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# A robust predictor–corrector entry guidance

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ABSTRACT

With the development of aerospace industry, the guidance system of an entry vehicle becomes more robust, reliable and autonomous. Based on fuzzy logic, a predictor–corrector guidance law is proposed in this paper, where the trajectory prediction is realized by numerical integration. The correction system consists of two fuzzy controllers, which correct longitudinal motion and lateral motion synergistically. A drag acceleration profile is designed through interpolating between upper drag boundary and lower drag boundary, which is corrected continually to eliminate the range error. Attack angle, a secondary control variable in the paper, is used to eliminate the altitude error. In addition, the lateral error is removed by regulating the reversal time of bank angle. Compared with the traditional guidance laws, the method in this paper not only can correct synergistically the longitudinal motion and lateral motion of the vehicle, but also can easily cope with the flight constraints using interpolated drag acceleration profile. Moreover, in a correction cycle, the method designed in this paper only needs a single trajectory prediction, which reduces the on-board computation. The guidance law demonstrates a high precision and robustness in the simulation scenario.



## 1. Introduction

The research on lifting entry guidance has experienced two stages. The first stage started in the 1970s. The main study was aimed at the entry of shuttle plane and the classical guidance law based on drag acceleration profile was shaped [1]. The second development upsurge arose in the 90s of the last century. With the development of the new generation RLV, NASA started the research for advanced guidance and control systems. During that period, many guidance methods have been proposed. The remarkable achievements are the Evolved Acceleration Guidance Logic for Entry (EAGLE), proposed by Mease [2,3], and the guidance law based on Quasi-Equilibrium Glide Condition (QEGC), advocated by Lu [4]. In recent years, the study of entry guidance has entered a new era. The robustness, reliability and autonomy of entry guidance systems are increasingly gaining attention.

The entry guidance methods can be divided into two categories: trajectory planning–tracking guidance methods and predictor–corrector guidance methods. The first class has been successfully used in shuttle plane, whereas it closely depends on a reference trajectory. The other class includes trajectory prediction and command correction. Because the guidance commands are continually corrected based on the prediction results, these methods exhibit a better performance in robustness and flexibility. However, they can hardly be used in engineering due to large amounts of computation.

The research on predictor–corrector guidance can date back to the 80s of the last century, which was started in the exploration of Mars. Because of the limited capacity of computing, the analytical way of trajectory prediction is developed. Due to some simplifications within the procedure, the prediction precision is low [5,6]. With the development of computer technology, researchers gradually turn to the numerical way of prediction. In 1970s, Powell designed a predictor–corrector guidance law for rescue spacecraft and Mars probe [7]. The Runge–Kutta numerical integration was used to predict trajectory and the dichotomy was used to correct roll angle. Xue [8] and Li [9] transform flight constraints into the limits of bank angle based on QEGC, and use Newton–Raphson iteration to correct the linear bank angle profile. The bank angle reversal is determined by a cross-range function or an azimuth error band. Yong [10] uses some waypoints to divide the flight trajectory into several subsections. In each subsection, the state at the next waypoint, instead of the terminal state, is predicted, which reduces the prediction time. But a reference trajectory is necessary which restricts the feasibility of the method. Xu [11] uses BP network to predict flight trajectory, in which a great amount of flight data is required to train the network. Lu [12] extends the results in Reference [8], and proposes a universal guidance method for vehicles with both high lift-to-drag ratio and low high lift-to-drag ratio. Moreover, a Fully Numerical Entry Guidance Algorithm (FNEGA) is

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proposed by Lu [13], which can be applied to both direct entry and skip entry, regardless of the lift-to-drag ratio of vehicle. However, the lateral guidance still uses a cross-range function in FNEGA.

In this paper, we develop a predictor–corrector guidance method based on fuzzy logic. The entry course is divided into two phases, initial phase and glide phase. The initial phase is guided by a constant bank angle, which is determined by the errors of initial flight state, atmospheric density and aerodynamic coefficients. In the glide phase, flight trajectory is predicted by Runge–Kutta numerical integration. Two fuzzy controllers are designed to guide the 3-dimensional motion of the vehicle. The longitudinal motion is guided by adjusting the drag acceleration and attack angle. The lateral errors are eliminated by adjusting the reversal time of bank angle. Considering the longitudinal motion and lateral motion are corrected synergistically, the predictor–corrector guidance method improves the robustness and flexibility of entry motion. In view of the fact that the drag acceleration profile is obtained by interpolating between the upper and lower boundaries of flight corridor, the flight constraints can be easily dealt with. Moreover, the traditional correction strategy is improved. Only a single trajectory prediction is needed in a guidance cycle, which is favorable for on-board computation.

## 2. Basic model

### 2.1. Dynamic equations

The dynamic equations of entry vehicle are given by

$$\begin{cases} \dfrac{dr}{dt} = V\sin\theta \\ \dfrac{d\lambda}{dt} = \dfrac{V\cos\theta\sin\psi}{r\cos\phi} \\ \dfrac{d\phi}{dt} = \dfrac{V\cos\theta\cos\psi}{r} \\ \dfrac{dV}{dt} = -D - g\sin\theta + C_V \\ \dfrac{d\theta}{dt} = \dfrac{L\cos\sigma}{V} - \dfrac{g\cos\theta}{V} + \dfrac{V\cos\theta}{r} + C_\theta \\ \dfrac{d\psi}{dt} = \dfrac{L\sin\sigma}{V\cos\theta} + \dfrac{V\tan\phi\cos\theta\sin\psi}{r} + C_\psi \end{cases} \tag{1}$$

where $r$ is the radial distance from the center of the Earth to the vehicle, $V$ is the velocity of the vehicle, $\lambda$ is the longitude, $\phi$ is the latitude, $\theta$ is the flight path angle, and $\psi$ is the heading angle. In addition, $\sigma$ is the bank angle, $g$ is the gravitational acceleration, $L$ and $D$ represent the lift and drag accelerations, respectively. $C_V$, $C_\theta$ and $C_\psi$ account for the contribution of Coriolis acceleration and convected acceleration.

$$\begin{cases} C_\psi = 2\omega_e(\sin\phi - \cos\psi\tan\theta\cos\phi) \\ \qquad + \dfrac{\omega_e^2 r\cos\phi\sin\phi\sin\psi}{V\cos\theta} \\ C_\theta = 2\omega_e\sin\psi\cos\phi \\ \qquad + \dfrac{\omega_e^2 r}{V}\cos\phi(\sin\phi\cos\psi\sin\theta + \cos\phi\cos\theta) \\ C_V = \omega_e^2 r\left(\cos^2\phi\sin\theta - \cos\phi\sin\phi\cos\psi\cos\theta\right) \end{cases} \tag{2}$$

where $\omega_e$ is the self-rotation rate of the Earth. For simplification, the dynamic equations are transformed into the P coordinate system [14].

In Fig. 1, $N$ is the north pole of the Earth. The longitude and latitude of the entry point ($I$) are denoted by $(\lambda_0, \phi_0)$. $A_0$ is the angle between meridian plane and the plane determined by entry point and target point $T$ (the reference plane). The P coordinate system is described as follows: $X_P$ is aligned in the direction of the initial radial vector, and $Y_P$ is perpendicular to $X_P$ in the reference plane. $X_P$, $Y_P$, and $Z_P$ constitute a right-hand coordinate system. $P$ is on the $Z_P$ axis, and denotes the "north pole" of the P coordinate system. $PNI$ is a spherical triangle, whose arc $PI$ is $\pi/2$ rad.

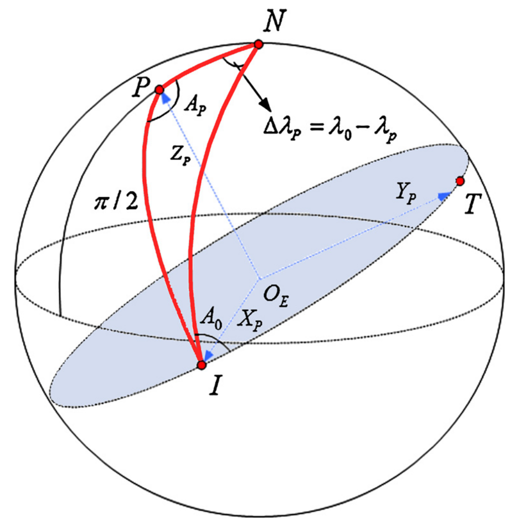

**Fig. 1.** P coordinate system.

In the P coordinate system, $\lambda_0$ and $\phi_0$ are set as zeros. The reference plane is the zero-latitude plane. The latitude denotes the lateral deviation of the vehicle. The variables in the rest of this paper are in the P coordinate system.

### 2.2. Constraints

In the flight, the constraints on heating rate, aerodynamic load, and dynamic pressure should be considered. In the traditional guidance method, a drag acceleration corridor is built based on those constraints. Within the corridor, a drag acceleration profile is designed to guide the vehicle. The lower boundary of the corridor is determined by QEGC.

$$D_{\mathrm{QEGC}} = \frac{(g - V^2/r) + K}{C_L/C_D\cos\sigma} \tag{3}$$

where $K$ is the self-rotation effect of the Earth. $C_L$ and $C_D$ are respectively the lift and drag coefficients. The upper boundary of the corridor is determined by the maximum heating rate $Q_{\max}$, maximum aerodynamic load $q_{\max}$, and maximum dynamic pressure $n_{\max}$.

$$\begin{cases} D \le D_Q = \dfrac{C_D S_r Q_{\max}^2}{2Mk_Q^2 V^{2m-2}} \\ D \le D_q = \dfrac{q_{\max} C_D S_r}{M} \\ D \le D_n = \dfrac{n_{\max} g_0}{\sqrt{1 + (C_L/C_D)^2}} \end{cases} \tag{4}$$

where, $S_r$ is the reference area of the vehicle, $M$ is the mass of the vehicle, $m = 3.15$ and $k_Q$ is the parameter of heating model.

To meet the requirement of Terminal Area Energy Management (TAEM), the terminal states of the entry course are limited by

$$\begin{cases} r_f = r_{TAEM} \\ V_f = V_{TAEM} \\ S_{togo,f} = R_{TAEM} \\ \Delta\psi_f \le \varepsilon \end{cases} \tag{5}$$