890

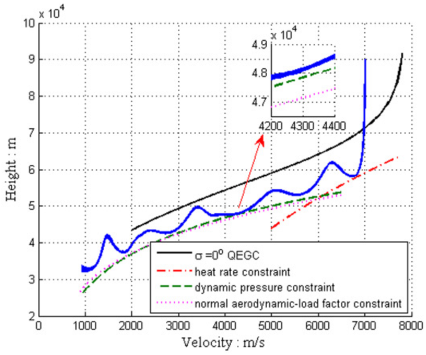

Fig 8 Entry trajectory in deviation conditions

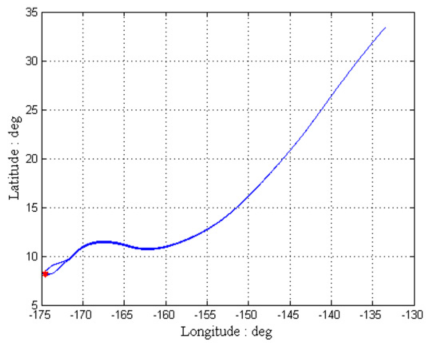

Fig 9 Entry sub-satellite track in deviation conditions

5. Conclusions

In this paper, a hybrid re-entry guidance approach has been developed for reusable launch vehicle. This study has the following traits: 1) The guidance precision has been improved and calculating time has been reduced; 2) The heating of RLV has been reduced by optimizing the bank angle; furthermore, this approach could also meet the path constraints and guidance requirements in deviation conditions.

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