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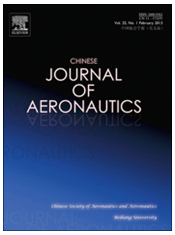

Autonomous gliding entry guidance with geographic constraints

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Abstract This paper presents a novel three-dimensional autonomous entry guidance for relatively high lift-to-drag ratio vehicles satisfying geographic constraints and other path constraints. The guidance is composed of onboard trajectory planning and robust trajectory tracking. For trajectory planning, a longitudinal sub-planner is introduced to generate a feasible drag-versus-energy profile by using the interpolation between upper boundary and lower boundary of entry corridor to get the desired trajectory length. The associated magnitude of the bank angle can be specified by drag profile, while the sign of bank angle is determined by lateral sub-planner. Two-reverse mode is utilized to satisfy waypoint constraints and dynamic heading error corridor is utilized to satisfy no-fly zone constraints. The longitudinal and lateral sub-planners are iteratively employed until all of the path constraints are satisfied. For trajectory tracking, a novel tracking law based on the active disturbance rejection control is introduced. Finally, adaptability tests and Monte Carlo simulations of the entry guidance approach are performed. Results show that the proposed entry guidance approach can adapt to different entry missions and is able to make the vehicle reach the prescribed target point precisely in spite of geographic constraints.

1. Introduction

As a primary focus of entry technology, entry guidance is concerned with steering the vehicle to the designated target with prescribed conditions while satisfying all necessary path constraints in spite of the internal and external disturbances of system. Path constraints are usually designed for the sake of vehicle's safety and operation and the typical ones include heating rate, aerodynamic load and dynamic pressure which would present a great challenge for entry guidance design. Moreover, when it comes to the relatively high lift-to-drag ratio L/D entry vehicles, the large longitudinal phugoid oscillations of the gliding trajectory further increase the difficulty in designing effective flight control systems which are usually based on aerodynamic control effectors. As a result, large longitudinal phugoid oscillations are needed eliminating.[1] Furthermore, the relatively high L/D vehicles possess a capability of lateral maneuvers without power. Additional flight

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mission requirements such as flying over specified waypoints and avoiding prescribed no-fly zones may be introduced to the long-range maneuverable hypersonic entry vehicles. To be more specific, waypoints are predetermined positions for multiple payload deployments or reconnaissance missions, and no-fly zones are exclusion zones that cannot be passed for threat avoidance or due to geopolitical problem.[2] The waypoints and no-fly zones are collectively referred to geographic constraints. Jorris and Cobb[3,4] first optimized the entry trajectory that satisfied geographic constraints for the hypersonic cruise vehicle (HCV) in a two dimensional platform and extended the approach into the three-dimensional models for common aero vehicle (CAV). Zhao and Zhou[5] presented a multi-phase technique based on Gauss pseudo-spectral method to generate an optimal reentry trajectory satisfying geographic constraints. The development of pseudo-spectral method makes it possible to optimize the entry trajectory subject to typical path constraints onboard.[6–8] Furthermore, some novel fast trajectory planning methods are developed from the previous idea.[8,9] Xie et al.[2,10] proposed two trajectory planning methods considering geographic constraints based on the equilibrium glide assumption and drag-versus-energy profile, respectively. However, both of the planning methods have not been extended to entry guidance algorithm.

Generally, the entry guidance algorithm can be grouped into two categories: guidance using predictor–corrector and guidance using reference trajectory.[11] The predictor–corrector guidance predicts the terminal condition employing analytical or numerical propagations and adjusts the design parameters so that the errors of terminal constraints can be corrected. The guidance algorithm enjoys the main advantage of little need for a pre-stored reference trajectory but enlarge the difficulty for predictor–corrector guidance in enforcing various path constraints strictly.[12,13] Joshi et al.[14] proposed a predictor–corrector guidance considering typical path constraints. Moreover, for the aforementioned high L/D entry vehicles, a unique phenomenon is that the entry trajectory is prone to large oscillations. To eliminate those oscillations, Xu et al.[15] combined a predictor–corrector guidance with Quasi-Equilibrium glide condition (QEGC) which made the generated trajectory smooth, but also enabled the guidance to enforce typical path constraints. Lu et al.[1,16] presented an effective feedback compensation in conjunction with the predictor–corrector guidance algorithm to eliminate phugoid oscillations.

For guidance using reference trajectory, guidance algorithm comprises a trajectory planner and a trajectory tracker. Shuttle entry guidance[17,18] uses drag acceleration as a surrogate control variable. The drag acceleration profile can be mostly designed offline according to trajectory optimization algorithm, while minor online adjustments are also utilized to mollify predicted down-range errors. The required downrange is obtained under the assumption that the vehicle flights on a great circle arc to the target point. The drag tracking law specifies the magnitude of a bank angle, while the sign of bank angle is determined by a heading error corridor. With great success in application, shuttle entry guidance has become a baseline approach for many entry vehicles. Mease et al.[19] presented a reduced-order entry trajectory planning method which was also based on drag acceleration profile. Since the strategy combines the longitudinal and lateral motion, the trajectory planning methods realize large crossrange entries. Saraf et al.[20] developed Mease's method and presented the design and performance assessment of evolved acceleration guidance logic for entry (EAGLE). Leavitt and Mease[21] presented trajectory planner by constructing a more easily tracked drag profile using interpolation, meanwhile the planner possessed near-maximum downrange and crossrange capabilities. With the aid of the QEGC, Shen and Lu[22,23] introduced the altitude-versus-velocity profile and divided entry trajectory into initial descent phase, quasi-equilibrium glide phase and pre-TAEM phase. Li et al.[24] proposed a unified analytical expression to describe the three typical path constraints, which greatly simplified the reference trajectory design.

The trajectory tracker follows the reference trajectory profile during flight. Shuttle entry guidance employs a gain-scheduled proportional-integral-derivative (PID) control logic to track the reference trajectory.[17] However, PID is problematic for tedious gain scheduling and tuning issues. As a result, Mease[25] and Lu[26] et al. introduced guidance laws based on feedback linearization and Morio et al.[27] proposed general guidelines for the application of flatness theory to the entry guidance. The trajectory tracker can also be designed by optimal control theory. Dukeman[28] utilized linear quadratic regulator theory to track the reference profile. This method treated the trajectory-tracking problem as a regulation problem in the state space about the reference trajectory. Since the online computational burden associated with solving Riccati differential equation is an impediment for applications of the method, Lu[29] introduced a method that is based on the approximate state and control at discrete time points to avoid the online integration of the Riccati differential equation. Similarly, the indirect Legendre pseudo-spectral method[30,31] and the generating function method[32,33] are also efficient numerical algorithms capable of freeing the equation solving from online integration.

Active disturbance rejection control (ADRC) proposed by Han[34] is an emerging nonlinear control algorithm. ADRC inherits the quality of PID but combines with nonlinear control strategy. Vincent's tests[35] show that ADRC control makes a significant improvement over the PID control under the same conditions. ADRC control method employs an extended state observer (ESO) that can precisely estimate the internal and external disturbances of the system and dynamically compensate the system accordingly. That makes the control method not depend on the accurate mathematical of the unknown object model. Compared to PID, ADRC outstands with more static and dynamic performance, strong robustness and adaptability.

The overall objective of this study is to develop a novel three-dimensional autonomous entry guidance considering the geographic constraints. In this paper, the feasible reference trajectory is designed onboard based on drag-versus-energy plane and the trajectory tracking method is designed based on ADRC. The other parts of this paper are organized as follows. Section 2 describes the entry dynamics and the constraints for the entry guidance problem. Section 3 presents the strategy of the rapid entry trajectory planner. Then a novel tracking law for altitude tracking based on ADRC is presented in Section 4. In Section 5, the performance of the proposed guidance method is assessed by numerical adaptability tests and Monte Carlo simulations. Finally, the conclusions are presented in Section 6.