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An adaptive predictor–corrector reentry guidance based on self-definition way-points

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ABSTRACT

An adaptive predictor–corrector reentry guidance algorithm with self-defined way-points is proposed. In the guidance process, the reentry trajectory is divided into the predictor–corrector phase and the trajectory onboard generation and tracking phase which is near to the endpoint position of reentry and utilized to improve the accuracy and adaptivity of the guidance. In the first phase, the predictor–corrector algorithm is applied to solve the guidance problem between the self-defined way-points. Moreover the position parameters of reentry trajectory are translated into the parameters related to the reentry plane by orthogonal transformation in the spherical coordinate to improve robustness of guidance algorithm. In addition, the predictor–corrector algorithm is implemented using a brain emotional learning based intelligence controller (BELBIC). In the second phase, the trajectory from the current point to the endpoint is generated onboard and the linear–quadratic regulator (LQR) theory is employed for trajectory tracking. The effectivity of the proposed guidance is validated by simulations in conditions of the nominal case, the environment dispersed case and the endpoint maneuvering case. The advantages of this guidance in coping with disturbances, reducing time of numerical trajectory prediction and being suitable for maneuver endpoint are analyzed with the simulation results.

1. Introduction

Various hypersonic and reentry vehicle technologies are being pursued to enable a prompt global reach ability, such as the Falcon plan vehicle of U.S. Air Force, e.g., the Common Aero Vehicle. The reentry guidance plays an important role in steering the vehicle safely through the dispersed reentry flight environment, while meeting the mission requirements [7]. A high degree of autonomy and adaptability is desirable for future reentry vehicles.

Much of the reentry guidance techniques in development today are influenced by the Space Shuttle reentry guidance. This guidance and other similar acceleration guidances, like drag acceleration planning and tracking guidance, are almost based on the assumption that the vehicle will follow a great circle arc connecting the initial entry point to the target point. So the accuracy of this kind of guidance is reduced at high crossrange [4,9,10,14,19]. The Evolved Acceleration Guidance Logic for Entry (EAGLE) is originally presented by Saraf et al. [15]. It is a direct extension of the Shuttle's longitudinal acceleration guidance to include the lateral dimension. Leavitt improves the EAGLE for its application in suborbital entry scenario [8]. The reference heading angle is also tracked with bank angle as the control variable. However, manual tuning of the trajectory tracking law is needed in EAGLE. It is expected that the need for manual tuning could eventually be eliminated.

Other researchers break away from the traditional drag guidance approach. Dukeman has developed a linear state-feedback longitudinal tracking law [3]. The energy-varying gains are tuned offline using an LQR. Strength of the tracking law is the near trajectory independence of its gain tuning. Zimmerman et al. have developed an onboard trajectory planner [27]. Trajectory design is implemented in two parts. In the earlier part, a constant thermal flux is followed. In the second part, the planner designs a linear bank angle profile with bank reversals to meet the final range, heading, and altitude requirements. Shen and Lu also plan and track complete three-degree-of-freedom entry trajectories [16,17]. The planning occurs onboard before entry. During trajectory design, the entry phase is broken into three sub-phases, the most significant of which is the quasi-equilibrium glide (QEG) phase. Then the authors have developed a trajectory planner for suborbital entry which does not use the QEG assumption [18]. During entry phase, the planned longitude dynamics are followed by tracking law which is similar to Dukeman's guidance. The bank reversals are commanded using the logic similar to the Shuttle's, though the crossrange is used as a reversal criterion instead of heading angle.

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Due to the enhancement of the capability of the computer, the numerical predictor–corrector guidance is developed in the past few decades. Youssef designs a predictor–corrector guidance to handle widely dispersed entry conditions [26]. The control variables are perturbations of the bank angle, the angle-of-attack and the time for roll reversal. The bank angle and the angle-of-attack profiles are the nominal profiles plus the perturbations. The altitude, heading and range errors at terminal area energy management interface are used to correct the initial guess of the control variables. Several perturbed state cases for initial entry conditions and different initial guesses are used to test the performance of the guidance for the X-33 operations. However, the real-time application of the algorithm needs further demonstration. A predictor–corrector guidance algorithm for atmospheric reentry is presented by Joshi et al. [7]. The control variables are parameterized with variation over nominal angle-of-attack (AOA) profile and a bank angle at a predefined velocity for constructing linear variation of the bank angle with respect to relative velocity. Otherwise the guidance methodology includes the path constraint control law as a part of the predictor algorithm, namely the bank angle is modulated when the drag and drag rate of predict trajectory exceed the boundaries decided by path constraints. Xue also develops a constrained predictor–corrector entry guidance algorithm for vehicles with medium to higher lifting capability [22]. The algorithm enforces the path constraints by transforming them into the energy-dependent upper and lower bounds in the velocity-altitude space with the help of quasi-equilibrium glide condition (QEGC) for the magnitude of the bank angle. In addition, the numerical predictor–corrector is used as the core algorithm in newly developed entry guidance for the lifting interplanetary re-entry vehicle and the capsule return from the Moon [1,2,20].

In this paper, an adaptive predictor–corrector reentry guidance based on self-definition way-points is proposed for the medium to high lift-to-drag ratio reentry vehicles. The strategy of the guidance is purposed to improve its performance in crossrange control, adaptivity to disturbed circumstances and dealing with maneuverable target.

2. Outline of the presented guidance strategy

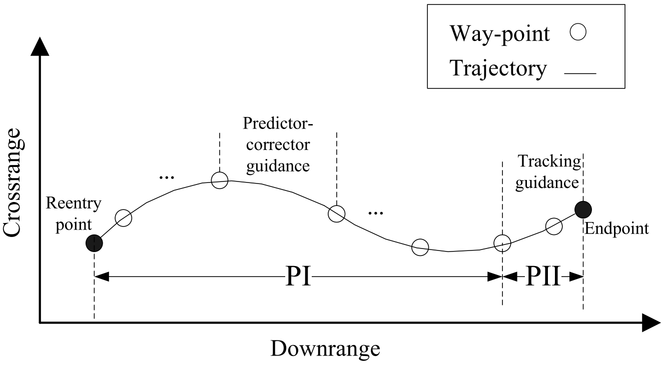
The presented reentry guidance is divided into two phases from the initial point to the endpoint of reentry, as described in Fig. 1. In the first phase (PI), the predictor–corrector guidance between self-defined way-points is implemented. In the second phase (PII), which is near the endpoint, an onboard trajectory generation and tracking guidance is adopted to enhance the adaptability of the guidance. Furthermore, the key points of the guidance strategy are as following:

A. In the predictor–corrector phase, the normal sphere coordinate system is translated to a new sphere coordinate system by orthogonal transformation, in which the plane of zero latitude is coincidence to the reentry plane.

B. The way-points are defined in the new sphere coordinate and generated by the optimal trajectory which is obtained by Gauss pseudospectral method. In addition, the way-points are corresponding to the Gauss nodes of the optimal trajectory.

C. The predictor–corrector algorithm, which is implemented between the self-defined way-points, is developed by the Brain Emotional Learning Based Intelligence Controller for its robustness and less computation time.

D. In the second guidance phase, a three dimensional reference trajectory, from the current position to the endpoint, is generated onboard. And the linear–quadratic regulator is employed for trajectory tracking.



PI: Predictor-corrector Phase
PII: Trajectory generation and tracking phase

Fig. 1. Sketch map of the presented guidance.

3. Coordinate transformation and way-points determination

3.1. Coordinate transformation for guidance

In normal sphere coordinate system, supposing a rotational sphere earth model, we use the radial distance from the center of the earth, longitude and latitude to describe the position of the vehicle relative to the Earth. And we also use the magnitude of velocity, flight path angle and azimuth angel to describe the vehicle velocity relative to the Earth [21]. Here, the motivation is to present a new sphere coordinate to denote the position and velocity of the vehicle relative to reentry plane through orthogonal transformation. The new sphere coordinate is obtained as the following steps.

3.1.1. Orthogonal rotation of sphere coordinate system

Firstly the reference plane can be determined by the two vectors: one is from the center of the Earth to the reentry point, another is from center of the Earth (the same start point) to the endpoint of reentry. Then the sphere coordinate system is rotated to let the zero latitude plane (so called the equatorial plane) be coincidence to the reentry plane. In the new sphere coordinate system, we use $\widehat{\theta}, \widehat{\varphi}, \widehat{r}, \widehat{V}, \widehat{\gamma}, \widehat{\psi}$ to denote the reentry states. According to the definition of reentry plane, the new longitude $\widehat{\theta}$ and the new latitude $\widehat{\varphi}$ can directly indicate the downrange and crossrange of the reentry vehicle respectively. And it is obviously that $\widehat{r} = r$, $\widehat{V} = V$, $\widehat{\gamma} = \gamma$. In addition, to establish the dimensionless equations of motion for guidance the r is normalized by the average radius of the Earth $R_0 = 6378$ km and denoted as z. And the Earth relative velocity V is normalized by $V_c = \sqrt{g_0 R_0}$, where $g_0 = 9.81\ \mathrm{m/s^2}$ and denoted as u. So in dimensionless formulation, we have

$$\widehat{z} = z \qquad \widehat{u} = u \qquad \widehat{\gamma} = \gamma \tag{1}$$

3.1.2. Coordinate transformation

In order to establish the relationship between the normal sphere coordinate system and the transformed one, three rectangular coordinate systems, diagrammed in Fig. 2, are introduced here. Two of them are the Earth frame $O–X_E Y_E Z_E$ and rotated Earth frame $O–\widehat{X}_E \widehat{Y}_E \widehat{Z}_E$. The plane $X_E O Y_E$ is the equatorial plane and the plane $\widehat{X}_E O \widehat{Y}_E$ is the reference reentry plane. So we have the relationship

$$\begin{bmatrix} X_E \\ Y_E \\ Z_E \end{bmatrix} = \begin{bmatrix} r\cos\varphi\cos\theta \\ r\cos\varphi\sin\theta \\ r\sin\varphi \end{bmatrix}, \qquad \begin{bmatrix} \widehat{X}_E \\ \widehat{Y}_E \\ \widehat{Z}_E \end{bmatrix} = \begin{bmatrix} \widehat{r}\cos\widehat{\varphi}\cos\widehat{\theta} \\ \widehat{r}\cos\widehat{\varphi}\sin\widehat{\theta} \\ \widehat{r}\sin\widehat{\varphi} \end{bmatrix} \tag{2}$$