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Waypoint constrained guidance for entry vehicles

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ABSTRACT

A guidance algorithm for the waypoint constrained atmospheric entry is presented. To guarantee that the vehicle is able to reach all the waypoints and the final target accurately, the flyby direction constraint for each waypoint is investigated. The controllable and reachable sets for the vehicle's velocity heading angle are defined and calculated. The expected heading angle is obtained from these sets and used as a direction constraint for the corresponding waypoint. Under the location and direction constraints, a bank reversal strategy based on the trajectory prediction is developed. With this strategy, a lateral trajectory that satisfies the waypoint constraint is generated online. Tracking laws for the longitudinal and lateral trajectories are designed. Finally, the guidance algorithm is tested on the Common Aero Vehicle model in highly constrained flights. Results show that the conventional path constraint, the terminal constraint and the additional waypoint constraint are all well satisfied, which indicates the effectiveness of the proposed guidance algorithm.

1. Introduction

An atmospheric entry flight is with multiple constraints and uncertainties, thus a reliable guidance system is required. During the past decades, considerable studies have been conducted for the entry guidance [1–7]. In previous research, two types of entry constraints are mainly considered. The first type is the path constraint including limits for the heating rate, the aerodynamic load and the dynamic pressure. The second type is the constraint for terminal conditions such as the altitude, the velocity, and the range-to-go. Apart from these conventional constraints, geographic constraints are currently focused on for special missions of maneuvering entry vehicles [8]. The two typical geographic constraints are waypoints and no-fly zones. Waypoints are specified locations for the scene matching or other navigation requests. The vehicle is required to accurately fly past the waypoints before reaching the final target. On the contrary, no-fly zones are areas that the vehicles must avoid flying into for geopolitical restrictions or threat avoidance [9]. The trajectory planning and guidance algorithms under geographic constraints have been widely studied for the Unmanned Aerial Vehicle (UAV) [10–14]. However, these algorithms are hard to be employed on the entry vehicle. In contrast to the conventional UAV, the entry vehicle is unpowered, the entry trajectory is highly constrained, and the entry environment is dispersed. Hence, constraints for the waypoint and the no-fly zone make the entry flight more challenging.

Under the new geographic constraints, several trajectory planning algorithms are proposed. Jorris and Cobb [15] optimized the simplified two-dimensional trajectory for hypersonic cruise vehicles using analytical methods. In a further study [9], they employed a numerical approach to compute the constrained three-dimensional entry trajectory for the Common Aero Vehicle (CAV). Since the lateral entry trajectory is controlled by bank reversals which change the sign of bank angle to the opposite [16], the geographic constraints can be satisfied by several particular bank reversals. Xie et al. [17] designed two bank reversal methods for the waypoint and the no-fly zone to generate a highly constrained entry trajectory. In another research [18], they developed a unified bank reversal approach based on reference points which correspond to either a waypoint or a no-fly zone. Algorithms presented in [9,15,17–19] perform well in optimizing or generating constrained trajectories off-line in the nominal case. However, during the actual entry flight, aerodynamic parameters such as the lift and drag coefficients are usually dispersed. Thus, an adaptive guidance algorithm is required online for the entry flight under dispersions and uncertainties.

The guidance method in this study focuses mainly on the waypoint constraint, and the no-fly zone constraint will be considered in further research. In general, a waypoint is expressed as a location constraint for the vehicle's longitude and latitude. Note that previous guidance methods for the final target cannot be directly used for the waypoint, because the precision request for the way-

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point matching is usually higher than that for the target. Besides, the waypoint is an internal point of the trajectory, thus the flyby direction at the waypoint is also constrained. For the waypoint's location constraint, it can be satisfied by searching for a single bank reversal [17] or two cooperative reversals as designed in our previous study [20]. However, the flyby direction constraint has not been considered yet.

For some scene matching missions, the flyby direction at the waypoint is limited. Since the entry vehicle's control authority is much lower than that for the UAV, it cannot reach the waypoint from all directions. The flyby direction can be described by the vehicle's velocity heading angle. Thus, the reachable set for the vehicle's heading angle at the waypoint is concerned by the mission designer. Moreover, entry dispersions have strong impacts on the heading angle. Different heading angles would result in different trajectories after the current waypoint. In some significantly dispersed cases, the vehicle is hard to reach the next waypoint or the final target after passing the current waypoint. Therefore, the controllable set for the heading angle at the waypoint is necessary to be investigated. Investigations on the controllable and reachable sets provide the heading angle constraint for each waypoint. This constraint can be considered by the guidance system to improve the guidance performance. In addition, the controllable and reachable sets are references which can help the designer to assess the reasonability of a selected waypoint.

In this paper, the controllable, reachable and feasible sets for vehicle's velocity heading angle at the waypoint are defined and investigated. These sets are employed to provide an expected heading angle which is most likely to be achieved by the entry vehicle. Then, based on the expected heading angle, a bank reversal strategy is designed for waypoints with both the location and direction constraints. In order to guarantee the guidance performance under dispersions, tracking laws for the longitudinal and lateral trajectories are designed. Finally, the presented guidance algorithm is verified in waypoint constrained missions.

2. Entry dynamics and constraints

The point-mass dynamics of an entry vehicle over a spherical, rotating Earth are given by the following equations [21]:

$$\dot{r} = v\sin\gamma \tag{1}$$

$$\dot{v} = -D - g\sin\gamma + \Omega^2 r\cos\phi(\sin\gamma\cos\phi - \cos\gamma\sin\phi\cos\psi) \tag{2}$$

$$\dot{\gamma} = \frac{1}{v}\left[L\cos\sigma - g\cos\gamma + \frac{v^2\cos\gamma}{r} + 2\Omega v\cos\phi\sin\psi + \Omega^2 r\cos\phi(\cos\gamma\cos\phi + \sin\gamma\sin\phi\cos\psi)\right] \tag{3}$$

$$\dot{\theta} = \frac{v\cos\gamma\sin\psi}{r\cos\phi} \tag{4}$$

$$\dot{\phi} = \frac{v\cos\gamma\cos\psi}{r} \tag{5}$$

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

where r is the radial distance from the Earth center to the vehicle, v is the Earth-relative velocity, γ is the flight-path angle, θ and ϕ are the longitude and latitude, and ψ is the velocity heading angle. g is the gravitational acceleration, and Ω is the Earth's self-rotation rate. σ is the bank angle (positive to the right). L and D are the lift and drag accelerations given by

$$L = \frac{1}{2m}\rho v^2 S_A C_L(\alpha, Ma), \qquad D = \frac{1}{2m}\rho v^2 S_A C_D(\alpha, Ma) \tag{7}$$

where m is the mass of the vehicle, ρ is the atmospheric density, and S_A is the reference area. C_L and C_D are the lift and drag coefficients that depend on the angle of attack α and the Mach number Ma.

Typical path constraints for entry vehicles include the heating rate limit $\dot{Q}_{\max}$, the aerodynamic load limit $n_{\max}$, and the dynamic pressure limit $q_{\max}$ [22]. These constraints are described by Eq. (8), where K_Q is a constant. Generally, the path constraints are considered in the trajectory optimization, thus can be satisfied online through tracking the optimized longitudinal trajectory.

$$\begin{cases} \dot{Q} = K_Q\rho^{0.5}v^{3.15} \le \dot{Q}_{\max} \\ n = \sqrt{L^2 + D^2} \le n_{\max} \\ q = \frac{1}{2}\rho v^2 \le q_{\max} \end{cases} \tag{8}$$

Terminal constraints for the entry phase are utilized to provide a good initial condition for the terminal phase. The vehicle is required to reach the terminal zone with specified altitude, velocity and heading angle. Supposing that the entry phase ends at the terminal zone interface, these constraints are expressed as

$$\begin{cases} h(s_{\text{togo},f}) = h_f \\ v(s_{\text{togo},f}) = v_f \\ \left|\Delta\psi(s_{\text{togo},f})\right| \le \Delta\psi_f \end{cases} \tag{9}$$

where h is the altitude of the vehicle, s_{togo} is the range-to-go from the vehicle to the final target, and $\Delta\psi$ is the heading error defined as the error between the velocity heading angle and the line-of-sight angle towards the target. Variables denoted 'f' are desired terminal conditions of the entry trajectory. Generally, terminal constraints for the altitude and the velocity are considered by the longitudinal guidance, and the terminal heading error constraint is focused on by the lateral guidance.

Apart from conventional constraints above, the waypoint constraint should be considered in some missions with special request such as the navigation. This type of constraint requires the vehicle to pass through several waypoints accurately during the flight. Assuming W_i $(i = 1, 2, \ldots, N)$ is a waypoint and (Θ_i, Φ_i) is the corresponding coordinate, the constraint for W_i is

$$\begin{cases} \theta(t_i) - \Theta_i = 0 \\ \phi(t_i) - \Phi_i = 0 \end{cases} \tag{10}$$

As the passage time t_i for the waypoint is usually not concerned, the constraint is simplified into $\phi(\Theta_i) = \Phi_i$. Hence, the waypoint is a constraint for the ground track in the lateral plane. Together with the terminal heading error constraint, the waypoint constraint is considered by the lateral guidance in this study.

3. Flyby direction constraint for waypoint

Under the location constraint for a waypoint, the vehicle is allowed to pass through the waypoint from different directions, in other words, with different velocity heading angles. Unreasonable flyby directions at the waypoints would make the highly constrained entry flight unreliable in dispersed cases. In this section, the flyby direction constraint is investigated using the concept of controllable reachable, and feasible sets for the vehicle's velocity heading angle.