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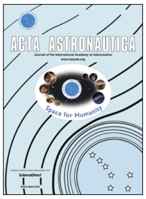

On-line reentry guidance algorithm with both path and no-fly zone constraints

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ABSTRACT

This study proposes an on-line predictor–corrector reentry guidance algorithm that satisfies path and no-fly zone constraints for hypersonic vehicles with a high lift-to-drag ratio. The proposed guidance algorithm can generate a feasible trajectory at each guidance cycle during the entry flight. In the longitudinal profile, numerical predictor–corrector approaches are used to predict the flight capability from current flight states to expected terminal states and to generate an on-line reference drag acceleration profile. The path constraints on heat rate, aerodynamic load, and dynamic pressure are implemented as a part of the predictor–corrector algorithm. A tracking control law is then designed to track the reference drag acceleration profile. In the lateral profile, a novel guidance algorithm is presented. The velocity azimuth angle error threshold and artificial potential field method are used to reduce heading error and to avoid the no-fly zone. Simulated results for nominal and dispersed cases show that the proposed guidance algorithm not only can avoid the no-fly zone but can also steer a typical entry vehicle along a feasible 3D trajectory that satisfies both terminal and path constraints.

1. Introduction

Entry guidance algorithm for a hypersonic vehicle plays an important role in steering the vehicle safely to the specified termination point with prescribed condition while satisfying all necessary path constraints [1]. High lift-to-drag (*L*/*D*) gliding hypersonic vehicles, such as Common Aero Vehicle [2] and Hypersonic Technology Vehicle 2 [3], refer to hypersonic *L*/*D* ratios that are considerably greater than 1. A distinct characteristic of these high L/D gliding hypersonic vehicles is their capability to cover large crossranges [4]. On the basis of this characteristic, a feasible and robust guidance algorithm should be proposed to avoid the no-fly zone.

Entry guidance approaches can generally be classified into two types. One type involves the track of a predetermined reference trajectory, and the other utilizes the prediction error to generate the desired on-line trajectory. When the curvature of the ground track of the trajectory is ignored and flight-path angle is small, drag acceleration has an exact kinematic relationship with the arc length of the flying trajectory and is measurable on-line [5]. Approaches of planning and tracking aerodynamic drag acceleration profiles are developed, and they have been successfully implemented in the Apollo program [6] and the Space Shuttle [1]. Evolved acceleration guidance logic for entry (EAGLE) [7] has been proposed to simplify or automate the design of the reference drag profile for X-33 [8] and Mars entry guidance mission [9]. EAGLE has two integrated components. One is a 3D trajectory planner that generates reference drag and lateral acceleration profiles, and the other is a profile tracking law based on feedback

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linearization that generates the required angle-of-attack and bank angle. Another iterative predictor–corrector method has been proposed to meet the required energy height at the Terminal Area Energy Management interface in the guidance scheme for Hope-X [10]. Various entry guidance methods have also been proposed over the years using the shuttle acceleration-based approach [5,11]. However, for high *L/D* gliding hypersonic vehicles, when using the general guidance approach, large phugoid oscillations occur along the trajectory; this phenomenon can induce high thermal load and dynamic load stresses [12].

A novel class of entry guidance algorithms has evolved and emerged to show significant potential, which can effectively eliminate the phugoid oscillations in the entry trajectories of medium to high *L/D* ratio vehicles. Quasi-equilibrium glide condition (QEGC) is used in reentry guidance algorithms [13,14]. Equilibrium glide is a frequently observed phenomenon in the hypersonic lifting flight of vehicles with moderate and high *L/D* ratios. In consideration of QECG, efficient methods have been developed for the fast design of three-degrees-of-freedom reentry trajectories, which are subjected to all common equality and inequality constraints [4,15]. In particular, a unified entry guidance method was proposed in [12]. For either low-lifting or high-lifting vehicles, the long-standing challenge of enforcing common inequality trajectory constraints (such as heating rate and load factor) with a predictor–corrector algorithm is satisfactorily overcome. However, for high *L/D* gliding hypersonic vehicles, in consideration of the effect of the no-fly zone, algorithms based on QEGC have not been presented to avoid the no-fly zone during the flight [16].

Complex constraints are inevitably involved in trajectory guidance problems, such as the no-fly zones for threat avoidance or geopolitical restrictions. Optimal control algorithms are generally used to solve these entry guidance problems with complex constraints [17,18]. Optimal trajectories are typically obtained off-line, because adopting optimal control algorithms on-line is difficult with limited computational resources. To propose a feasible and effective guidance algorithm to avoid the no-fly zone, artificial potential field (APF) method is adopted in this study. APF [19,20] is universally used in mobile robot local path plans [21], because of its brief mathematical description, simplicity, real-time function and high efficiency [22]. Threat zones can be avoided by the definition of repulsion force, and a target can be reached by the definition of attraction force. The flight direction of a vehicle is determined by the effect of the resultant force.

In this study, an on-line predictor–corrector reentry guidance algorithm that satisfies path and no-fly zone constraints is developed for high *L/D* gliding hypersonic vehicles. Numerical predictor–corrector approaches are adopted to generate a feasible trajectory at each guidance cycle during the entry flight. In the longitudinal profile, the reference drag profile is generated and tracked on-line. Bank angle is taken as the guidance command and generated to null the predicted error. The stopping criteria and convergence discussion of the proposed algorithm are presented. In the lateral profile, a novel approach is presented. The velocity azimuth angle error threshold and APF method are used to reduce heading error and to avoid the no-fly zone.

The rest of this paper is organized as follows. Section 2 presents the entry guidance problem. Section 3 provides the on-line reference drag profile-generating algorithm based on numerical predictor–corrector approach for the longitudinal guidance. Section 4 discusses the velocity azimuth angle error threshold and APF method that are used for the lateral guidance considering no-fly zone. Section 5 indicates the simulation results for nominal and dispersed cases, which show that the proposed guidance algorithm can realize the no-fly zone while steering a typical entry vehicle along a feasible 3D trajectory that satisfies both terminal and path constraints. Finally, Section 6 concludes and provides future research directions.

2. Problem formulation

This section describes the entry dynamic model and multiple constraints for hypersonic entry vehicles.

2.1. Dynamic equations

In consideration of the spherical and rotating Earth , the three dimensional point-mass dynamic equations of an entry vehicle are presented as follows [4]:

$$\frac{\mathrm{d}r}{\mathrm{d}t}=v\sin\gamma \tag{1}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t}=\frac{v\cos\gamma\sin\psi}{r\cos\phi} \tag{2}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t}=\frac{v\cos\gamma\cos\psi}{r} \tag{3}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t}=-D-g\sin\gamma+\omega_e^2 r\cos\phi(\sin\gamma\cos\phi-\cos\gamma\sin\phi\cos\psi) \tag{4}$$

$$\begin{aligned}\frac{\mathrm{d}\gamma}{\mathrm{d}t}=&\frac{L\cos\sigma}{v}-\frac{g}{v}\cos\gamma+\frac{v}{r}\cos\gamma+2\omega_e\cos\phi\sin\psi\\&+\frac{\omega_e^2 r}{v}\cos\phi(\cos\gamma\cos\phi+\sin\gamma\cos\psi\sin\phi)\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{\mathrm{d}\psi}{\mathrm{d}t}=&\frac{L\sin\sigma}{v\cos\gamma}+\frac{v}{r}\cos\gamma\sin\psi\tan\phi-2\omega_e(\tan\gamma\cos\psi\cos\phi\\&-\sin\phi)+\frac{\omega_e^2 r}{v\cos\gamma}\sin\psi\sin\phi\cos\phi\end{aligned} \tag{6}$$

where r is the radial distance from the Earth center to the vehicle; θ and ϕ are the longitude and the latitude, respectively; t is the time and ω_e is the rotational angular velocity of the Earth; v is the Earth-relative velocity; γ is the climb angle, which is the angle between velocity vector and local horizontal level; ψ is the air-path angle, which is the angle between local longitude line and projection of horizontal plane of velocity vector, and its value is positive along the clockwise rotation toward north; L and D represent the lift and drag accelerations, respectively:

$$L=\tfrac{1}{2}\rho(h)v^2 C_L S_{\mathrm{ref}}/m \tag{7}$$