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Guidance and control system design for hypersonic vehicles in dive phase

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ABSTRACT

A six-degree-of-freedom (6DoF) guidance and control (G&C) scheme for a hypersonic vehicle in the dive phase is proposed in this paper. The 6DoF translational and rotational dynamic and kinematical equations of the hypersonic vehicle are formulated. The intuitive analytical expressions of the 6DoF aerodynamic coefficients of a generic hypersonic vehicle (GHV) are presented. A two-loop control structure is applied for actualizing the 6DoF G&C scheme. The outer loop generates the commands of the angle of attack and the bank angle with the help of the terminal sliding mode control theory and frame system transformation. The inner loop tracks the anticipant Euler angles provided by the outer loop and deduces the required right elevon, left elevon, and rudder fin deflections. Furthermore, the aerodynamic uncertainties and dynamic model uncertainties are accounted for, and extended state observers are employed to estimate these unknown uncertainties. Finally, the effectiveness and robustness of the proposed 6DoF G&C scheme are verified and investigated using the GHV and 6DoF nonlinear simulations.

1. Introduction

Various interests of hypersonic vehicles have been identified due to the prospects for high speed transportation, affordable space access, and development of the next generation reusable launch vehicles [1–4]. Effective guidance and control (G&C) system design is essential for ensuring the feasibility and efficiency of a hypersonic vehicle [5,6]. However, because of the complex aerodynamic properties, high velocity, and complicated flight environment involved, the aerodynamic and motion models of hypersonic vehicles are highly nonlinear and rapidly vary in time, exhibit severe coupling and contain various uncertainties [7,8]. As a result, realizing a G&C system design that assures excellent properties is a key challenge for hypersonic vehicles.

The dive phase is the terminal phase for hypersonic vehicles [9]. The G&C system of the dive phase is expected to steer the hypersonic vehicle to reach the prescribed target and to guarantee that the autopilot subsystem tracks the guidance commands by rule and line. That is, the guidance precision and stability of rotational states are the essential objectives of the G&C system of hypersonic vehicles in dive phase. The design of dive guidance laws and the attitude controllers of hypersonic vehicles have been examined extensively based on modern advanced control techniques. The main objective of the dive guidance subsystem is to establish the relationships between the translational equations and anticipant centroid dynamics. Based on the principle of zeroing line-of-sight (LOS) angle rate and the theory of tracking a reference trajectory, nonlinear control theories such as feedback control [9,12], optimal control [10,13], and sliding mode control [11,14] have been well employed to realize the dive guidance objectives. The primary objective of the attitude control subsystem is to choose the appropriate and efficient automatic control theories to actualize accurate tracking. Consequently, nonlinear control techniques such as the dynamic inversion [15–17], sliding mode control [18,19], and robust control [20,21] have been primary approaches for the attitude controller design of hypersonic vehicles.

Several works have explored the design of guidance laws or attitude controllers of hypersonic vehicles in the dive phase; for example, the studies on the design of point mass guidance laws [9–13], autopilot systems [7,15,17,20], and two-dimensional longitudinal G&C system [1,2]. However, only a few focused on the 6DoF G&C system design of hypersonic vehicles. One reason for the lack of such studies is that the 6DoF aerodynamic models of hypersonic vehicles available in literature are insufficiency. In addition, the 6DoF aerodynamic and motion models of hypersonic vehicles are very complicated, and it is usually difficult to realize 6DoF simulation and analysis. Hence, there is a great need to examine the design and verification of the 6DoF G&C system development of hypersonic vehicles. For implementing the 6DoF G&C system design and simulation, a 6DoF aerodynamic model of

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the hypersonic vehicle should be obtained first. The 6DoF analytic aerodynamic coefficient models for an air-breathing generic hypersonic vehicle (GHV) are reformulated using the least square error criterion and quasi-Newton modified method in the Appendix. Unlike in previous studies [22,23], the problem of the large residual is accounted for in nonlinear curve fitting. For deriving the GHV's aerodynamic models, the original observed aerodynamic data were obtained from reference [24] by the point depiction method. Note that the 6DoF aerodynamic coefficients modeled in this work are suitable for the GHV's hypersonic flight conditions. This paper thus proposes a feasible approach to actualize the design of a 6DoF G&C system of hypersonic vehicles in the dive phase. In this approach, a conventional two-loop control structure is adopted. The outer loop generates the commands of the angle of attack and the bank angle based on the terminal sliding mode control theory and coordinate system transformations. The inner loop tracks the anticipant Euler angles provided by the outer loop and deduces the required right elevon, left elevon, and rudder fin deflections. The aerodynamic and dynamic model uncertainties are accounted for, and the extended state observers are employed to estimate these unknown uncertainties. Two approximate and analytical control allocations are applied for deriving the dive guidance law and the control surface fin deflection. The actual control surface fin deflections are adopted via three second-order fin actuators. Finally, the effectiveness and robustness of the proposed 6DoF G&C scheme are verified and investigated using 6DoF GHV models and 6DoF nonlinear simulations.

This paper is organized as follows. In Section 2, the 6DoF translational and rotational dynamic and kinematical equations of the hypersonic vehicle are described. In Section 3, the use of a two-loop control structure to implement the 6DoF dive guidance and control system scheme is explained; the outer loop is related to the guidance subsystem, and the inner loop is related to the attitude controller. The effectiveness and robustness of the newly proposed 6DoF G&C system are verified in Section 4. The conclusions are provided in Section 5.

2. Dynamic and kinematical models

The 6DoF translational and rotational dynamic and kinematical equations are explained in this section. Because of the high velocity and short range, the Coriolis and centripetal terms are ignored in the 6DoF model of the hypersonic vehicle [9].

2.1. Translational dynamic and kinematical equations

The translational dynamic model in the ballistic coordinate system is given as follows:

$$\begin{cases} \dot{V} = -\dfrac{qS_{ref}C_D}{M} - g\sin\theta + \dfrac{qS_{ref}\Delta C_D}{M} + \Delta_{\dot{V}} \\ \dot{\theta} = \dfrac{qS_{ref}}{VM}(C_L\cos\upsilon - C_N\sin\upsilon) - \dfrac{g\cos\theta}{V} + \Delta_{\theta.L.N} + \Delta_{\dot{\theta}} \\ \dot{\sigma} = -\dfrac{qS_{ref}}{VM\cos\theta}(C_L\sin\upsilon + C_N\cos\upsilon) + \Delta_{\sigma.L.N} + \Delta_{\dot{\sigma}} \end{cases} \tag{1}$$

where V is the velocity magnitude, θ is the flight path angle, σ is the heading angle. g is the gravity acceleration. $q = \rho V^2/2$ is the dynamic pressure, ρ is the atmospheric density. S_{ref} is the aerodynamic reference area. M is the mass of the hypersonic vehicle. υ is the bank angle. C_D, C_L and C_N are the nominal aerodynamic drag, lift, and side force coefficients, respectively. $\Delta_{\dot{V}}$, $\Delta_{\dot{\theta}}$, $\Delta_{\dot{\sigma}}$ are the dynamic model uncertainties with respect to V, θ, and σ. Variables $\Delta_{\theta.L.N}$, $\Delta_{\sigma.L.N}$ are denoted as follows:

$$\begin{cases} \Delta_{\theta.L.N} = \dfrac{qS_{ref}}{VM}(\Delta C_L\cos\upsilon + \Delta C_N\sin\upsilon) \\ \Delta_{\sigma.L.N} = \dfrac{qS_{ref}}{VM\cos\theta}(\Delta C_L\sin\upsilon + \Delta C_N\cos\upsilon) \end{cases} \tag{2}$$

In Eq. (1) and Eq. (2), ΔC_D, ΔC_L and ΔC_N are the aerodynamic drag, lift, and side force coefficient uncertainties, respectively.

Assumption 1. The dynamic model uncertainties denoted as $\Delta_{\dot{V}}$, $\Delta_{\dot{\theta}}$, $\Delta_{\dot{\sigma}}$ and the aerodynamic force coefficient uncertainties denoted as ΔC_D, ΔC_L, ΔC_N are all treated as unknown but bounded terms.

The nominal coefficients of aerodynamic drag, lift, and side forces are functions of several primary independent variables, including the angle of attack, Mach number, sideslip angle, and control surface fin deflections. C_D, C_L, C_N are expressed as follows:

$$\begin{cases} C_D = \boldsymbol{C}_{D,Ma}\boldsymbol{M}_{a,D} + \boldsymbol{C}_{D,\alpha}\boldsymbol{\alpha}_D + \boldsymbol{C}_{D,\delta}\boldsymbol{\delta}_{D,e,a,r} \\ C_L = \boldsymbol{C}_{L,Ma}\boldsymbol{M}_{a,L} + \boldsymbol{C}_{L,\alpha}\boldsymbol{\alpha}_L + \boldsymbol{C}_{L,\delta}\boldsymbol{\delta}_{L,e,a,r} \\ C_N = \boldsymbol{C}_{N,Ma}\boldsymbol{M}_{a,N}\beta + \boldsymbol{C}_{N,\alpha}\boldsymbol{\alpha}_N\beta + \boldsymbol{C}_{N,\delta}\boldsymbol{\delta}_{N,e,a,r} \end{cases} \tag{3}$$

where $\boldsymbol{C}_{D,Ma}, \boldsymbol{C}_{L,Ma}, \boldsymbol{C}_{N,Ma} \in \boldsymbol{R}^{1\times 6}$ are coefficient vectors with respect to Mach number. $\boldsymbol{C}_{D,\alpha}, \boldsymbol{C}_{L,\alpha}, \boldsymbol{C}_{N,\alpha} \in \boldsymbol{R}^{1\times 5}$ are coefficient vectors with regard to the angle of attack. The coefficient vectors related to the control surfaces are denoted as $\boldsymbol{C}_{D,\delta} \in \boldsymbol{R}^{1\times 12}$, $\boldsymbol{C}_{L,\delta} \in \boldsymbol{R}^{1\times 4}$, $\boldsymbol{C}_{N,\delta} \in \boldsymbol{R}^{1\times 10}$. Vectors of Mach number and angle of attack satisfy the following relation:

$$\begin{cases} \boldsymbol{M}_{a,D} = \boldsymbol{M}_{a,L} = \boldsymbol{M}_{a,N} = \left[M_a^0, M_a^1, M_a^2, M_a^3, M_a^4, M_a^5\right]^T \\ \boldsymbol{\alpha}_D = \boldsymbol{\alpha}_L = \boldsymbol{\alpha}_N = \left[\alpha, \alpha^2, \alpha^3, \alpha^4, \alpha^5\right]^T \end{cases} \tag{4}$$

where α is the angle of attack; β is the sideslip angle; and M_a is the Mach number. $\boldsymbol{\delta}_{D,e,a,r} \in \boldsymbol{R}^{12\times 1}$, $\boldsymbol{\delta}_{L,e,a,r} \in \boldsymbol{R}^{4\times 1}$ and $\boldsymbol{\delta}_{N,e,a,r} \in \boldsymbol{R}^{10\times 1}$ are composed of the left elevon δ_e, the right elevon δ_a, and the rudder δ_r. Vectors of the independent variables and the detailed expressions of the aerodynamic force coefficients are described in Appendix A.

The centroid kinematical equations of the hypersonic vehicle depicted in the ground coordinate system are given below.

$$\begin{cases} \dot{X} = V\cos\theta\cos\sigma \\ \dot{Y} = V\sin\theta \\ \dot{Z} = -V\cos\theta\sin\sigma \end{cases} \tag{5}$$

Here, X, Y, Z are the components of the position vector of the hypersonic vehicle with respect to the ground inertial frame system. Under the assumption of non-rotating spherical earth [9], the launcher-fixed ground frame given in [25] is used here as the ground inertial frame system.

2.2. Rotational dynamic and kinematical equations

The rotational dynamic model of the hypersonic vehicle described in the body frame system is denoted as follows:

$$\begin{cases} J_{xx}\dot{\omega}_x + (J_{zz} - J_{yy})\omega_z\omega_y = qS_{ref}L_x(m_x + \Delta m_x) \\ J_{yy}\dot{\omega}_y + (J_{xx} - J_{zz})\omega_x\omega_z = qS_{ref}L_y(m_y + \Delta m_y) \\ J_{zz}\dot{\omega}_z + (J_{yy} - J_{xx})\omega_y\omega_x = qS_{ref}L_z(m_z + \Delta m_z) \end{cases} \tag{6}$$

where J_{xx}, J_{yy}, J_{zz} are the roll, yaw, and pitch moments of inertia, respectively. $\omega_x, \omega_y, \omega_z$ are the roll, yaw, and pitch angular rates, respectively. L_x, L_y, L_z are the reference lengths corresponding to the roll, yaw, and pitch channels, respectively. Further, m_x, m_y, m_z are the roll, yaw, and pitch aerodynamic moment coefficients, respectively. Δm_x, Δm_y, Δm_z are aerodynamic moment uncertainties corresponding to m_x, m_y, m_z, respectively.

Assumption 2. The aerodynamic moment coefficient uncertainties denoted as Δm_x, Δm_y, Δm_z are treated as unknown but bounded terms.