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Entry guidance with smooth drag planning and non-linear tracking

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ABSTRACT

A guidance strategy is developed for the entry phase, meeting range requirements while honouring the constraints on heat flux, dynamic pressure and structural load on the vehicle. Space shuttle guidance is taken as the baseline and an improved strategy to plan and track a reference drag acceleration profile is developed. Trajectory planning is done in drag-energy plane. Drag acceleration and its derivatives are stored as function of specific energy. An analytical, continuous drag modulation strategy is developed for generating the reference trajectory on-board honouring the constraints. The modulated reference trajectory is tracked by a non-linear controller using Incremental Non-linear Dynamic Inversion technique (INDI). The guidance scheme is demonstrated in a short-range re-entry technology demonstrator vehicle. Simulation studies are carried out to establish the robustness of the guidance algorithm for a wide range of performance dispersions.

1. Introduction

Reusable Launch Vehicles(RLVs) are the next generation launch systems which provide cost effective space transportation. Descent phase of a typical RLV mission is subdivided into high Mach entry (from atmospheric entry to Mach 2.0), Terminal Area Energy Management (TAEM) and landing. The vehicle entering at high energy levels shall be delivered at the TAEM interface with sufficient energy for approach and landing. Thus the entry corridor is characterized by high levels of energy dissipation leading to active constraints on heat flux, dynamic pressure and structural loads. Entry guidance system steers the vehicle to the TAEM transit point meeting the range requirements and satisfying the constraints. Challenges in entry guidance algorithm development are as follows. Aerodynamic forces and constraints are non-linear functions of vehicle states resulting in a non-linear mathematical model. Optimal control approaches used for guidance law design results in non-linear two point boundary value problem. Hence analytical solution of the optimal control problem in entry phase is difficult.

Guidance algorithms employing a trajectory planner to generate a feasible trajectory and a tracker to follow the planned trajectory are used widely in literature. Trajectory planners can be classified into three categories.

In the first category, a reference trajectory is stored on-board and modulated during flight to meet the mission requirements. The bench mark for entry guidance is the space shuttle algorithm (Harpold and Graves, 1979). Trajectory planner of shuttle has five segments of nominal drag acceleration profiles stored as a function of relative velocity. The reference profiles are modulated segment-wise to meet the range requirements. In the adaptive entry scheme (Roenneke, 2003), the reference profile is represented by the rate-of-change of range polynomial as a function of energy. An alternate approach is to store drag acceleration as a function of specific energy which is modulated on-board to meet range requirements (Dukeman, 1998; Grim, 2003; Roenneke, 1994).

The second category use predictor-corrector approaches. In Evolved Acceleration Guidance Logic for Entry (EAGLE) (Mease and Teufel, 2002), a reduced order model is used for three dimensional trajectory planning. Based on terminal downrange and cross-range errors, the reference drag as well as lateral acceleration profiles are generated using a successive approximation technique. In the strategy by Youssef et.al, the states at end of entry phase are predicted using a six element state model. A corrector uses the errors in states to modify the control variable (Youssef & Lee, 2001).

Planners using optimal control approaches are grouped under the third category. An optimal entry problem is solved on-board by parametrization of state and control trajectories by B-splines (Singh, 2008). A state feedback guidance law is generated on-board using indirect Legendre pseudo-spectral feedback method by Tian (2011). The planner generates drag acceleration profile as a piecewise linear function of energy in Lu (1991). Equilibrium glide can used to generate three dimensional constrained trajectories (Shen, 2003). Linear perturbation based trajectory is generated during the coast phase prior to atmospheric entry by Lawrence (1965). It is observed that, though

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optimal trajectory planners does not require pre-launch data storage, they involve complex on-board computations.

Trajectory tracking controllers are subdivided into two: linear and non-linear trackers. Linear tracker is simple but calls for gain scheduling. Trajectory tracking by Dukeman (1998) uses a proportional-derivative controller. Energy based gain scheduling is used by Dukeman (2002). Tracking of reference profile in shuttle (Harpold & Graves, 1979) and Grim (2003) is done using a time varying linear feedback control law. Feedback linearisation based tracking schemes are available in Mease and Teufel (2002) and Roenneke (2003). A sliding mode observer is also designed to estimate the drag and drag rate for a feedback linearisation based tracking law (Talole & Mease, 2007). In the control scheme design by Cavallo (1996), the equations of motion are linearised along the nominal trajectory. Feasiblity of LQR design technique for tracking is also established (Carson & MacMynowski, 2006; Lu & Dukeman, 2000).

Shuttle entry guidance is revisited and a tracker using non-linear geometric techniques is designed by Mease (1999). Trajectory tracking can also be done by non-linear PID control (Lu, 1991). In the non-linear tracking scheme using differential flatness (Bharatwaj & Mease, 1997), bank angle and angle of attack are used for tracking ground trace reference. A non-linear predictive controller is used for tracking by Benito (2008). An active rejection control is developed for drag acceleration tracking in Xia and Pu (2014). Model Predictive Static Programming (MPSP) technique is used to guide the vehicle meeting the constraints by Chawla (2010).

The proposed guidance scheme meets the range requirements while satisfying the constraints on heat flux, dynamic pressure and aerodynamic load on the vehicle. The space shuttle entry guidance is taken as the base line. The salient contributions are listed below.

1. Trajectory planning is done in the drag-energy plane meeting the constraints. Reference trajectory is represented by drag acceleration profiles as a function of energy. An analytical drag modulating strategy is developed ensuring continuity of the modulated reference profile.
2. Trajectory tracking is performed using Incremental Non-linear Dynamic Inversion (INDI) which does not call for gain scheduling. The dependency of tracking controller design on trajectory and plant parameter changes is reduced.

The paper is outlined as follows: Mathematical model of the vehicle used for the development is given in Section 2. The trajectory planning, trajectory control and out of plane guidance are provided in Section 3. Section 4 presents the simulation results and analysis.

2. Mathematical model

The equations of motion of a point mass moving over a rotating earth are given in (1) to (9). Let w_e be the earth rotation rate. The state variables are the radial distance (r), relative velocity (V), flight path angle (γ), azimuth (η), latitude (χ) and longitude (λ). Normalized state variables are used to avoid computational complexities (Roenneke, 1994). Earth radius r_e(m) is taken as the unit distance. Velocity of a satellite moving on the surface of the earth is taken as unit velocity. Lift (L) and drag (D) accelerations are normalized by gravitational acceleration (g) on earth's surface.

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

$$\begin{aligned}\dot{V} = \; & -D - g\sin\gamma + \omega_e^2 r\cos\chi \\ & (\sin\gamma\, cos\chi - \cos\gamma\cos\eta\cos\chi)\end{aligned} \tag{2}$$

$$\begin{aligned}V\dot{\gamma} = \; & Du_d - \left[g - \frac{V^2}{r}\right]\cos\gamma \\ & +2\omega_e V\sin\eta\cos\chi + w_e^2 r\cos\chi \\ & (\cos\gamma\cos\chi + \sin\gamma\cos\eta\sin\chi)\end{aligned} \tag{3}$$

$$\dot{\lambda} = \frac{V\cos\gamma\sin\eta}{r\cos\chi} \tag{4}$$

$$\dot{\chi} = \frac{V\cos\gamma\cos\eta}{r} \tag{5}$$

$$\begin{aligned}V\dot{\eta} = \; & \frac{L\sin\sigma}{\cos\gamma} + \frac{V^2}{r}\cos\gamma\sin\eta\tan\chi - \\ & 2\omega_e V(\tan\gamma\cos\eta\cos\chi - \sin\chi) + \\ & w_e^2 r\sin\eta\sin\chi\cos\chi\cos\gamma\end{aligned} \tag{6}$$

where,

$$u_d = \frac{L}{D}\cos\sigma \tag{7}$$

$$D = \frac{1}{2M}\rho V^2 c_D s_{ref} r_e \tag{8}$$

$$L = \frac{1}{2M}\rho V^2 c_L s_{ref} r_e \tag{9}$$

u_d is the desired in-plane component of L/D, M is the mass of the vehicle, ρ is the atmospheric density, s_{ref} is the reference area, c_L is the coefficient of lift, c_D is the coefficient of drag. c_L and c_D are functions of angle of attack (α) which is the angle between body axis and relative velocity vector. Trajectory control can be achieved by varying bank angle (σ) (rotation of the vehicle about the relative velocity vector) and angle of attack(α). The state variables and forces acting on the vehicle are given in Fig. 1.

3. Drag planning and non-linear tracking

Entry guidance scheme has a trajectory planner and a trajectory tracker. The block schematic of entry guidance strategy is given in Fig. 2. During entry phase, the two parameters for trajectory control are angle of attack and bank angle. In the proposed scheme, it is assumed that the vehicle is oriented in trimmed condition (condition in which aerodynamic moments acting about the centre-of gravity should be zero). This is to minimize control effort. The trim angle of attack for

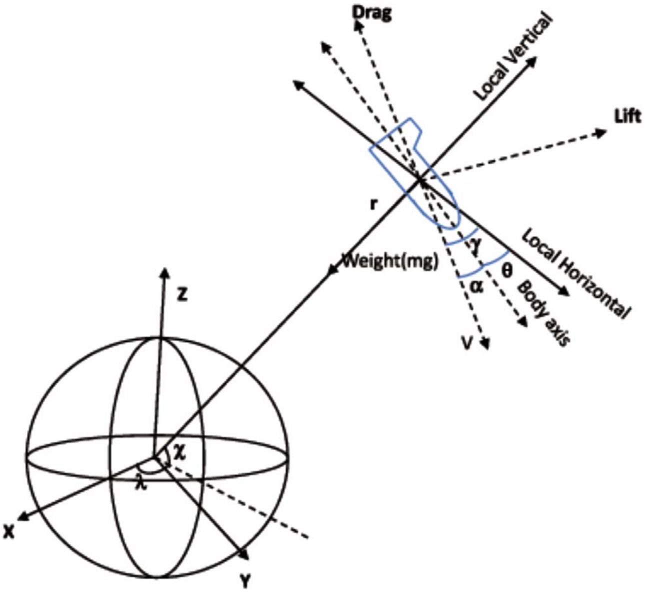

Fig. 1. Forces acting on the vehicle.