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Evolutionary Method Based Hybrid Entry Guidance Strategy for Reentry Vehicles

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Abstract: This paper presents a hybrid approach combining Pigeon Inspired Optimization (PIO) with Gauss-Newton method for entry guidance of winged vehicles. The bank angle modulation is considered as the primary control. In the hybrid guidance approach, PIO algorithm is initially used to find a bank angle that satisfies a predefined cost function. In the second phase, the corresponding bank angle is updated to correct the terminal errors using Gauss-Newton algorithm. Advantages of PIO algorithm are that it does not require an initial guess and that equality and inequality constraints can be incorporated, apart from the fact that it has global convergence and randomness. Gauss-Newton method, however, is deterministic and ensures global convergence with high accuracy given an initial guess. Thus, hybrid guidance algorithm exploits the benefits of both and determines an optimal bank angle profile that steers the vehicle to destination accurately, satisfying the path constraints. The simulation results show effectiveness of the proposed algorithm.

Keywords: Re-entry guidance, Trajectory optimization, Hybrid techniques, Pigeon inspired optimization, Gauss-Newton method.

1. INTRODUCTION

The atmospheric entry is considered to be the critical phase for an entry vehicle. In this phase, vehicle is subjected to high heat load, aerodynamic decelerations and dispersed flight environment. Thus, generating guidance commands for the entry vehicle to safely reach the destination is a challenging task. Over the years, entry trajectory optimization has been and is still the subject of interest for many researchers. In the current literature, three different approaches have been used to solve entry guidance problem.

The first category of guidance algorithms are based on generating reference trajectories and tracking them using control laws. Most often these reference trajectories are generated offline and are preloaded before flight. Roenneke and Markl (1994), presented a linear control law that achieves local tracking of drag-vs-energy reference. Saraf et al. (2004), has proposed an entry guidance algorithm called evolved acceleration guidance logic for entry (EAGLE), which has trajectory planner, that generates reference drag acceleration and heading profiles onboard. Then, a tracking law based on feedback linearization has been employed to follow reference drag and heading profiles.

The second category of guidance algorithms employ predictor corrector algorithm. This algorithm predicts the trajectories based on current state and updates the control variable to correct the terminal errors. Quasi Equilibrium Glide Condition (QEGC) has been used to reduce infinite dimensional problem of meeting the path constraints into a one-parameter search problem by Shen and Lu (2003). The path constraints are converted into limits on drag and drag rate and control law has been designed by Joshi et al. (2007).

The third type of approach adopts the direct trajectory optimization techniques like pseudospectral methods and evolutionary algorithms. Optimal guidance based on indirect Legendre pseudospectral method has been proposed by Tian and QunZong (2011). A nominal reference trajectory is first generated. A robust state feedback guidance law is generated in real time using indirect Legendre pseudospectral feedback method. The control variable, bank angle, has been discretized at a set of Legendre-Gauss collocation points and is optimized with artificial bee colony (ABC) algorithm by Duan and Li (2015).

This paper presents a new approach for solving entry guidance problem by merging swarm intelligence method PIO, with the traditional Gauss-Newton method. The advantages of PIO and Gauss-Newton method are exploited in the proposed hybrid algorithm. The PIO algorithm is independent of initial guess requirement and facilitates inclusion of inequality and equality constraints, apart from ensuring global convergence. Gauss-Newton method is a deterministic approach and ensures global convergence with high accuracy given an initial guess. These methods are integrated to solve entry guidance problem owing to their advantages. The hybrid guidance method uses PIO algorithm initially to find a bank angle that satisfies a predefined cost function. In the second phase, the corresponding bank angle is updated to correct the terminal errors using Gauss-Newton algorithm. This hybrid guidance scheme satisfies equality and inequality constraints, with minimum number of control variables to be found. This method is computationally simple and it has flexibility to incorporate additional equilibrium glide constraint or further reduction in heat rate by using altitude rate

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compensation in the second phase of the algorithm. The proposed algorithm is applied to Common Aero Vehicle (CAV-H) (Phillips, 2003). Simulation results show that constraints are met accurately.
This paper is organised as follows. Section 2 describes the entry dynamics and the constraints involved. Problem statement is defined in section 3. Section 4 formulates the cost function based on terminal and path constraints. Section 5 discusses the proposed hybrid entry guidance algorithm. Section 6 has results validating the proposed algorithm. Section 7 concludes the paper.

2. ENTRY DYNAMICS

The 3-DOF point mass dynamics of re-entry vehicle gliding over a spherical, rotating Earth in terms of non-dimensional variables considering energy as independent variable are

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

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

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

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

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

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

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

where, r is the radial distance from the Earth center to the vehicle O, θ and ϕ are the longitude and latitude, V is the Earth-relative velocity, γ is the flight-path angle, and 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. The gravity force is based on Newtonian gravity law. The differentiation in the previous equations are with respect to the dimensionless energy e. e is defined as negative of the specific mechanical energy used in orbital mechanics as mentioned in (Lu, 2014). It is monotonically increasing with time. Time of flight is also

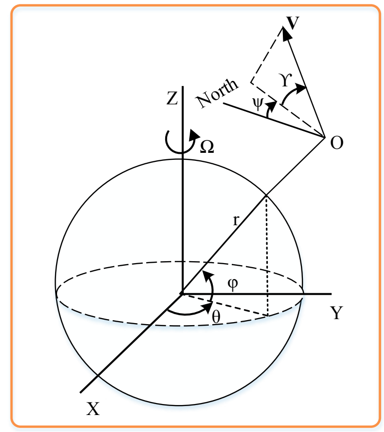

Fig. 1. Nomenclature used in equations of motion

considered as a state. Final time of flight can be found by integrating equation 9 from initial energy to final energy.

$$e = \frac{1}{r} - \frac{V^2}{2} \tag{8}$$

$$\frac{d\tau}{de} = 1/DV \tag{9}$$

The dimensionless variables are obtained by scaling them with appropriate factor as given in Lu (2014). The terms L and D are the non-dimensional aerodynamic lift and drag acceleration(in $g_0 = 9.8m/s^2$), 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. The bank angle σ is the roll angle of the vehicle about the relative velocity vector, positive to the right. Ω is the dimensionless Earth self rotation rate.

2.1 Path constraints

Entry flight has allowable limits on maximum heat rate $\dot{Q}$ on surface of vehicle, load factor a and dynamic pressure p as given by equations (12), (13), (14) respectively. They, together form path constraints.

$$\dot{Q} = k_Q\sqrt{\rho}V^{3.15} \le \dot{Q}_{max} \tag{12}$$

where $k_Q = 9.4369 \times 10^{-5} \times (\sqrt{g_0 R_0})^{3.15}$

$$a = \sqrt{L^2 + D^2} \le a_{max} \tag{13}$$

$$p = (g_0 R_0 \rho V^2)/2 \le p_{max} \tag{14}$$

Quasi equilibrium glide condition is considered to be soft constraint. Equilibrium glide refers to aerodynamic lift balancing the gravitational and centrifugal forces as given by equation (15).

$$Lcos\sigma = (1/r^2) - (V^2/r) \tag{15}$$

where, σ is specified bank angle. In equilibrium glide, the flight path angle should be constant. But, it usually varies with time. Hence, it is called quasi equilibrium glide condition.