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Adaptive optimal gliding guidance independent of QEGC

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ABSTRACT

A novel multiple constrained adaptive gliding guidance method which is independent of quasi-equilibrium gliding condition (QEGC) and standard trajectory is proposed in this paper. The gliding guidance task is decomposed into longitudinal and lateral directions. In longitudinal direction, an altitude control model is established independent of QEGC, a hierarchical adaptive guidance strategy is introduced to control the vehicle to achieve equilibrium flight state and to meet the terminal altitude and flight-path angle constraints. In lateral direction, a heading error control model is constructed and the optimal control is employed to eliminate the heading error in real time with minimum energy consumption. In addition, the terminal velocity magnitude is predicted and corrected analytically based on lift–drag ratio, and the coordination strategy between guidance and velocity control is proposed to realize multi-constraint gliding guidance. This algorithm can generate angle-of-attack and bank angle commands which can meet the given terminal constraints with high precision based on the current flight states analytically, and has strong robustness to the initial deviation and environmental deviation.

1. Introduction

Due to the long-range flight and strong maneuver capability, the hypersonic glide vehicle has become a popular research topic in the aerospace field [1]. Guidance which can control the vehicle to meet a variety of terminal constraints under the multiple path constraints is one of the core technologies. The standard trajectory tracking method is the most typical gliding guidance strategy. The method can be divided into two parts: first, the design of standard trajectory which can satisfy both path and terminal constraints, followed by the guidance command generation using trajectory tracking which can ensure the guidance accuracy and robustness [2]. The method has strong reliability and can reduce the amount of online computation, but it limits the adaptability to different guidance missions.

Be different from the standard trajectory tracking method, both the predictor–corrector (PC) and the quasi-equilibrium gliding guidance methods do not rely on the standard trajectory [3]. The PC method predicts the terminal states during the flight and corrects the guidance commands based on the difference between the predicted of the terminal expected states [4]. The analytical PC methods are organized based on the simplification of motion model which can introduce the guidance error inevitably, and lack of direct treatment of path constraints [5]. Although the numerical method has high guidance accuracy and robustness, its numerical prediction of the terminal states and the iterative calculation of the guidance parameters increase the amount of on-line calculation [6,7]. The hypersonic vehicle has special trajectory characteristic in the gliding flight, and the resulting guidance via QEGC is one of the focuses of the present studies. Lu employed QEGC to construct the guidance model, predicted the terminal altitude, and calculated the current required flight-path angle (FPA) and angle-of-attack (AOA) analytically. Besides, the bank angle was obtained via the heading error elimination [8]. Aiming at the velocity magnitude control problem, the velocity prediction model was established based on the motion equations, the terminal velocity was predicted by solving the definite integral, and the velocity error was fed back to the calculation of the bank angle [9]. Lu introduced a numerical predictor–corrector guidance algorithm applied to a capsule (CEV), a shuttle-class vehicle (X-33) and a high-lifting hypersonic gliding vehicle (CAV-H). The algorithm was organized based on Gauss–Newton and feedback control using QEGC, but the terminal FPA was uncontrolled and the robustness to the process deviation was unconsidered [10]. Furthermore, based on the above numerical predictor–corrector guidance law, Lu proposed an entry guidance law using time-scale separation, but the terminal FPA and altitude were uncontrolled [11]. In addition, Shen divided the reentry process into initial decline and gliding sections, taken QEGC to generate three-dimensional trajectory online, and then tracked the designed trajectory, the guidance does not get rid of the dependence on the standard trajectory and QEGC [12].

Optimal control can be well employed to design guidance law. In the previous work, we designed the analytical optimal glid-

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ing guidance law based on QEGC, but the velocity was not controlled and the initial deviation was not considered [13]. Ref. [14] designed an optimal guidance law with the maximization of impact velocity and terminal flight path angle constraint using Gauss Radau Pseudospectral method. It constructed the optimal guidance model, including dynamics equation, path and terminal constraints, but the complex optimal guidance problem was solved numerically and the trajectory tracker are not designed. In Ref. [15], Lu introduced an aerocapture guidance strategy, which can be used in both ascent and entry phase, based on numerical predictor–corrector and optimal control (bang–bang control). In this method, the AOA was prescribed and bank angle was the only control variable to satisfy terminal altitude, velocity and FPA constraints. However, the guidance was organized only in longitudinal direction and the terminal position can not be satisfied. Ref. [16] treated heading and flight path angles as control variables, designed an required trajectory, and then obtained the guidance law using dynamic inverse method to satisfy terminal FPA and velocity constraints. However, the target position constraints were not considered and the optimality can not be satisfied.

The gliding flight locates in the complex near space, the initial deviation of the glide phase and the uncertainty of the flight environment and the parameters of vehicle's body will lead to dissatisfy of QEGC, so that there are limitations in the above-mentioned guidance methods. Therefore, this paper will study a novel adaptive guidance strategy in analytical form independent of the standard trajectory and QEGC. Firstly, the guidance model is established without QEGC, a hierarchical guidance strategy will be introduced in longitudinal direction to meet the terminal altitude and FPA constraints and achieve QEGC. The lateral optimal guidance will eliminate the heading error in real time and reduce the energy consumption. Secondly, the analytical prediction method of terminal velocity is introduced based on lift–drag ratio is studied, and the coordination strategy between the adaptive guidance and velocity control is proposed to realize multi-constraint gliding guidance.

2. Adaptive guidance modeling

The previous optimal gliding guidance is based on the assumption that the Earth is homogeneous and does not rotate the sphere [13]. Although the guidance error caused by this assumption can be eliminated in most cases, it will affect the robustness and gliding trajectory characteristics of the guidance algorithm inevitably. In order to make the follow-up guidance law design more concise, the following equation is dealt with:

$$\begin{cases} \dot{v} = -\frac{\rho v^2 S_m C_D}{2m} + g'_r \sin\theta + C_v \\ \dot{\theta} = \dfrac{\rho v^2 S_m C_L \cos\upsilon}{2mv} + \dfrac{g'_r \cos\theta}{v} + \dfrac{v\cos\theta}{r} + C_\theta \\ \dot{\sigma} = \dfrac{\rho v^2 S_m C_L \sin\upsilon}{2mv\cos\theta} + \dfrac{v\tan\phi\cos\theta\sin\sigma}{r} + C_\sigma \\ \dot{\phi} = \dfrac{v\cos\theta\cos\sigma}{r} \\ \dot{\lambda} = \dfrac{v\cos\theta\sin\sigma}{r\cos\phi} \\ \dot{r} = v\sin\theta \end{cases} \tag{1}$$

where the position coordinates are the radial distance from the center of the Earth to the vehicle r, the longitude λ, the latitude ϕ; the velocity coordinates are the Earth-relative velocity magnitude v, the FPA θ, and the velocity azimuth angle σ measured from the north in a clockwise direction. ρ is atmospheric density; m is the vehicle mass; S_m is the reference area; C_D and C_L represent the drag and lift coefficients respectively. The forces caused by the self-rotation of the Earth C_v, C_θ, C_σ are given by:

$$\begin{cases} C_v = g_{\omega e}(\cos\sigma\cos\theta\cos\phi + \sin\theta\sin\phi) \\ \qquad + \omega_e^2 r\left(\cos^2\phi\sin\theta - \cos\phi\sin\phi\cos\sigma\cos\theta\right) \\ C_\theta = \dfrac{g_{\omega e}}{v}(\cos\theta\sin\phi - \cos\sigma\sin\theta\cos\phi) + 2\omega_e\sin\sigma\cos\phi \\ \qquad + \dfrac{\omega_e^2 r}{v}\left(\cos\phi\sin\phi\cos\sigma\sin\theta + \cos^2\phi\cos\theta\right) \\ C_\sigma = -\dfrac{g_{\omega e}\sin\sigma\cos\phi}{v\cos\theta} + \dfrac{\omega_e^2 r(\cos\phi\sin\phi\sin\sigma)}{v\cos\theta} \\ \qquad + 2\omega_e(\sin\phi - \cos\sigma\tan\theta\cos\phi) \end{cases} \tag{2}$$

In addition, gliding flight needs a balance kept between the lifting force and the gravity enables the vehicle to glide gently. In the later study, the Quasi-Equilibrium Glide Condition (QEGC) means $\dot{\theta} = 0$, so that the second equation in Eq. (1) can be expressed as [13]:

$$m\left(g - \frac{v^2}{r}\right)\cos\theta - L\cos\upsilon = 0 \tag{3}$$

2.1. Statement of feedback linearization

As shown in Eq. (1), the motion model in the trajectory coordinate system is a complex nonlinear equation, this character will increase the difficulty of the guidance law design undoubtedly. As a result, we will employ feedback linearization method to convert Eq. (1) into a term of linear equations with the equal orders. Based on the linear equation, the guidance law is designed and transformed into the original nonlinear equation to realize the guidance task. First, the basic theorem of feedback linearization is given.

Definition 1. The standard form of nonlinear system is:

$$\begin{cases} \boldsymbol{x} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})\boldsymbol{u} \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}) \end{cases} \tag{4}$$

where $\boldsymbol{x} \in R^n$ is system states, $\boldsymbol{u} \in R^m$ is system inputs, $\boldsymbol{y} \in R^m$ is system outputs. If the Eq. (4) satisfy

(1) $L_{gj}L_f^k h_i(x) = 0, (1 \le i \le m, 1 \le j \le m, 1 \le k \le r_i - 1)$

(2) The $m \times m$ matrix

$$\boldsymbol{P}(x) = \begin{bmatrix} L_{g1}L_f^{r_1-1}h_1(x) & \cdots & L_{gm}L_f^{r_1-1}h_1(x) \\ L_{g1}L_f^{r_2-1}h_2(x) & \cdots & L_{gm}L_f^{r_2-1}h_2(x) \\ \cdots & \cdots & \cdots \\ L_{g1}L_f^{r_m-1}h_m(x) & \cdots & L_{gm}L_f^{r_m-1}h_m(x) \end{bmatrix} \tag{5}$$

is nonsingular at $\boldsymbol{x} = \boldsymbol{x}_0$. The system (4) is then said to have a relative degree $r = \sum_{i=1}^m r_i$ [17].

Theorem 1. *The nonlinear system (4) is linearizable if sufficiently smooth function $\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x})$ exists so that the relative degree of the system is $r = \sum_{i=1}^m r_i = n$. And the transformation of the control input is:*

$$\boldsymbol{u} = \boldsymbol{P}^{-1}(\boldsymbol{x})\left[-\boldsymbol{Q}(\boldsymbol{x}) + \boldsymbol{u_n}\right] \tag{6}$$

in which $\boldsymbol{u_n}$ is the novel control input, the matrix $\boldsymbol{Q}(\boldsymbol{x})$ is:

$$\boldsymbol{Q}(\boldsymbol{x}) = \left[L_f^{r_1-1}h_1(x), L_f^{r_2-1}h_2(x)\cdots L_f^{r_m-1}h_m(x)\right]^T \tag{7}$$

The converted state variables are:

$$\boldsymbol{\xi}_i^k(\boldsymbol{x}) = \boldsymbol{T}_i^k(\boldsymbol{x}) = L_f^{k-1}\boldsymbol{h}_i(\boldsymbol{x}) \tag{8}$$

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