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Evolutionary method based integrated guidance strategy for reentry vehicles

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A B S T R A C T

In this paper, the guidance problem of winged re-entry vehicle with path constraints has been solved using an integrated guidance strategy that combines evolutionary method based pigeon inspired optimization (PIO) with gradient based Gauss Newton (GN) optimization algorithm. Re-entry phase is an unpowered flight that has bank angle modulation as the primary control variable. The bank angle is parametrized to be linear with respect to energy. This reduces the guidance problem to single parameter search problem. In the first phase of the integrated guidance scheme, PIO is used to find a bank angle that satisfies a predefined objective function. The corresponding bank angle is further updated by the GN algorithm to minimize the terminal error in the range-to-go. GN algorithm is used as a part of predictor–corrector guidance algorithm that requires an initial guess of the bank angle in each guidance cycle. The choice of initial guess has been eliminated in the proposed algorithm by incorporating PIO. Results of the proposed algorithm have been compared with the traditional predictor–corrector (PC) algorithm. It has been observed that the performance of proposed algorithm is as good as that of PC algorithm with added advantage of being insensitive to initial guess requirement and also overcomes the divergence issues.

1. Introduction

The entry phase of a typical winged re-entry vehicle starts when it is at an altitude of 120 km until the velocity decreases to Mach 2–3. In this phase the vehicle is unpowered and trajectory control is obtained mostly through bank angle modulation. Moreover, in this phase, the vehicle experiences peak heat rates, g-loads, and dynamic pressure. Thus the trajectory of the vehicle is constrained by the allowable limits on heat rate, g-loads, and dynamic pressure which form the path constraints. The entry guidance problem is to find the bank angle command at any instant so as to make the vehicle reach the destination safely without violating the path constraints. This problem of guiding the entry vehicle is solved in the literature using two approaches.

The first approach is based on tracking the stored reference trajectories onboard. The reference trajectories are usually generated offline before the mission starts and are preloaded before the vehicle is launched. The traditional Shuttle entry guidance is based on designing the drag deceleration-vs-velocity profile that achieves the desired range to the target. During entry flight, the level of drag deceleration profile is adjusted and a control law is formulated to track the drag deceleration profile as described by Harpold and Gavert (1983). Roenneke and Markl (1994) has proposed the concept of designing drag-vs-energy profile. A linear control law with constant feedback gains at discrete energy values is suggested for tracking the reference drag profile. Saraf et al. (2004) has proposed a guidance algorithm that has two components. The first component is the planner that generates reference drag acceleration and is capable of updating it onboard. The second component is the tracking law, based on feedback linearization, which commands the bank angle and angle of attack. The main issues of the guidance laws based on tracking the reference trajectory are their over dependency on the reference trajectory and lack of flexibility to accommodate the real time circumstances. Moreover, tracking laws use gain-scheduled parameters which are to be tuned off-line for every mission.

The generation of the reference trajectory holds high importance in the guidance approaches described previously. In recent time, however, evolutionary method based trajectory optimization has gained interest due to their simplicity. Rahimi et al. (2013) has applied PSO to generate optimal trajectories for a spacecraft. Zhao and Zhou (2015a, b) has used particle swarm optimization (PSO) and PIO to generate entry trajectories

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for hypersonic gliding vehicle using a simple formulation. However, the control formulation requires finding multiple parameters to get the complete control profile.

The second approach is based on predictive guidance. With the advances in onboard computational capability, guidance laws based on predictor–corrector approach have also gained attention. This approach predicts the trajectories based on current state and corrects the control variable to attain the desired terminal range in real time. This approach does not rely on predefined reference trajectory, also there is no requirement of separate trajectory planner and tracking law. Moreover, such algorithms are highly adaptive to trajectory dispersions as described by Lu (2014). Youssef et al. (2001) has implemented predictor–corrector algorithm on X-33 vehicle. But, this method lacks effective means of incorporating the path constraints. Shen and Lu (2003), made use of quasi equilibrium glide condition (QEGC) for enforcing the inequality constraints. Xue and Lu (2010), have converted the inequality constraints to velocity dependent upper bound on the magnitude of the bank angle using QEGC. A unified entry guidance approach that has the ability to satisfy inequality constraints and is universally applicable for any type of re-entry vehicle is proposed by Lu (2014). This algorithm combines the theory based on time scale separation and predictive control for incorporating path constraints into predictor–corrector guidance. Yong et al. (2014) has presented an adaptive predictor–corrector guidance based on self defined way points. The PC algorithm is applied between the way points and a linear–quadratic regulator (LQR) is employed for tracking the trajectory generated by PC between the current way point and the end point.

This paper proposes an integrated guidance scheme which falls under the category of predictive guidance approach. This integrated guidance scheme combines evolutionary method based optimization algorithm with gradient based optimization algorithm for solving entry guidance problem. In this regard, it should be noted that PIO algorithm is independent of the initial guess requirement and also has faster convergence rate compared to PSO (Zhao and Zhou, 2015b). However PIO algorithm has inherent randomness; i.e it might not converge in fixed time interval. Whereas, GN algorithm is a gradient based approach which converges with high accuracy for a given initial guess. These two methods are integrated so that respective benefits are combined, in order to solve the entry guidance problem. The integrated guidance algorithm is executed in two phases. In the first phase PIO algorithm is used to find the bank angle that satisfies a predefined objective function. The converged bank angle from first phase is given as initial guess to the GN algorithm in the second phase. Additional modification of the bank angle to satisfy equilibrium glide and path constraints have been incorporated in both the phases. This integrated guidance algorithm is implemented on Common Aero Vehicle (CAV-H) with high L/D ratio. One nominal case and another case with perturbations in nominal case at the entry interface has been considered for simulation. A fixed angle of attack profile for a given Mach number has been taken from Lu (2014).

This paper is organized as follows. Re-entry vehicle model is presented in Section 2. The entry guidance problem formulation along with entry constraints is discussed in Section 3. Section 4 gives the overview of PIO and GN algorithms that are part of the proposed guidance scheme. Section 5 discusses the integrated guidance scheme. Simulation results validating the proposed algorithm are presented in Section 6. Section 7 concludes the paper.

2. Re-entry vehicle model description

Entry phase starts when the vehicle enters the Earth's atmosphere from the space and ends at the beginning of Terminal area energy management phase (TAEM). In the entry phase, the vehicle is considered to be point mass, gliding over a spherical, rotating Earth. The 3-DOF equations of motion of the vehicle considering dimensionless negative of specific mechanical energy e given in Eq. (9) as the independent variable are given below as per Lu (2014)

$$\frac{dr}{de} = \frac{sin\gamma}{D} \tag{1}$$

$$\frac{d\theta}{de} = \frac{\cos\gamma\sin\psi}{rD\cos\phi} \tag{2}$$

$$\frac{d\phi}{de} = \frac{\cos\gamma\cos\psi}{rD} \tag{3}$$

$$\frac{dV}{de} = \frac{1}{DV}\left[-D-\left(\frac{\sin\gamma}{r^2}\right)+\Omega^2 r\cos\phi(\sin\gamma\cos\phi-\cos\gamma\sin\phi\cos\psi)\right] \tag{4}$$

$$\frac{d\gamma}{de} = \frac{1}{DV^2}\left[L\cos\sigma+\left(V^2-\frac{1}{r}\right)\left(\frac{\cos\gamma}{r}\right)\right.$$
$$\left.+\,2\Omega V\cos\phi\sin\psi+\Omega^2 r\cos\phi(\cos\gamma\cos\phi+\sin\gamma\cos\psi\sin\phi)\right] \tag{5}$$

$$\frac{d\psi}{de} = \frac{1}{DV^2}\left[\frac{L\sin\sigma}{\cos\gamma}+\frac{V^2}{r}\cos\gamma\sin\psi\tan\phi\right.$$
$$\left.-\,2\Omega V(\tan\gamma\cos\psi\cos\phi-\sin\phi)+\frac{\Omega^2 r}{\cos\gamma}\sin\psi\sin\phi\cos\phi\right] \tag{6}$$

$$\frac{ds}{de} = -\frac{\cos\gamma}{rD} \tag{7}$$

$$\frac{d\tau}{de} = 1/DV \tag{8}$$

where r is the radial distance from the Earth center to the vehicle O, it is normalized with respect to the radius of the Earth R_0. θ and ϕ are the longitude and latitude respectively. V is the Earth-relative velocity, normalized with $\sqrt{R_0 g_0}$, $g_0 = 9.8$ m/s^2 is the acceleration due to gravity. γ is the flight-path angle (taken to be positive when velocity vector is above the horizontal plane). ψ is the heading angle of the velocity vector, measured clockwise in the local horizontal plane from the north as shown in Fig. 1. s denotes the range-to-go(in radians) on the surface of a spherical Earth along the great circle connecting the current location of the vehicle and the site of the final destination, and s is normalized with respect to the radius of the Earth. The gravitational force is $g = \mu/r^2$, where μ is Earth's gravitational constant, which is equal to 1 when normalized. Time of flight τ is also considered as a state as given in Eq. (8). The final time of flight can be found by integrating Eq. (8) from initial energy e_0 to final energy e_f. τ is normalized by $\sqrt{R_0/g_0}$. The bank angle σ is defined as the clockwise positive rotation of the lift vector about the relative velocity vector. Ω is the dimensionless Earth self rotation rate. The dimensionless energy e is defined below. It is clear from Eq. (8) that energy e is a monotonically increasing function of time.

$$e = \frac{1}{r} - \frac{V^2}{2}. \tag{9}$$

The terms L and D are the non-dimensional aerodynamic lift and drag acceleration(in $g_0 = 9.8$ m/s^2), respectively.

$$L = \frac{1}{2mg_0}\rho V^2 C_L S_{ref} \tag{10}$$

$$D = \frac{1}{2mg_0}\rho V^2 C_D S_{ref}. \tag{11}$$

The aerodynamic coefficients C_L and C_D are functions of angle of attack α and Mach number. m is the mass of the vehicle and S_{ref} is vehicle's reference surface area, ρ is the atmospheric density. In this paper, atmosphere is modeled using 1976 U.S. Standard Atmosphere model developed by Anon (1976). The bank angle modulation is considered as the control variable to re-orient the vehicle. A nominal angle of attack profile for a given Mach number is considered as given in Fig. 2.

3. Entry guidance problem formulation

The objective of the guidance algorithm is to provide guidance commands i.e the magnitude and sign of the bank angle in each guidance cycle based on the current state variables. These guidance commands should ensure that the vehicle reaches the landing site satisfying all the path and terminal constraints accurately.

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