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Mars atmospheric entry guidance for reference trajectory tracking based on robust nonlinear compound controller

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ABSTRACT

A robust entry guidance law based on terminal sliding mode and second-order differentiator is designed for trajectory tracking in this paper. The bank angle is regarded as the control variable. A novel nonlinear compound controller is designed to make the system with the trajectory-tracking error and its rate as states be input-to-state stable (ISS) with respect to uncertainties. The terminal sliding mode controller is designed to the problem of entry guidance by using the second-order differentiator to estimate the total disturbances. The proposed nonlinear compound control law by employing the second-order differentiator and the terminal sliding mode controller, provide robustness, higher control precision. Also, simulation results are presented to illustrate the effectiveness of the control strategy.

1. Introduction

Although further improvements in approach navigation will reduce the landing ellipse, it is clear that closed-loop entry guidance will be necessary to achieve landing accuracy on the order of 10 km from a designated target. Several hundreds of kilometers may be covered by an Mars entry vehicle before it lands, while a few tens of kilometers are covered during descent, and usually there is the least possible lateral motion during landing. This means that much of the vehicles landing precision will first and foremost be affected by the state dispersion accumulated during the entry phase, with only small remaining errors that are recoverable during the descent and landing phases(see [1–5]).

For the entry phase of low Lift-to-Drag ratio vehicles, any closed loop guidance system relies on the bank angle to provide active trajectory control. Therefore, a bank angle program must be determined and actively implemented to achieve the desired targeting performances. Generally, schemes for atmospheric entry guidance are divided into major categories, i.e., a) reference trajectory tracking methods and b) predictive trajectory planning methods(see [6–10]).

Recent years, there are some researches on control designs for Mars lander with highly nonlinear characteristics using nonlinear control techniques(see [11–14]). Some of the research results have been achieved in the research of the atmospheric entry guidance and control method of the Mars Lander (see [9,10,15–20]). In [15], a continuous finite time sliding mode controller is designed for the trajectory tracking control of the Martian atmosphere. Non singular terminal sliding mode and finite time control law based on the super screw algorithm. It is realized that the tracking error can converge to zero in finite time. In [20], a multi sliding mode surface navigation method is proposed to track the reference trajectory. But the algorithm does not consider the uncertain disturbance. In the case of multiple constraints, the proposed method is used to solve the problem of trajectory tracking control of the whole state by using the Legendre spectral transform in [21]. In addition to track a reference trajectory of ideas, most of the resistance to tracking navigation method is need to drag velocity, which for Martian atmospheric entry section of the lander, under the real situation is hard to measure precisely [9,10]. In addition, the most effective way to improve the accuracy of the landing point in the complex Martian atmosphere is to ensure that the Mars Lander runs on a predetermined reference trajectory throughout the atmosphere [22]. Then, the Mars Lander if Mars in the complex atmospheric environment, accurate tracking of preset atmospheric entry trajectory for Mars mission critical guidance (see [23,24,15]). Therefore, this paper considers the high speed to replace resistance speed as the feedback information of the reference trajectory tracking control strategy.

The differential observer is proposed by the famous scholar Aire Levant. Differential observer technique can accurately estimate the perturbation (see [25,26]). A two order differential sliding mode

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observer is proposed for the mechanical system [27]. In [28], a sliding mode controller based on the differential observer is designed to achieve the missile's accurate interception. However, the use of the differential observer to deal with the uncertainty and disturbance of the Mars Lander system is relatively fewer. Moreover, the differential observer is robust and accurate. Therefore, this paper will use the differential observer to deal with the uncertainty and disturbance of the Mars Lander system.

In this paper, the density uncertainty of the Martian atmosphere and the lander gas dynamic uncertain parameters, initial state errors and modeling errors based on non-singular full order terminal sliding mode technique and the differential observer of the Mars Lander atmosphere into the period of robust and high accurate trajectory tracking control problem is discussed. Analysis of the atmospheric into atmospheric density uncertainty, lander gas dynamic uncertain parameters, initial state errors and modeling errors mainly interference effects, design the Mars Lander atmospheric entry trajectory tracking control scheme, the Mars Lander in atmospheric entry the finite time trajectory tracking control. Non-singular full order terminal sliding mode observer to estimate the differential technology and methods, design of anti- interference guidance and control methods compared with the traditional control method of guidance in the aspect of anti-jamming ability is more prominent. The proposed nonlinear compound control law by employing the second-order differentiator provide robustness, higher control precision.

The paper is organized as follows. The Mars entry longitudinal guidance problem is formulated in Section 2. Terminal Sliding Mode Control is presented in Section 3. A novel nonlinear compound controller is presented in Section 4. Simulation results are presented in Section 5 and the paper ends with the conclusion in Section 6.

2. Mars entry guidance problem

The equation of motion of an entry vehicle defined with respect to a planet-fixed coordinate frame are

$$\begin{cases} \dot{\theta} = \frac{V\cos\gamma\sin\psi}{r\cos\phi} \\ \dot{\phi} = \frac{V\cos\gamma\cos\psi}{r} \\ \dot{r} = V\sin\gamma \\ \dot{V} = -D - g\sin\gamma \\ \dot{\gamma} = \frac{1}{V}[L\cos\sigma - (g - \frac{V^2}{r})\cos\gamma] + C_\gamma \\ \dot{\psi} = -\frac{1}{V}[\frac{L\sin\sigma}{\cos\gamma} + \frac{V^2}{r}\cos\gamma\sin\psi\tan\phi] + C_\psi \end{cases} \tag{1}$$

where θ is the longitude, ϕ is the latitude, r is the distance from the center of the planet to the vehicle center of Mars, ψ is the heading angle with $\psi = 0$ as due east, V is the velocity and γ is the flight path angle. L and D are the lift and drag accelerations, defined by

$$L = \frac{1}{2}\frac{\rho S C_L}{m}V^2 \tag{2}$$

$$D = \frac{1}{2}\frac{\rho S C_D}{m}V^2 \tag{3}$$

The drag and lift coefficients C_D and C_L are functions of the Mach number, S is the reference area, m is the lander mass, and ρ is the atmospheric density. The gravity is modeled as $g = \frac{\mu_M}{r^2}$, where μ_M is the Mars gravitational parameter. The term C_γ and C_ψ are the Coriolis accelerations due to Mars rotation, and given as

$$C_\gamma = 2\omega_p\cos\psi\cos\phi \tag{4}$$

$$C_\psi = 2\omega_p(\tan\gamma\sin\psi\cos\phi - \sin\phi) \tag{5}$$

where ω_p is the planet angular rate. Parameters of the entry vehicle dynamics are referred to (1) and given in Table 1.

The attitude control system uses small thrusters to rotate the vehicle in the path and yaw axes, thus to respond to bank angle commands from the guidance system. The control is the bank angle σ and it is defined such that a positive value corresponds to banking to the right. To account for limits in bank rate (20°/s) and bank acceleration (5°/s^2), a first order bank dynamics controller has been implemented. Commanded bank acceleration is calculated using

Table 1
Parameters of Mars entry vehicle dynamics.

Parameters	r_0 (km)	μ_M (m^3/s^2)	$S(m^2)$	ω_p (rad/s)
Values	3387	4.284	12.8825	7.095e−5
Parameters	C_D (1)	C_L (1)		
Values	1.4595	0.3515		

$$\dot{\sigma} = \frac{\sigma_c - \sigma}{\tau} \tag{6}$$

where σ is the current bank angle, σ_c is the commanded bank angle and time constant τ of 1 s was chosen for the numerical results in this paper. Then, limits are applied to both commanded bank acceleration and commanded bank rate to obtain the executed bank.

Finally, the cosine of the bank angle is the parameter employed to control the longitudinal motions. The overall goal is to design and test our algorithm that generates a bank angle program that guides the lander to the desired target point during the entry portion of the descent.

3. Terminal sliding mode control

Here, the goal is to develop a novel non-linear guidance approach for the Mars entry phase based on the application of recent advancements in TSMC theory (see [29–31]). The overall objective is to derive a guidance law (bank angle program) that is a) robust against parameters uncertainties, and b) guarantees good targeting performances at the end of the entry phase. The guidance model employed to develop the terminal sliding mode guidance algorithm is longitudinal descent model described by Eq. (1).

Let

$$\begin{cases} x_1 = r - r_d \\ x_2 = \dot{r} - \dot{r}_d \end{cases} \tag{7}$$

Here, r_d is the desired distance from the center of the planet to the vehicle center of Mars along the reference trajectory, which are a series of values that are stored as a function of range or range-to-go.

Then, take the derivation of (7), we obtain:

$$\dot{x}_1 = x_2\dot{x}_2 = [-D\sin\gamma - g + \frac{V^2}{r}\cos^2\gamma + V\cos\gamma C_\gamma - \ddot{r}_d] + L\cos\gamma\cos\sigma \tag{8}$$

where, we denote

$$f(x, t) = -D\sin\gamma - g + \frac{V^2}{r}\cos^2\gamma + V\cos\gamma C_\gamma - \ddot{r}_d g(x, t)$$
$$= L\cos\gamma u = \cos\sigma \tag{9}$$

where $x = (\theta, \phi, r, V, \gamma, \psi)$.

Then, we can get

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x, t) + g(x, t)u \end{cases} \tag{10}$$

The task of Terminal Sliding Mode Control (TSMC) (see [33,34]) for nonlinear system (10) is to design a control strategy which induces an ideal sliding-mode motion in the prescribed sliding-mode surface and forces system (10) to the origin along the sliding-mode surface asymptotically for TSMC. It is assumed that all constants are known, as well as functions $f(x, t)$ and $g(x, t)$ in system (10), and all coordinates are exactly measurable in real time.