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Analytical entry guidance for no-fly-zone avoidance

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ABSTRACT

This paper is devoted to designing an analytical entry guidance for steering a hypersonic glide vehicle of high Lift-to-Drag ratio (L/D) in the presence of numerous No-Fly Zones (NFZs). The NFZ constraints pose serious challenges to the guidance design: (1) because there is no engine to provide thrust, the vehicle needs to manage the energy of motion carefully and cannot perform avoidance maneuvers arbitrarily; (2) due to disorder distribution of NFZs, there are multitudinous complicated cases to consider. As the basis of the guidance, the adopted 3-D analytical glide formulae are improved by posing a more accurate Earth-rotation compensation model. Then, the guidance uses the new downrange formula to plan longitudinal reference profile according to the energy-management requirement, and mainly employs the new crossrange formula to schedule proper bank reversals under the NFZ and terminal-position constraints. Here, a complex but rigorous scheme is proposed for fast planning bank-reversal sequence based on six analytical iteration algorithms, which are designed to search the nearest trajectory point to NFZ, to adjust the existing bank reversals or add a new one for NFZ avoidance, and to regulate the last bank reversals for eliminating terminal crossrange error, respectively. The scheme begins with two bank reversals and then gradually adds more bank reversals according to the needs of avoiding the NFZs. As the scheme prefers to adjust the existing bank reversals to address the NFZ constraints, it commonly requires only a few bank reversals. The superior performance of the guidance is verified by sufficient trajectory simulations in disturbed environments.

1. Introduction

Common Aero Vehicle (CAV) [1] is a hypersonic vehicle mainly gliding in the near space, the region of atmosphere with altitude of 20–100 km. With the benefit of L/D up to 3 and initial speed close to the first cosmic velocity, the glide range of CAV can be more than ten thousand kilometers while its lateral maneuver range can also be up to thousands of kilometers. Despite the powerful capability, the vehicle suffers from harsh restrictions yet. In addition to being constrained by heating rate, dynamic pressure, and load factor, sometimes the vehicle is challenged by multiple no-fly zones set up due to geopolitical or military factors. However, it is not easy to handle the NFZ constraints because: (1) as the vehicle needs to manage the energy of motion carefully, the lateral maneuvering capability is severely limited; (2) due to random distribution of NFZs, there are numerous complex issues to address. There are three major kinds of NFZs needing to be considered: radar surveillance area, effective interception area of air defense system, and area set up for political considerations. Influenced by the Earth's curvature and flight altitude, the radius of radar surveillance area is generally limited within 800 km. The interception range of some advanced air defense systems can be up to hundreds of kilometers. In case that the vehicle cannot avoid all NFZs, the guidance system will have to selectively ignore some NFZs of low threat levels. In general, the interception area has a higher threat level than radar surveillance area and the threat level of the area due to political factor depends on specific missions.

Conventional entry guidance laws [2–15] for lifting atmospheric entry flight generally consist of four parts: (1) determine an entry corridor satisfying all path constraints; (2) plan a reference trajectory meeting terminal requirements in the corridor; (3) design a tracking law to follow the reference trajectory where the bank angle is used as the major control means; (4) design a threshold to reverse the bank angle in due time so as to eliminate heading error. However, in the application to CAV, a new problem arises: these guidance laws cannot effectively suppress the

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underdamped, phugoid trajectory oscillations, which are induced by high L/D, may result in excessive heating rate, and can severely reduce guidance accuracy, especially in the presence of substantial disturbances. In [16], Yu and Chen proposed the Trajectory-Damping Control Technique (TDCT) for suppressing the oscillations. Hu et al. [17] made a thorough analysis of the TDCT using regular perturbation method and introduced the concept of steady glide. Zhang et al. [18] applied the TDCT in subsonic glide problem. Due to the good performance, the TDCT has been widely used in entry guidance design [19–24], trajectory optimization [25–27], and multidisciplinary optimization of hypersonic vehicle [28]. Lu applied a simplified TDCT to assist a predictor–corrector gliding guidance in guiding CAV [19]. However, the rough control of lateral maneuvers leads to large terminal heading error and frequent bank reversals. In [20], 3-D analytical glide formulae were obtained from a non-rotating, spherical Earth model, and an entry guidance was designed based on these formulae to steer CAV, where the TDCT was also applied to suppress the trajectory oscillations. However, the guidance does not give full consideration to the effect of the Earth's rotation, and thus fails in some cases. In the follow-up studies [21,22], by fully compensating the effect, two improved guidance laws were developed and capable of steering CAV to any place on the Earth. Their essential difference is that the entry flight is observed from the inertial space in [21] whereas the frame of reference is always fixed on the rotating Earth in [22]. Because the Earth-rotation-compensating measures presented in [22] are more suitable for handling the NFZ constraints, they are also adopted in this paper.

Compared with cruise vehicle [29], it is quite difficult for a gliding vehicle to address multiple NFZ constraints because its lateral maneuvering capability is severely constrained by the energy-management requirement. The existing studies [27,30–35] only take into account a few NFZs since more NFZs tends to greatly increase the algorithm complexity. In [27,30], two entry trajectory optimization methods considering waypoint and NFZ constraints were developed. Xie et al. [31] adopted the trajectory planning method based on reduced-order entry dynamics [3] but modified the lateral sub-planner by considering NFZ constraints, where a special heading-angle threshold was designed such that the great circle tangent to heading direction keeps clear of NFZ. Liang et al. [32] designed a trajectory-planning method based on waypoint vectors, which needs a large number of trajectory simulations to iteratively regulate bank reversals such that the vehicle can fly over the waypoints distributed outside the NFZs from specified directions. Zhang et al. [33] employed the artificial potential field method to determine a heading-error threshold considering a single NFZ constraint, where it is assumed that the NFZ generate an abstract repulsive potential field but the target produces an abstract attractive potential field. He et al. [34] posed an iterative algorithm to seek virtual waypoints under NFZ constraints and then command the vehicle to pass these waypoints in order. In [35], the posed method makes full use of the lateral maneuver ability of a hypersonic glider to bypass a big circular NFZ.

This paper focuses on the study of the entry guidance problem with multiple NFZ constraints. To offset the effect of the Earth's rotation, the profiles of the pseudo-aerodynamic forces [22], the combinations of the aerodynamic and inertial forces, are adopted here as reference profiles. In more concrete terms, the profile of the ratio of the vertical component of pseudo-lift to pseudo-drag ($\overline{\mathrm{L}_1/\mathrm{D}}$) is used as the longitudinal reference profile and planned by the analytical downrange formula according to the glide-range and energy-management requirements, and the profile of the ratio of the horizontal component of pseudo-lift to pseudo-drag ($\overline{\mathrm{L}_2/\mathrm{D}}$) is treated as the lateral reference profile and planned mainly by the analytical crossrange formula under the NFZ and terminal-position constraints. Here, to cope with the Earth rotation better, the 3-D analytical glide formulae are improved by designing more accurate models of the $\overline{\mathrm{L}_1/\mathrm{D}}$ and $\overline{\mathrm{L}_2/\mathrm{D}}$ profiles. It should be pointed out that the key to avoiding the NFZs is to perform proper bank reversals, because the magnitude of $\overline{\mathrm{L}_2/\mathrm{D}}$ is determined with $\overline{\mathrm{L}_1/\mathrm{D}}$ specified and thus the turning radius cannot be adjusted arbitrarily. Here, an analytical iteration scheme is proposed for fast planning bank-reversal sequence, which has three major advantages: (1) the planning process is rigorous and thorough as almost all possible cases about distribution of NFZ, disturbances, and threat levels are considered carefully; (2) as the scheme relies entirely on the improved analytical glide formulae to seek the closest trajectory point to NFZ, address the NFZ constraints, and eliminate the terminal crossrange error, it has a very high computational efficiency; (3) since the scheme attempts to adjust the existing bank reversals first to address the NFZ constraints, it requires only a few bank reversals in general, which helps to release the demand on Flight Control System (FCS) and prevent the trajectory from violently oscillating. In order to overcome various time-varying disturbances, the radius of the NFZs are artificially enlarged in the planning process such that the planned trajectory can keep safe distances from the actual NFZs, where the radius increments vary with the distances between the NFZs and the vehicle. Additionally, if the vehicle is unable to bypass some NFZs, the scheme will selectively ignore some NFZs with low threat levels.

The structure of the paper is like this: Sec. 2 describes the entry guidance problem with multiple NFZ constraints, Sec. 3 presents the improved 3-D analytical glide formulae and guidance process, Sec. 4 shows the analytical iteration scheme of planning bank-reversal sequence in detail, Sec. 5 provides sufficient examples to verify the guidance performance, Sec. 6 draws the conclusions, and the references are listed finally.

2. Entry guidance problem

2.1. Path constraints

The entry dynamic model [20,36] adopted here is established over a rotating, spherical Earth, where the location of the vehicle is described by longitude λ, latitude ϕ and altitude H, and the velocity vector is specified by speed V, flight-path angle γ and heading angle ψ.

As the thermal protection system, flight control system, and lightweight structure put harsh requirements on flight environment, the entry trajectory should be subject to the constraints on heating rate $\dot{Q}$, dynamic pressure q and load factor n [20]. Meanwhile, due to limited capacity of FCS, there is a need to restrict the ranges and changes rates of Angle Of Attack (AOA) and bank angle [20].

In addition to the above conventional constraints, multiple NFZ constraints are further taken into account here. Use n_{NFZ} to represent the number of the NFZs, and mark the NFZs as $p_1, p_2, \ldots, p_{n_{NFZ}}$, respectively. The centers of the NFZs are denoted as $C_{p_1}, C_{p_2}, \ldots, C_{p_{n_{NFZ}}}$, and their radii are represented by $r_{p_1}, r_{p_2}, \ldots, r_{p_{n_{NFZ}}}$. The longitude and latitude of C_{pi} are denoted by $\lambda_{C_{pi}}$ and $\phi_{C_{pi}}$, respectively.

2.2. Terminal conditions

The termination condition of the entry phase is $s_{go} = S_{TAEM}$, where s_{go} stands for range to go, and S_{TAEM} is a specified distance and set to 50 km here. The desired terminal conditions are $|\Delta\psi_{TAEM}| \le 5°$, $V_{TAEM} = 2000$ m/s, $H_{TAEM} = 25$ km, and $|\sigma_{TAEM}| \le 30°$, where $\Delta\psi_{TAEM}$, V_{TAEM}, H_{TAEM}, and σ_{TAEM} are the desired terminal heading error, speed, altitude, and bank angle, respectively.