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A three-dimensional predictor–corrector entry guidance based on reduced-order motion equations

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ABSTRACT

A three-dimensional predictor–corrector entry guidance algorithm is proposed in this paper. More accurate solutions of flight path angle and velocity are obtained with the guidance algorithm to reduce the order of motion equations, which greatly lower the amount of calculation for generating on-board three-dimensional trajectories. By planning two bank angle reversals, the burden on attitude control system is significantly reduced and the reliability of the lateral guidance is well guaranteed. Using the developed solutions and integrating the reduced-order motion equations numerically, the three-dimensional trajectory planning problem is transformed into two one-parameter searching problems: one is for the right guidance parameter and the other one is for the bank angle reversal points. Given the guidance parameter and bank angle reversal points, a feasible three-dimensional trajectory can be generated quickly and the guiding commands for the vehicle heading towards the landing site can be directly obtained. By comparing with the actual guided entry trajectory, the feasibility of the planned three-dimensional entry trajectory is evaluated. Though there are some differences between them, the actual trajectory is well approximated with the present method. Additionally, extensive numerical simulations have been carried out to test the validity and robustness of the proposed entry guidance algorithm. The simulation results demonstrate that the entry guidance works well and has a good flexibility.

1. Introduction

For the costly reusable launch vehicle (RLV), security is the most important requirement, which should be taken into consideration for every subsystem of vehicles in the designing phase. For entry guidance system, flexibility is one of the most important criteria to guarantee the security of entry vehicles in complex and changeable entry conditions. In traditional entry guidance, such as Apollo entry guidance and the shuttle entry guidance, although the entry trajectory is planned off-line, they both have been prepared to deal with various entry conditions. Apollo has several alternative entry trajectories [1] and the shuttle can revise its reference profile on-board [2]. The flexibilities in Apollo entry guidance and the shuttle entry guidance make them a great success in engineering applications.

However, with the development of the new generation of multi-functional RLV, greater demands are being placed on the flexibility of the entry guidance algorithm. In the NASA's Space Launch Initiative (SLI) Program, the flexibility of the entry guidance algorithm is examined, which not only helps vehicles to enhance their adaption to various entry missions, but also improves the robustness of the entry guidance. In abnormal entry conditions, the flexibility even becomes the best quality of the algorithm. Moreover, the flexibility in entry guidance algorithm makes vehicles more autonomic and intelligent, which is the tendency of developing new generation of entry vehicles.

In the field of entry guidance, many researchers have made contributions to extending the flexibility of entry guidance. Their works can be divided into three mainstreams: 1) improving trajectory planning method for on-board implementation; 2) extending longitudinal trajectories to three-dimensional trajectories; 3) planning entry trajectories directly with guidance commands profiles. In the first direction, Roenneke developed an autonomous on-board trajectory planning method, which was able to plan longitudinal entry trajectory on-board within corridor [3]. Lu proposed a rapid planning method for entry trajectories by transforming the trajectory planning problem to a parameter optimization problem [4]. Lin established a two-level optimization algorithm to solve flight trajectory rapid design problem for temporary reconnaissance mission [5]. However, with the advancement of computer

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technology, the difficulty in the on-board generation of entry trajectory has been greatly lowered. Thus, some researchers turn to the second direction. The representative works in this direction are from Mease [6] and Shen [7]. Mease expanded the traditional longitudinal profile to three dimensions by taking the lateral motion into consideration [6]. Zhang improved practicability of this method by transforming the three-dimensional trajectory planning problem into a two-stage trajectory-design problem [8]. Shen designed a dynamic lateral entry guidance logic based on Lu's work on equilibrium glide theory [9,10] and developed an on-board generation method of three-dimensional constrained entry trajectories through numerical methods. Compared to the longitudinal trajectory, the three-dimensional trajectory reveals complete characteristics and is more precise in predicting the remaining range-to-go. However, traditional on-board planned three-dimensional trajectories can not be linked to guidance commands directly. Instead, they have to be tracked through an additional tracking law, which makes the entry guidance algorithm more complex but less reliable.

To improve the flexibility of the planning method and simplify the entry guidance, some researchers try to plan entry trajectories directly with guidance commands profiles. The best way to do this is to develop the complete closed-form solutions of the motion equations. In the 1950s and 1960s, driven by "Apollo Program" and "Shuttle Program", many significant works came out [11–13]. In the next decades, they were further improved by followed researchers [14,15]. However, many of them were criticized for their poor applicability and low accuracy. Their applications were greatly limited by their assumptions in the theory development. It is almost impossible to develop the complete closed-form solutions due to the high nonlinearity of the motion equations. Thus, most of the researchers turn to numerical approaches. Through integrating the motion equations with parameterized guidance commands profile, an entry trajectory can be obtained. By correcting the parameters of the guidance commands profile, the right guidance commands guiding the vehicle to the landing site can be found. This form of entry guidance algorithm is generally called numerical predictor–corrector entry guidance algorithm. In the recent decades, predictor–corrector entry guidance has evolved and emerged to show a great potential [16]. Employing different guidance strategies, Bairstow [17] and Lu [18,19] developed PreGuid and FNPEG entry guidance algorithms respectively for low lift-to-drag ratio entry vehicles. Xue [20], Lu [16] and Wang [21] made their contributions to develop the predictor–corrector entry guidance for vehicles with high lift-to-drag ratio. Though numerical predictor–corrector entry guidance shows good performance and robustness, the cost of the calculation is still the bottle-neck blocking its way to applications. The application of predictor–corrector entry guidance on Chang'e 5 entry flight tester (CE-5/T1) shows the computational cost of pure numerical predictor–corrector entry guidance is still too high for engineering application [22].

In this paper, we propose a three-dimensional predictor–corrector entry guidance. With developed solutions of flight path angle and velocity, the order of motion equations is reduced and the amount of calculation is greatly lowered compared to the numerical predictor–corrector entry guidance. The bank angle is planned with two reversal points to reduce the burden in attitude control system. Given the guidance parameter and the bank angle reversal points, a feasible three-dimensional entry trajectory heading towards the landing site can be generated. The whole trajectory planning problem is transformed into two one-parameter searching problems: 1) the guidance parameter searching; 2) the bank angle reversal points searching. The magnitude of the bank angle is calculated with guidance parameters, while the sign of the bank angle is determined by the reversal points. Using a vehicle model similar to X-34 vehicle, the reliability of the developed solutions (analytical solutions) is tested by comparing with numerical results. The feasibility of the planned three-dimensional entry trajectory is evaluated by comparing with the actual guided entry trajectory. In the end, the Monte-Carlo simulations also demonstrate the validity and robustness of the entry guidance algorithm.

2. Preliminaries

2.1. Motion equations

The three-dimensional motion equations of a glide entry vehicle over a spherical and rotating Earth are

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

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

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \frac{v\cos\theta\cos\psi}{r} \tag{3}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{\rho v^2 S_{ref} C_D}{2m} - g\sin\theta \tag{4}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{\rho C_L S_{ref} v\cos\sigma}{2m} + \left(\frac{v}{r} - \frac{g}{v}\right)\cos\theta + 2\omega\cos\varphi\sin\psi \tag{5}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{\rho C_L S_{ref} v\sin\sigma}{2m\cos\theta} + \frac{v}{r}\cos\theta\sin\psi\tan\varphi - 2\omega(\cos\varphi\tan\theta\cos\psi - \sin\varphi) \tag{6}$$

where λ and φ are the longitude and latitude, respectively, v is the relative velocity, θ is the flight path angle, ψ is the velocity heading angle, r is the radial distance from the earth center to the vehicle, σ is the bank angle, ω is the earth rotation rate, C_L and C_D are the lift and drag coefficient, respectively, S_{ref} is the reference area of the entry vehicle, m is the mass of the vehicle, ρ is the atmosphere density, and g is the gravitational acceleration rate taken to be constant ($g = 9.81\ \mathrm{m/s^2}$). According to the spherical assumption, the relationship between the radial distance r and altitude h is

$$r = R_0 + h$$

where R_0 is the mean radius of the earth. For purposes of developing the analytical solutions, the atmosphere model we adopted should be uncomplicated. In the approximation of atmosphere, the atmospheric density can be considered as an exponential function of altitude [23]. The atmospheric model can be described as

$$\rho(h) = \rho_0 e^{-\beta h} \tag{7}$$

where β is the barometric coefficient considered as a constant and ρ_0 is the standard atmospheric density at the sea level.

2.2. Entry trajectory constraints

In the entry flight, the vehicle is constrained by several typical inequality entry path constraints, which include the maximum heat flux, the maximum load and maximum dynamic pressure. These hard constraints form the boundaries for the entry trajectories. According to their definitions, these typical inequality entry path constraints are expressed in Eqs. (8)–(10).

$$\dot{Q} = K_{\dot{Q}}\sqrt{\rho}v^{3.15} \le \dot{Q}_{\max} \tag{8}$$

$$n_g = \sqrt{D^2 + L^2}/g \le n_{g_{\max}} \tag{9}$$

$$q = \frac{1}{2}\rho v^2 \le q_{\max} \tag{10}$$