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Disturbance observer-based robust guidance for Mars atmospheric entry with input saturation

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Abstract With low-lifting capability taken into account, a robust guidance law for Mars entry vehicles with low lift-to-drag ratios, such as Mars Science Laboratory (MSL), is presented. Consider the nonlinear term in the drag dynamic equation and bounded disturbances as a lumped disturbance, and design a linear disturbance observer (DOB) to estimate it. With the consideration of the control input saturation, an innovative sliding surface and a virtual system are introduced to design the guidance law. Analyses of disturbance observer performance and Lyapunov-based transient performance are also presented. It is shown that the drag tracking error can be adjustable by explicit choices of design parameters. Simulation results confirm the effectiveness of the proposed guidance law.

1. Introduction

On 5 August 2012, Mars Science Laboratory (MSL) successfully landed inside Gale Crater and became the seventh U.S. vehicle landing successfully on Mars. With the application of a hypersonic guidance, MSL successfully carried out a more accurate landing than previous spacecraft to Mars, such as Vikings I and II, MER Spirit and Opportunity, Pathfinder and Phoenix. The MSL mission finally delivered a nearly 900 kg rover to a final position approximately 2 km from the 4.5965 °S and 137.4019 °E target within an expected touchdown ellipse of 19.1 km × 6.9 km.[1] Also, MSL entry vehicle is the first Mars entry vehicle to perform a guided entry.

MSL entry guidance is divided into three distinct phases according to the order that they occur[2]: pre-bank, range control and heading alignment. Once the filtered drag acceleration magnitude exceeds 1.96 m/s^2 (0.2 Earth g), the MSL entry guidance ceases the pre-bank and begins the range control. During this phase, MSL entry vehicle adopts the entry terminal point controller (ETPC) which is derived from the Apollo final entry phase guidance algorithm[2–5] and modulates the bank angle to control the range flown. A three-segment bank profile is used to meet the parachute deployment constraints and generate a reference trajectory.[2] The time-varying controller gains of the ETPC are generated using influence coefficients with respect to errors about the reference trajectory stored by range-to-go, drag acceleration and altitude rate as a function of relative velocity.[6–9] Similar to the Apollo entry guidance, a bank-reversal logic is used to determine the sign of the bank angle. Whenever the cross range

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to the target exceeds the dead band,[2] which is described as a quadratic function of velocity, the sign of the bank angle is changed to the opposite. Due to larger atmospheric density variations and shorter flight times, a tighter cross range corridor is added for the first bank reversal,[2,8] which improves the performance and reduces the cross range overshoot.

A Mars entry guidance task is to safely and accurately deliver an entry module from its initial conditions to a designated parachute deployment target at the end of the entry phase. To date, quite a few researchers have considered the problem of Mars entry guidance law design. It is universally acknowledged that Mars entry guidance can be divided into two categories[10]: predictive path-planning methods and reference-path tracking methods. Predictive path-planning methods rely on onboard computation for a real-time path planning and guidance solution, such as the predictive drag-based guidance law,[11] the numerical predictive-corrector guidance law[12,13] and analytical predictor–corrector guidance algorithms.[14,15] Reference-path tracking methods require not only a reference trajectory which is preplanned using nominal initial entry states and nominal dynamic models, but also a trajectory tracking control law. To address the problem of trajectory tracking control law design, some advanced control methods like the linear quadratic regulator method,[16,17] the feedback linearization method,[18,19] the state-dependent Riccati equation method,[20] the model reference adaptive control method,[21] active disturbance rejection control[22] and neural networks-based sliding mode variable structure control[23] etc., have been applied to the trajectory tracking control law design.

However, most studies mentioned above rarely take the low-lifting capability of a Mars entry module into account and assume the control input to work perfectly. It should be pointed out that lift-to-drag ratios are quite low and typically about 0.3 or even lower for Mars entry vehicles such as the MSL entry vehicle. These vehicles have a low-level control authority and limited maneuverability.[10,24] The control input is often subjected to saturation. Control input saturation often severely limits system performance, giving rise to undesirable inaccuracy or leading to instability.[25] Therefore, the design of a trajectory tracking controller with the consideration of control input saturation is an important issue and needs to be handled carefully. Another problem for the trajectory tracking controller design is the handling of large dispersions, mainly due to uncertainties of Martian atmosphere.

This paper develops a robust disturbance observer-based trajectory tracking controller for Mars entry vehicles with the control input saturation and the robustness problem taken into account. The nonlinear term and bounded disturbances in drag dynamics are regarded as a lumped disturbance. A linear disturbance observer, derived by the disturbance observer technology,[26–29] is employed to estimate the lumped disturbance. The estimate value is used as a feed-forward compensation to restrain the effects of the lumped disturbance on the trajectory tracking performance. With the difference between the control input and the saturated input as the input, a virtual system is constructed to compensate the effect of saturation. By introducing a novel sliding surface which relies on the drag tracking error and the virtual state, the disturbance observer-based trajectory tracking controller is finally obtained. It is shown that this controller is robust against the unknown bounded time-varying disturbance. Transient performance, which can be adjusted by tuning certain design parameters, is also analyzed in this paper.

2. Entry guidance problem formulation

For an unpowered atmospheric flight over the nonrotating, windless, spherical Mars and the longitudinal translational motion of the entry vehicle can be described by the downrange R, the radial distance form center of Mars r, the relative velocity V and the flight path angle γ as follows:[11]

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

$$\dot{V} = -D - g\sin\gamma \tag{2}$$

$$\dot{\gamma} = [L\cos\sigma - (g - V^2/r)\cos\gamma]/V \tag{3}$$

$$\dot{R} = V\cos\gamma \tag{4}$$

where σ is the bank angle, defined as the angle about the velocity vector from the local vertical plane to the lift vector; the gravitational acceleration g, the aerodynamic drag acceleration D and the lift acceleration L are given by

$$D = 0.5\rho V^2 S_{\text{ref}} C_D/m \tag{5}$$

$$L = 0.5\rho V^2 S_{\text{ref}} C_L/m \tag{6}$$

$$g = \mu/r^2 \tag{7}$$

where μ is the gravitational parameter; S_{ref} is the vehicle reference surface area; C_D and C_L are the aerodynamic drag and lift coefficients; ρ is the Mars atmospheric density; m is the mass of the vehicle. Assume an exponential atmospheric density model as

$$\rho = \rho_0 \exp((r_s - r)/h_s) \tag{8}$$

where ρ_0 is the density at the reference radius; r_s is the reference radius; h_s is the constant scale height.

Energy is used in place of time as the independent variable with the consideration that time is not critical in the entry flight. Define the energy as[13,21,22]

$$E = \frac{V^2}{2} - \frac{\mu}{r} \tag{9}$$

The derivative of E with respect to time is given by

$$\dot{E} = -DV < 0 \tag{10}$$

Therefore, the energy is a monotonically decreasing variable. Considering Eqs. (4) and (10), we obtain the derivate of downrange with respect to energy as

$$\frac{\mathrm{d}R}{\mathrm{d}E} = -\frac{\cos\gamma}{D} \tag{11}$$

Let's assume that the flight path angle is small in the entry flight. Then the downrange flown from the current energy E_0 to the final energy E_f can be approximated by Eq.(12):[10,11]

$$R = -\int_{E_0}^{E_f} \frac{\mathrm{d}E}{D} \tag{12}$$

It is clear that the downrange, as a function of the energy, depends mainly on the drag profile. The drag of an entry vehicle, in turn, can be controlled through the bank angle. If the drag profile is specified by a so-called reference drag profile D_r in advance and a drag tracking guidance law for bank angle magnitude modulation is employed to follow the reference drag profile ideally, then the downrange at the point where $E = E_f$ is also determined. In the guidance scheme of the range control phase, the outer loop predicts the downrange flown