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Entry guidance with real-time planning of reference based on analytical solutions

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Abstract

In this paper, first, we develop new analytical solutions to hypersonic gliding problem. In the derivation of these solutions, we propose an innovative method based on spectral decomposition for solving a special type of linear system with variable coefficients, where the system matrix can be expressed as the product of a scale function and a constant matrix. Next, we design an entry guidance based on these analytical solutions. In the guidance, the downrange analytical expression is used to plan the longitudinal reference profile satisfying the downrange requirement in real time. Two bank reversals are needed to eliminate the crossrange error. The first is planned by the crossrange analytical expression such that the second is at a specified point near the end of the flight. After the first bank reversal is performed, the second is slightly corrected using the trajectory simulation. Because the longitudinal reference profile and bank reversals are planned onboard, the entry guidance can handle various urgent tasks and deal well with large dispersions in the initial conditions, aerodynamic model and atmospheric model.

Keywords: Entry guidance; Hypersonic vehicle; Analytical solutions; Linear system with variable coefficients; Trajectory-oscillation suppressing scheme

1. Introduction

A Common Aero Vehicle (CAV) (Phillips, 2003) is a hypersonic gliding vehicle that is boosted to the speed of about Mach 20 by a launch vehicle and reenters the atmosphere without power. The flight of CAV can be roughly divided into two phases: the entry and terminal guidance phases. The entry phase starts shortly after the CAV is separated from the launch vehicle and ends at a specified distance from the target. In the entry phase, the CAV performs lateral maneuvers under the heating rate, dynamic pressure and load factor constraints to manage its energy. In the terminal guidance phase, the CAV attacks the ground target from a near-vertical orientation. In this paper, we study the guidance problem in the entry phase.

There are two categories of entry guidance: reference-tracking guidance and predictor–corrector guidance. Shuttle entry guidance (Harpold and Graves, 1979) is the benchmark for reference-tracking guidance. This guidance plans a longitudinal reference in the drag-vs-speed corridor using an offline calculation. The reference is tracked by modulating the bank angle. To eliminate the crossrange error, the sign of the bank angle changes when the heading error exceeds a pre-defined threshold. Hanson et al. (1998) applied shuttle entry guidance to the X-33 program. Mease et al. (2002) proposed a fast drag-profile planning method that predicts the final states by integrating a reduced-order system and then corrects the reference profile. Later, Dukeman (2002) used the Linear-Quadratic Regulator (LQR) method to simultaneously track the reference profiles of the range to go s_{go}, altitude H and flight-path

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angle γ with respect to the specific energy E. Simulation results demonstrated the good performance of the method. Shen and Lu (2003) presented an onboard planning method that can quickly plan the $V(s_{go}), H(s_{go})$ and $\gamma(s_{go})$ profiles (where V is speed), and also used the LQR method to track these references. In the traditional guidance laws, using a heading error threshold to determine the bank reversals may result in a large crossrange error if there are large aerodynamic dispersions. To overcome the problem, Shen and Lu (2004) proposed a new lateral guidance logic that uses the crossrange error threshold to determine the bank reversals. The other type of entry guidance is the predictor–corrector guidance (Powell, 1993; Graesslin et al., 2004), in which the control profiles are typically parameterized to simplify the complexity of the algorithm and increase its robustness. Later, Zimmerman et al. (2003) proposed a predictor–corrector entry guidance that satisfies the heating rate constraint by breaking the entry trajectory into two parts. Additionally, Yu and Chen proposed a guidance scheme that can effectively suppresses the trajectory oscillations (Yu and Chen, 2011). Lu et al. (2013) simplified the scheme by neglecting the effects of the Earth curvature and then applied it to adaptive predictor–corrector entry guidance. In Li and Peng (2011, 2012), Li et al. proposed an optimization method for planning the reference trajectory, and then designed an adaptive tracking guidance to track it. In Xia (2014), Xia et al. proposed a new tracking law named active disturbance rejection control.

Many analytical solutions to hypersonic gliding problems exist. In Harpold and Graves (1979), Eggers et al. (1957), Gazley (1960), Lees et al. (1959), Ting and Wang (1960), Loh (1963), Vinh (1980), Loh (1963) and Cohen (1965), only the longitudinal motion is considered. In Eggers et al. (1957) and Gazley (1960), the downrange analytical solution is obtained as a function of V by assuming that the Lift to Drag ratio (L/D) is constant and γ is zero. In Lees et al. (1959), Ting and Wang (1960) and Loh (1963), three kinds of analytical relations among V, H and γ are presented. In Vinh (1980), the relationships among the analytical solutions presented in Lees et al. (1959), Ting and Wang (1960) and Loh (1963) are revealed. In Loh (1963), Loh obtained the downrange analytical solutions to three different entry problems: (1) ρV^n is constant where ρ is the air density and n is a positive constant; (2) γ is constant; and (3) γ is a special function of ρ. In Cohen (1965), Cohen obtained the downrange solutions where the lift and drag are special functions of V and ρ. In Nyland (1965), Bell (1965) and Chen (1966), all the authors considered lateral motion and almost simultaneously derived the same analytical solutions for downrange, crossrange and heading angle. In the derivation, the L/D and bank angle are limited to constants, and the influence of the Earth's curvature on the heading angle is neglected. Chen (1966) obtained the analytical solutions to the constant-deceleration gliding problem.

In this paper, we first develop the new analytical solutions for downrange, crossrange, and heading angle where the L/D and bank angle are functions of energy. To improve the accuracy of the analytical solutions for crossrange and heading angle, we consider the effect of the Earth curvature on the heading angle and then obtain a linear system with variable coefficients by linearization. However, this system cannot be solved by traditional methods such as the Laplace transform. This is why the Earth curvature is neglected in the derivation of the traditional analytical solutions (Nyland, 1965; Bell, 1965; Chen, 1966). To solve such a system, we propose an innovative method based on spectral decomposition (Meyer, 2000). Next, we design an entry guidance based on the new solutions. The analytical solutions show that the profile of the vertical Lift to Drag ratio (L_1/D), the ratio of the vertical component of the lift to the drag, has a significant effect on the downrange. Therefore, the entry guidance plans the L_1/D profile using the downrange expression in real time to satisfy the downrange requirement, and tracks this profile by modulating the bank angle. For the sake of lessening the demands on the Flight Control System (FCS), the trajectory is planned with only two bank reversals. Different from the traditional guidance laws, the proposed entry guidance does not need a heading or crossrange error threshold to control the bank reversals. As the new analytical solutions have sufficient accuracy, we propose a new scheme for bank reversals based on these solutions: If there are more bank reversals, the crossrange expression is used to plan all the bank reversals, and after the penultimate reversal is performed, the trajectory simulation is used to correct the last bank reversal slightly and accurately. Such a scheme avoids the repeated simulations of the whole trajectory and thus significantly reduces the computational load. Since the CAV trajectory has a weakly-damped phugoid oscillation, we extend the scheme used for suppressing the oscillation, presented in Yu and Chen (2011), to a 3-Dimensional (3-D) scheme and then apply it to the entry guidance. Because no offline planning is needed for specific mission, the entry guidance can handle various urgent tasks and deal well with large aerodynamic and atmospheric dispersions.

The structure of this paper is as follows. Section 2 shows the equations of motion considering the rotation of the Earth. Section 3 illustrates the entry guidance problem. Section 4 derives the new analytical solutions to the entry problem. Section 5 presents the new entry guidance based on these analytical solutions. Section 6 gives some examples to show the performance of the entry guidance. Section 7 summarizes the major contributions of the paper. Appendix A shows the method of getting the states of motion relative to an auxiliary frame.

2. Equations of motion

Before introducing the equations of motion, we need to define two coordinate systems first, as shown in Fig. 1.

Geocentric Equatorial Rotating (GER) frame: the origin E is at the Earth's center; the z_e axis is along the north polar axis; and the x_e and y_e axes are perpendicular to each