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Robust virtual target guidance for the fixed-trim vehicle under multi-constraints

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ABSTRACT

This paper investigates a robust virtual target guidance algorithm for the fixed-trim Maneuverable Reentry Vehicle. The vehicle is faced with multi-constraints including terminal and process constraints. A virtual target integrated spinning guidance law is developed, and the virtual target's capability of handling multi-constraints is validated through analysis. A parametric optimization approach is proposed to determine the virtual target motion. The approach is further developed into a robustness optimization approach, which introduces a measurement of robustness into the optimization and estimates the measurement by Monte Carlo sampling. Illustrative results indicate the constraint-handling capability of the virtual target and the robustness of the proposed guidance algorithm.

1. Introduction

The fixed-trim reentry vehicle has gained much attention in the development of efficient and reliable reentry missions. Using an offset center of gravity position or a non-axisymmetric aerodynamic configuration, the vehicle usually exploits its inherent lifting capability from a fixed-trim and uncontrolled angle of attack (AOA). It falls in between ballistic and lifting vehicles since there exists control capability while it is limited. For the fixed-trim vehicle, the lift can be used to reshape the trajectory; but only the direction of lift can be controlled. Such a "semi-lifting" vehicle obtains a good balance between the ballistic vehicle's advantages of low complexity, low cost and high reliability and the lifting vehicle's maneuverability [1,2]. Therefore, a variety of vehicles, from Gemini and Apollo to Orion and Mars Science Laboratory (in Mars entry), have adopted the fixed-trim design [3–6].

Given the advantages, the fixed-trim Maneuverable Reentry Vehicle (MaRV) also attracts great interests in the military domain. However, the fixed-trim MaRV, as discussed in this paper, has raised the much higher demand for precision guidance than those civil applications. Military reentry maneuvers mainly focus on two tasks: 1) to avoid interceptions of an anti-missile system; 2) to achieve robust precision guidance and maximize the striking effect under multi-constraints. Task 1 is easy to fulfill as the maneuvers can be open-loop. For example, MK-500 follows open-loop programmed commands to avoid interceptions at the cost of guidance precision [7]. Challenges arise when Task 2 conflicts with the limited control authority. To meet all the constraints under uncertainties, it is fundamental to use the limited authority to reshape the trajectories and allocate the limited control capability over all the trajectories. Beyond that, since the magnitude of lift cannot be adjusted directly by AOA, aerodynamic characteristics along the trajectories should be given enough attention. Exploiting the aerodynamic characteristics can influence the velocity and the lift coefficient, which gives the vehicle the capability of adjusting the lift implicitly. Aerodynamic characteristics also have deep connections with multi-constraints like dynamic pressure or normal acceleration.

In the literature, guidance algorithms for the fixed-trim MaRV are seldom investigated while some literature covers the control algorithms [8,9]. First, high demanded precision like miss distances by meters excludes the applications of guidance algorithms designed for the above spacecraft-type fixed-trim vehicles. Those algorithms like Apollo-derived guidance in [5,10–12] often yield miss distances by kilometers. Second, traditional homing guidance designs for the lifting MaRV like hypersonic glider are also inapplicable. Those designs are developed in two orthogonal planes and require two independent acceleration commands [13,14]. Only controlling the direction of lift can hardly meet the commands simultaneously. More seriously, those designs cause chattering of bank command when the lift is redundant [15].

Because it can avoid the chattering, spinning guidance has drawn much attention. The spinning guidance, one of the hom-

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ing guidance methods, was first proposed under the assumption of constant velocity [16]. It averages the redundant lift by spinning instead of chattering (high-frequency bank reversal). This idea can trace back to the rolling reentry guidance logic of Gemini spacecraft [17]. One of the biggest differences is that the Gemini's rolling guidance logic was based on a zero-lift reference trajectory, which utilized a predicted range computed from pre-stored reference quantities. Then constant roll rate was commanded to track the trajectory. Unlike the spinning guidance law, no online closed-loop guidance was formed. As the pre-stored quantities may be biased in practice, high precision cannot be ensured. Recently, this method combined with a Virtual Target (VT) was proposed to control the terminal angle [18]. However, no interactions between the VT and the vehicle were analyzed, and no methodology of choosing an appropriate motion of the VT was provided. In all these spinning guidance methods, multi-constraints and robustness issues were not considered; the flight dynamics were ignored, and only the kinematics of engagement was considered. Besides, aerodynamic characteristics were not exploited in these methods.

In this paper, a robust Virtual Target Integrated Spinning (VTIS) guidance law considering multi-constraints is proposed for the fixed-trim MaRV. Based on numerical analysis of traditional designs, we emerge the traditional spinning guidance with a VT. Then analysis including interactions between the VT and the vehicle is developed. The interactions indicate the feasibility of the VT in reshaping the trajectories, exploiting the aerodynamic characteristics, and handling multi-constraints. Then a parametric optimization (PO) approach is proposed to help choose the appropriate motion of the VT. Considering the uncertainties, PO is modified to a Robustness Optimization (RO) approach by introducing Monte Carlo (MC) sampling.

The main contributions are as follows: First, the proposed VT scheme can exploit the aerodynamic characteristics of the vehicle and handling multi-constraints including terminal constraints (impact angle and impact velocity) and process constraints (dynamic pressure, normal acceleration, and rate of bank angle). Second, the proposed PO approach provides a methodology to determine the VT motion, which helps fulfill the above capabilities of VT. Third, the proposed RO approach helps improve the robustness by introducing a measurement of robustness into the optimization.

The remainder of this paper is organize as follows: Section 2 presents the guidance problem formulation for the fixed-trim MaRV. Then, VTIS guidance law is developed in Section 3. Analysis of VTIS is presented in Section 4. PO and RO approaches are developed in Section 5 and 6, respectively. Numerical simulations and analysis are provided in Section 7 and the main work is summarized in Section 8.

2. Guidance problem formulation

First, an Earth-fixed coordinate system S_g is defined under the flat Earth assumption as shown in Fig. 1. The origin is fixed on Earth and is the initial subastral point of the fixed-trim vehicle. The x axis is pointed to the north, the y axis to the east, and the z axis completes the right-hand system. The vector $\mathbf{r}$ represents the line-of-sight (LOS) from the vehicle to the target and is determined by its elevation angle ϕ and azimuth angle θ.

The 3-degree-of-freedom (3-DOF) model of the fixed-trim vehicle can be derived as follows:

$$\dot{x}_g = V\cos\gamma\cos\chi \tag{1}$$

$$\dot{y}_g = V\cos\gamma\sin\chi \tag{2}$$

$$\dot{z}_g = -\dot{h} = V\sin\gamma \tag{3}$$

$$\dot{V} = -\frac{D}{m} - g\sin\gamma \tag{4}$$

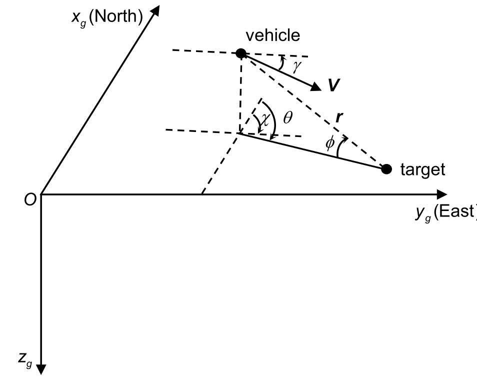

Fig. 1. Earth-fixed coordinate system S_g.

$$\dot{\chi} = \frac{L\sin\phi_V}{mV\cos\gamma} \tag{5}$$

$$\dot{\gamma} = \frac{L\cos\phi_V}{mV} - \frac{g}{V}\cos\gamma \tag{6}$$

x_g, y_g and z_g (or altitude h) represent the vehicle's position in S_g. V, χ and γ denote the velocity, heading angle and flight-path angle, respectively. D and L are the aerodynamic drag and lift forces. The bank angle is ϕ_V and the vehicle's mass is m. The gravity acceleration g can be calculated by the inverse-square law.

Denote the initial position vector $\mathbf{P}_0$ of the vehicle in S_g as

$$[\mathbf{P}_0]_g = [x_{g0}, y_{g0}, z_{g0}]^T = [x_{g0}, y_{g0}, -h_0]^T \tag{7}$$

and the position vector $\mathbf{P}_T$ of the target as

$$[\mathbf{P}_T]_g = [x_{gT}, y_{gT}, z_{gT}]^T = [x_{gT}, y_{gT}, -h_T]^T \tag{8}$$

where the superscript T means transposition of a vector.

The objective of the guidance law design is to find an appropriate way to steer the vehicle from $\mathbf{P}_0$ to $\mathbf{P}_T$ and simultaneously satisfy the multi-constraints, including the terminal and process constraints. The terminal constraints are the angle and velocity of the terminal impact, namely

$$\gamma_f = \gamma_{impact} \tag{9}$$

$$V_f = V_{impact} \tag{10}$$

where the subscript f means the terminal states of the vehicle and the subscript *impact* means the desired states of the impact. And the process constraints cover dynamic pressure, normal acceleration and rate of bank angle,

$$Q \le Q^c_{max} \tag{11}$$

$$n \le n^c_{max} \tag{12}$$

$$|\dot{\phi}_V| \le |\dot{\phi}_V|^c_{max} \tag{13}$$

where Q and n are the dynamic pressure and normal acceleration respectively, and Q^c_{max}, n^c_{max} and $|\dot{\phi}_V|^c_{max}$ are the time-variant profiles of constraints.

Note that the only available control variable of the fixed-trim vehicle is ϕ_V since the AOA α cannot be adjusted. The vehicle would face greater difficulties than other vehicles.

3. Baseline guidance law design

3.1. Motivation of the VTIS guidance law

Considering the multi-constraints, VTIS guidance is demanded by the vehicle due to the fixed-trim configuration. In this section, a more detailed simulation of traditional homing guidance