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A New Compound Control for Mars Entry Guidance

Ganghui Shen, Yuanqing Xia *, Lijun Zhang, Jinhui Zhang, Bing Cui

School of Automation, Beijing Institute of Technology, Beijing 100081, China

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Abstract

In this paper, a novel compound control method consisting of adaptive finite-time sliding mode control (AFTSMC) law and final position guidance (FPG) is proposed to achieve high-precision guidance for Mars entry. In the first stage of entry, by employing adaptive law and extended state observer (ESO), an AFTSMC law is designed to avoid the overestimating control gains and then eliminate the chattering effectively. Furthermore, the proposed AFTSMC law not only provides strong robustness against uncertainties but also achieves finite-time convergence of tracking error. In the second stage, a new FPG is used to accurately deliver the vehicle to the required target in three-dimensional space. Therefore, the compound controller combines the advantages of AFTSMC law and FPG method, and numerical simulation results show that the proposed compound controller can not only provide favorable control performance but also improve the entry guidance precision under large uncertainties.

Keywords: Mars entry; Compound control; AFTSMC; FPG; ESO

1. Introduction

In 2012, the latest vehicle named Mars Science Laboratory (MSL) successfully delivered the rover to the surface of Mars in Gale crater. Different from the former unguided Mars landing missions, the MSL mission utilized an active and closed-loop guidance law to improve landing accuracy during entry phase (Prakash et al., 2007). Entry is the mission phase from atmospheric entry interface to parachute deployment point and entry guidance precision has a vital influence on pin-point Mars landing (Garcia et al., 2012; Braun and Manning, 2007). However, the complex Mars environment generating uncertainties and strict constraints are significant error sources leading to large landing dispersions (Prakash et al., 2007; Kornfeld et al., 2014). Moreover, future Mars missions require that the vehicle can precisely reach the scientifically interesting sites in three-dimensional space (Garcia et al., 2012; Liang et al., 2017). Therefore, to improve the entry guidance accuracy and meet the stringent requirement of future Mars missions, effective entry guidance algorithms should be designed.

Generally, there are two main entry guidance algorithms: predictor–corrector guidance and reference trajectory tracking guidance. Predictor–corrector guidance can deliver the vehicle to a target and it is not sensitive to initial dispersions and disturbances (Kluever, 2008; Xia et al., 2015; Brunner and Lu, 2008). But requirements of strong online computing capability restrict its application in engineering practice. Therefore, the reference trajectory tracking method obtains extensive attention in Mars entry guidance (Kluever, 2008). Based on trajectory tracking method, a great number of approaches are employed to improve entry guidance accuracy, such as PID (Mease and Kremer, 1994), feedback linearization (FL) (Saraf et al., 2004), linear quadratic regulator (LQR) (Dukeman, 2002), adaptive control (Li and Peng, 2012),

* Corresponding author.
E-mail addresses: xia_yuanqing@bit.edu.cn (Y. Xia), zhangjinh@bit.edu.cn (J. Zhang).

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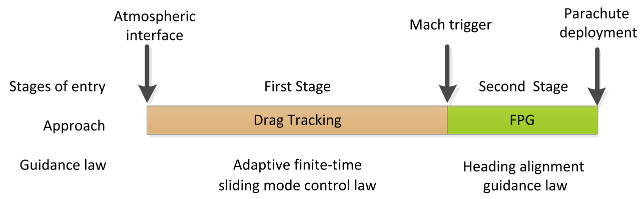

Fig. 1. The timeline of the compound control algorithm.

active disturbance rejection control (ADRC) (Xia et al., 2014) and sliding mode control (SMC) (Li and Jiang, 2015; Huang et al., 2015). However, the above control approaches only obtain asymptotic convergence of the tracking error. Note that finite-time stability of closed-loop system usually exhibits faster convergence rate, better robustness and higher precision. As such, the controller with finite-time convergence property is more attractive for Mars entry trajectory tracking.

Some finite-time control laws are provided for aerospace vehicles based on terminal SMC and integral SMC (Dai and Xia, 2015; Lee et al., 2017; Zhao et al., 2016). Note that control gains of the aforementioned SMC methods are usually relative large to reduce the effect of uncertainties. Large gains may result in chattering phenomenon. Chattering is undesired because it excites high frequency dynamics and leads to instability. In (Con et al., 2012; Utkin and Poznyak, 2013; Zhou et al., 2015; Qiao and Zhang, 2017), the adaptive gain SMC (ASMC) is used to overcome this drawback by adaptive adjusting control gains regardless of uncertain terms. But the gain adaptive law directly depends on the distance between sliding variable and sliding surface, thus overestimation of control gain cannot be avoided and the chattering still exists. To the best of author's knowledge, there is no result on ASMC methods that are designed for achieving both finite-time tracking performance and non-overestimation of control gains simultaneously.

Although the tracking algorithm guarantees that the reference trajectory can be tracked by real state, the heading error reducing horizontal accuracy and altitude error are not considered (Manrique, 2010). It implies that the guidance law only using trajectory tracking method is difficult to ensure that the vehicle precisely reaches the target in three-dimensional space (Liang et al., 2017; Liang and Ren, 2018). Therefore, some final position guidance (FPG) methods are designed to improve guidance precision (Xia et al., 2015; Manrique, 2010). Yet, these method used at the end of entry phase only guarantee the convergence of heading error. To accurately deliver the vehicle to the required horizontal position and altitude, the entry guidance law should switch to a new FPG method in the second stage of entry, which can eliminate the heading error while shaping the heading transient to control the final altitude.

Motivated by aforementioned problems, a novel compound control approach is proposed for Mars entry, which can achieve high-precision Mars landing. The timeline of the compound method is given in Fig. 1. The proposed compound control method includes the merits of adaptive finite-time SMC (AFTSMC) law and FPG method, and main innovations of the paper are summarized as follows: (i) In the first stage of entry, the proposed AFTSMC law not only guarantees the finite-time convergence of tracking error, but also provides strong robustness to uncertainties. (ii) Using the adaptive gain scheme, the AFTSMC law can avoid gain overestimation problem so that the undesirable chattering can be attenuated. In addition, the extended state observer (ESO) is used to reduce the effect of uncertainties and help to resolve the gain overestimation problem. (iii) In the second stage of entry, the new FPG method can drive the heading error to zero while shaping the heading transient by predictor-corrector scheme to control the final altitude. Thus the FPG method can accurately deliver the vehicle to the target. (iv) The proposed compound control method can improve the entry guidance performance and guarantee that the vehicle precisely reaches the desired parachute deployment point in three-dimensional space.

This paper is organized as follows: The entry dynamic problem is formulated in Section 2. The AFTSMC law, used for the first stage of entry, is presented in Section 3. Section 4 presents a new FPG – heading alignment guidance law based on predictor-corrector updating scheme. Section 5 gives simulation results and some discussions. Finally, conclusions are given in Section 6.

2. Model description and problem formulation

2.1. Entry dynamics of Mars vehicle

The MSL utilizes an offset of mass center to create a constant angle of attack which can generate sufficient lift during peak heating and peak deceleration (Manrique, 2010). Since the angle of attack is kept to be the trim angle during Mars entry, the vehicle can be modeled as a point mass flying in a planet-fixed coordinate frame (Benito and Mease, 2010). The vehicle configuration and forces acting on the vehicle during entry phase are shown in Fig. 2. Without taking into account of the Mars' rotation, the standard simplified equations of motion for entry are (Xia et al., 2014; Zhao et al., 2015)

$$\dot{\theta} = \frac{V}{r}\frac{\cos\gamma\cos\psi}{\cos\phi} \tag{1}$$

$$\dot{\phi} = \frac{V}{r}\cos\gamma\sin\psi \tag{2}$$

$$\dot{r} = V\sin\gamma \tag{3}$$

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

$$\dot{\gamma} = \frac{1}{V}\left[L\cos\sigma - \left(g - \frac{V^2}{r}\right)\cos\gamma\right] \tag{5}$$

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

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